Discover Sustainability

Review

Scientists' warning on sustainability: the ecologist point of view, with examples from marine ecosystems

Monica Montefalcone[1,2] · Carla Morri[1,3] · Carlo Nike Bianchi[1,3]

Received: 17 December 2024 / Accepted: 18 March 2025
Published online: 14 April 2025
© The Author(s) 2025 OPEN

Abstract
In recent years, the urgency of achieving sustainability has become a central focus across various scientific disciplines due to the escalating impacts of human activities on the environment in the Anthropocene. In this contribution to the scientists' warning series, we review key ecological insights essential for shaping sustainability strategies to mitigate environmental degradation, and we issue a warning on how sustainability should be pursued in response to these challenges. Drawing on the expertise of ecologists, who understand the complex interactions that underpin natural systems, we explore the balance between ecological, economic, and social dimensions of sustainability, providing examples of case studies on marine ecosystems. Fundamental ecological principles—such as biodiversity conservation, ecosystem services, resilience, and disturbance—are examined to highlight their role as the foundations of sustainable development. This review also underscores the importance of interdisciplinary collaboration in advancing sustainability practices that are both ecologically sound and socially viable. By identifying gaps in current knowledge and advocating for a paradigm shift toward prioritizing ecological integrity, we emphasize the urgent need for science-based policies to address today's environmental issues. Ultimately, this work frames the human-nature relationship as central to sustainable development, calling for enhanced ecological awareness to combat global change, decelerate biodiversity loss, and promote environmental protection.

Keywords Sustainability · Ecological economics · Resilience · Conservation · Global change · Anthropocene

1 Introduction

Over 30 years ago, a group of more than 1700 scientists issued the first "Warning to Humanity", calling for urgent measures to combat the escalating environmental crises caused by human activities [87]. This call was reinforced 25 years later by over 15,000 scientists who signed a second warning [77], highlighting that most of the critical issues identified in the original warning—including climate change, biodiversity loss, and ecosystem degradation—had worsened rather than improved. Today, we stand at a pivotal moment where sustainability is no longer an abstract goal but an urgent necessity. As marine ecologists, we are deeply concerned about the sustainability of our oceans and the life they support. The marine environment, which plays a fundamental role in regulating climate, sustaining biodiversity, and providing

✉ Monica Montefalcone, monica.montefalcone@unige.it | [1]Seascape Ecology Laboratory, Department of Earth, Environment and Life Sciences (DiSTAV), University of Genoa, Corso Europa 26, Genoa, Italy. [2]National Biodiversity Future Center (NBFC), Piazza Marina 61, Palermo, Italy. [3]Department of Integrative Marine Ecology (EMI), Stazione Zoologica Anton Dohrn–National Institute of Marine Biology, Ecology and Biotechnology, Genoa Marine Centre (GMC), Villa del Principe, Piazza Principe 4, Genoa, Italy.

essential resources, is under unprecedented pressure from overfishing, pollution, habitat destruction, and climate change. If we fail to act, we risk crossing ecological thresholds that could lead to irreversible damage.

In this review, we present a "warning to humanity" by critically examining the concept of sustainability from an ecological perspective, stressing the necessity of introducing elements of ecological theory into economic theory. We recall current knowledge on the resilience and vulnerability of ecosystems, with selected examples from the marine environment, and discuss key scientific insights that should inform conservation and management strategies. By emphasizing the need for science-driven policies rooted in ecological sustainability, our goal is to enrich the broader sustainability debate highlighting the urgency for transformative action.

In recent years, many terms from the ecological lexicon have entered common usage, becoming fashionable in various social and economic contexts. In an era of growing human impact on nature, the so-called Anthropocene [22], this trend may positively indicate a growing interest in the natural environment. However, it may also lead to the misuse or even abuse of these terms. This may be true also for "sustainability" [95], a word now prevalent in advertising, electoral programs, and industrial and commercial projects. It is, therefore, essential to explore the concept of sustainability within an ecological framework.

Ecologists define sustainability as the ability of a process or state to be maintained at a certain level indefinitely over time. The term derives from the English verb 'to sustain', which primarily means to hold up or support. It is only secondarily, and depending on the context, that the notion of duration over time is emphasized. In ecological terms, the primary importance is that the process or state must continue over time, not just be sustained momentarily. Other languages stress duration more explicitly, such as the German *Nachhaltigkeit* or the French *durabilité*. Other Romance languages have adopted, like English, the term sustainability (Italian: *sostenibilità*, Spanish *sostenibilidad*, Portuguese *sustentabilidade*).

The guiding principle of sustainability is the "sustainable development", a phrase first introduced by the Brundtland Commission of the United Nations on March 20th, 1987 [95]. The concept of sustainable development emerged from the growing environmental awareness among the international community, leading to the establishment of regulations aimed at mitigating the negative effects of pollution and the exploitation of natural resources caused by uncontrolled economic growth. Since then, this term has become the cornerstone of international environmental protection legislation. Sustainable development involves resource exploitation, investment planning, technological progress, and institutional changes that enhance existing potential to meet the needs and aspirations of both current and future generations.

From a more formal perspective, sustainability was historically conceptualized through the "three-pillar model" [17], which emphasizes the interconnectedness of three core dimensions: economy, society, and environment (Fig. 1). This framework posits that true sustainability can only be achieved when these three pillars—economic growth, social equity, and environmental protection—are in balance and mutually reinforcing. It asks for policies and practices that simultaneously promote economic development, social well-being, and the health of the natural world, recognizing that progress in one area cannot come at the expense of the others. The economy must hold the ability to generate income and employment to support the population. Society must ensure human well-being (safety, health, and education) for all, without discrimination based on class or gender. The environment must be allowed keeping its quality to safeguard the renewability of natural resources. There is equity if economic development does not create social imbalances, feasibility if it is compatible with the availability of environmental resources and services, and livability if society thrives in a non-degraded environment. However, only a harmonious relationship between economy, society, and environment can guarantee sustainability. Another way to represent the concept of sustainability is through the analogy of a three-legged

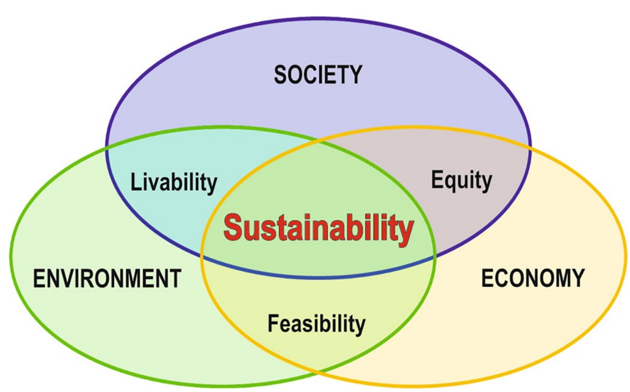

Fig. 1 The concept of sustainability as in the "three-pillar model", with the intersection of three sets: economy, society, and environment

stool, where the legs are economy, society, and environment: if one leg breaks, the stool cannot stand. The interconnection between these three pillars highlights the importance of an integrated approach to policymaking. For instance, economic policies should not undermine environmental regulations, and social policies should be designed to support sustainable economic growth.

The concept of sustainability has evolved beyond the traditional "three-pillar model", moving toward a more integrated perspective that recognizes the nested relationship between ecological systems and human societies [51]. In this "one-pillar" framework, sustainability is understood through a multilevel approach that considers values—societal, personal, and global—as well as spatial and temporal scales [33]. This perspective maintains that the well-being of human societies is fundamentally dependent on the health of the environment. Societal stability, in turn, relies on the continuous and predictable flow of goods and services from the ecosystems in which it is embedded, assuming ecological integrity as a foundation for sustainable development. The synergy between all these dimensions can drive innovation and resilience, fostering a balanced and enduring development model. Additionally, many authors emphasize the importance of the institutional framework, which must ensure conditions of stability, democracy, participation, and justice, as without these, no development can be truly sustainable. In summary, sustainability is a multi-faceted concept that requires a long-term vision and a holistic approach. It demands a balance between economic growth, social inclusion, and environmental protection, underpinned by strong institutional frameworks. By adhering to these principles, we can work towards a future where the needs of the present are met without compromising the ability of future generations to meet their own needs.

In this review, sustainability will be examined predominantly from an ecological perspective, with a strong emphasis on environmental considerations. While it is unavoidable to touch upon societal and economic aspects—given their increasingly intertwined relationship with ecological issues—the core objective of this work is to delve deeply into the environmental challenges that we face. The examples brought forward are drawn from Mediterranean (and Italian in particular) marine ecosystems, reflecting the authors' own experience [9]. However, the insights gained from these examples are broadly applicable and can provide valuable perspectives in a variety of other ecological contexts.

2 Economy and ecology: sisters separated?

Both the words "ecology" and "economy" share the same Greek root, *oikos*, meaning home. However, the term "home" in an ancient Greece context was more complex than its modern usage. It encompassed all the material goods of the household (lands, flocks, treasures, buildings) as well as human beings (family members, employees, slaves). In the Homeric era, the *oikos* represented the basic unit of society, a unit of both consumption and production with comparatively limited external connections. The *oikos* included the lands for crops and pastures where flocks and people lived, the family's living space, and the storage of food reserves and precious objects. Flocks were inseparable from the lands and considered part of the wealth. Thus, *oikos* should be understood as everything that contributes to the sustenance of life. The contemporary term closest to this concept is "environment" (from the French *environnement*, coming in turn from *environ*, meaning "around"). In the scientific literature, the idea of environment was first introduced with the German word *Umwelt*, derived from *um* (around) and *Welt* (world), indicating the world surrounding an observer in a central position. The corresponding Italian word is *ambiente* (from Latin *amb* + *ire*, meaning "that flows around"); the homologous word "ambient" in French and English has a similar but more restricted meaning. Ecology, therefore, is the study (from the Greek *logos*, meaning discourse, reasoning, discussion) of the environment, which surrounds and supports organisms, including humans. In contrast, the economy deals with the management (from the Greek *nomos*, meaning law or act of legislating) of the environment, or—more specifically—its resources.

The common root of "economy" and "ecology" underscores the affinity between the two disciplines, suggesting that they should follow common paradigms. Charles R. Darwin (1809–1882), renowned for his work on evolution, was deeply involved in what we now call ecology. He was an ecologist *ante litteram*, as the term "ecology" had not yet been coined at his time. The word was introduced in 1866 by the German physician and naturalist Ernst Heinrich Haeckel (1834–1919), a follower and admirer of Darwin's work. To refer to what Haeckel later named "ecology", Darwin used the very appropriate phrase "economy of nature". Unfortunately, despite their obvious affinity, economy and ecology have seemingly diverged and are often viewed as conflicting. Until a few decades ago, many politicians and public managers widely held the belief that a choice had to be made between economic development and environmental protection. Even in recent times, the Trump Administration in the USA based its political agenda on the assumption that ecology hinders economic progress. However, reality might not align with this point of view. For instance, a study conducted in the Ligurian Sea (NW

Mediterranean) on the seagrass *Posidonia oceanica* demonstrated that the implementation of environmental protection policies did not hinder regional economic growth [18].

Posidonia oceanica, a seagrass endemic to the Mediterranean Sea, forms extensive subtidal meadows (Fig. 2a) that play a crucial role in the functionality of entire coastal ecosystems [89]. These meadows are characterized by structural and functional complexity [66] and harbour an elevated biodiversity [61]. Like other seagrasses, *P. oceanica* is a recognized indicator of water quality and seafloor integrity [55]. Consequently, seagrasses are the focus of conservation efforts [57]. Regrettably, seagrass meadows in the Mediterranean are generally degraded (Fig. 2b–d) due to coastal anthropization [84] and invasive macroalgal species [71], which can replace *P. oceanica* within its meadows [56].

The Ligurian Sea, the northernmost and coldest sector of the Mediterranean, boasts a rich history of research on seagrass meadows. Knowledge of *P. oceanica* in Liguria (an administrative region in NW Italy) dates back over a century, thanks to the pioneering work of Raffaele Issel (1878–1936). In the first Italian textbook of marine biology, Issel [41] wrote: “It would be interesting to know the distribution of the seagrass, which forms a green belt along our coasts”. However, it took nearly three-quarters of a century to achieve this goal, with comprehensive mapping efforts conducted along the entire Ligurian coastline [10]. This large-scale mapping became feasible due to modern survey technologies (e.g., aerial photography, acoustic surveys, remotely operated vehicles, scientific scuba diving, etc.) not available in Issel’s times.

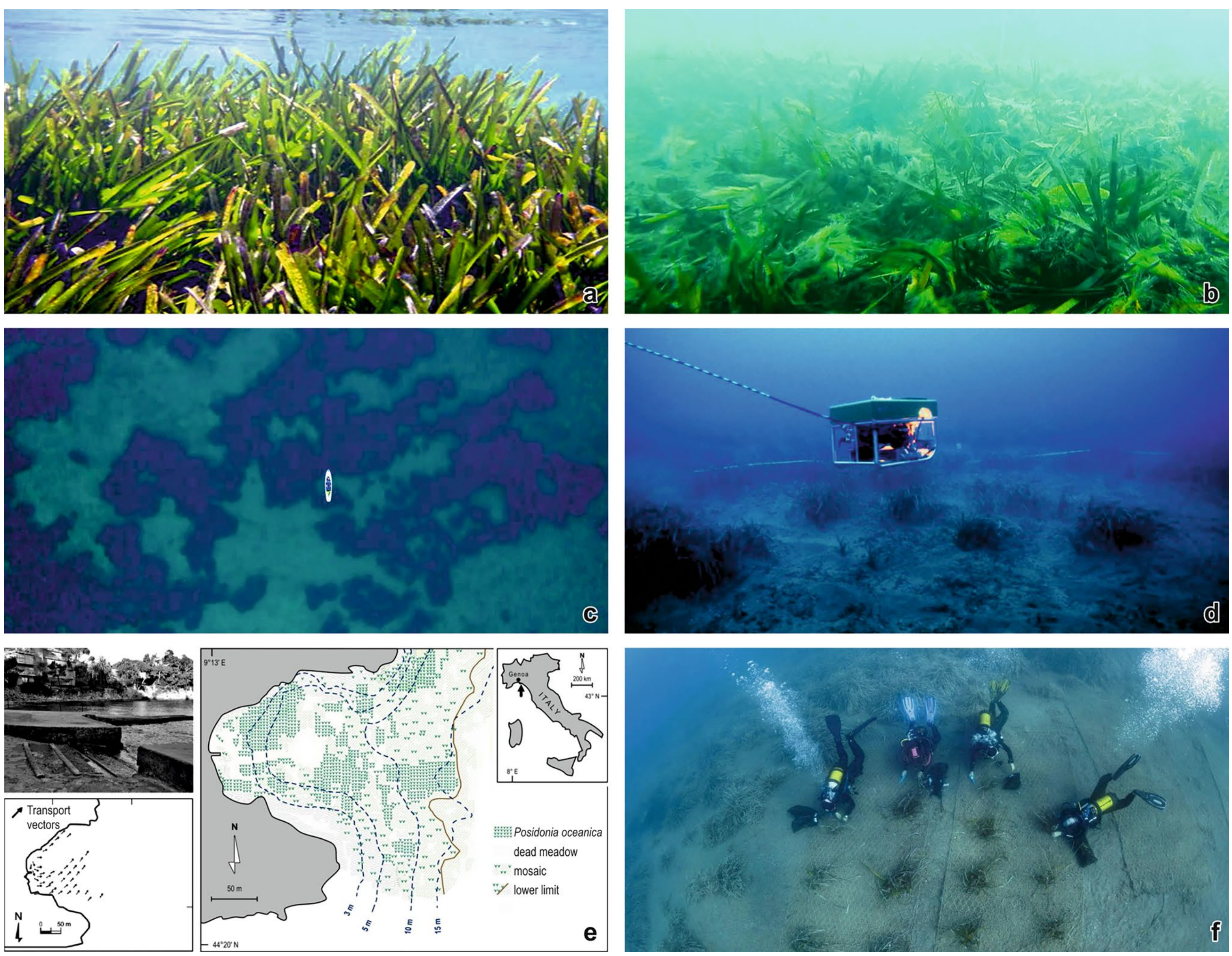

Fig. 2 *Posidonia oceanica* meadows: **a** an healthy meadow; **b** severely degraded meadow; **c** fragmented upper limit; **d** regressive lower limit; **e** map of the residual meadow of Prelo cove (Ligurian Sea), where the construction of a mooring pier and a slipway for small boats in the first decades of the twentieth century (photo top left) required excavation of the meadow and led to the alteration of the morphodynamics of the cove (bottom left diagram), resulting in a loss of over 50% of the original extent of the meadow; **f** restoration of a *P. oceanica* meadow, planting bundles in areas where it has disappeared due to human impacts

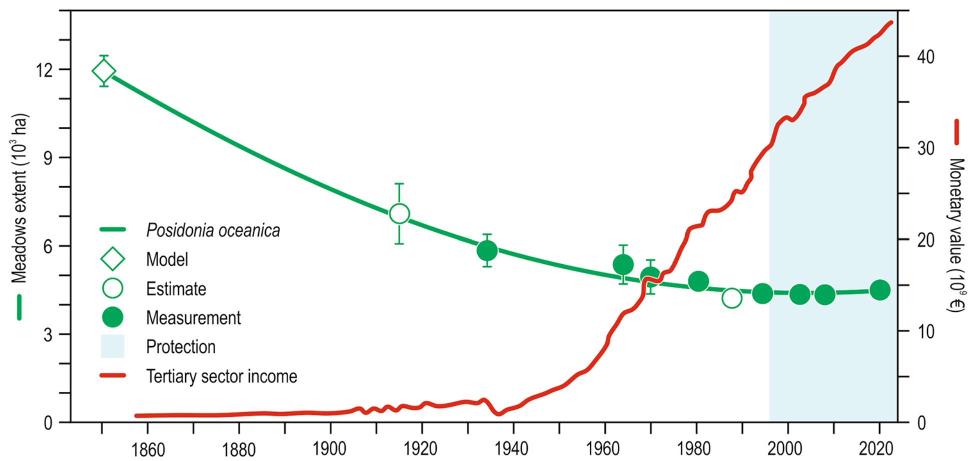

Fig. 3 Temporal trends in the extent of *Posidonia oceanica* meadows (derived from modelling, expert estimates, and cartographic measurements) and the economic value of the tertiary sector in Liguria (NW Italy)

The information collated, including cartographic measurements, educated guesses by experts, and morphodynamic modelling [90], enabled the reconstruction of historical changes in *P. oceanica* meadows in Liguria [19]. It was estimated that, starting from the mid-nineteenth century—coinciding with the construction of the Ligurian coastal railway, which significantly impacted the coastal zone—more than half of the original extent of the seagrass beds has been lost. From a potential extent of 12,000 hectares, it has dwindled to approximately 5,000 hectares. However, over the last two or three decades, the implementation of protective measures—such as local regulations by the Liguria Region, the designation of Natura 2000 sites (in accordance with the EU Habitat Directive 92/43/EEC), and the establishment of national marine protected areas—appears to have halted the degradation of *Posidonia oceanica* meadows, and even facilitated some recovery [3]: similar instances of local recovery in *P. oceanica* meadows have recently been reported on a Mediterranean-wide scale [25]. During these decades of protection, the Ligurian economy has continued to grow, much like in previous decades when such measures were not yet in effect (Fig. 3). The case of *P. oceanica* in Liguria thus suggests that environmental protection and economic development are not inherently incompatible [18].

Recently, growing concerns over environmental degradation have led to the emergence of two distinct economic paradigms: the "green" economy, primarily focused on terrestrial environments, and the "blue" economy, which centres on marine systems. Both approaches aim to integrate ecological principles into economic frameworks, promoting sustainable resource use while maintaining ecosystem integrity. This review explores the role of ecological theory in shaping these paradigms, examining how past and present ecological insights have influenced, or could further contribute to, the development of truly sustainable green and blue economies. Key topics of discussion will include:

- Demoecology (i.e., population ecology);
- The concept of ecological footprint;
- The importance of ecosystem services;
- The value of natural capital;
- The potential existence of insurmountable limits to economic development;
- The meaning of resilience;
- The intermediate disturbance hypothesis.

3 Demoecology

Demoecology (from the Greek *dèmos* = people) is the branch of ecology that studies the structure and dynamics of populations, including the human one. Natural populations, whether of animals, plants, bacteria or fungi, tend to grow according to what is known as the biotic potential curve (Fig. 4). This is an exponential curve, which can be represented by the equation:

$$dN/dt = r \cdot N$$

where N is the number of individuals, t is time, dN/dt is the growth rate per unit time, and r is the intrinsic growth rate. However, the biotic potential is never fully realized, as it would quickly result in a number of individuals that the

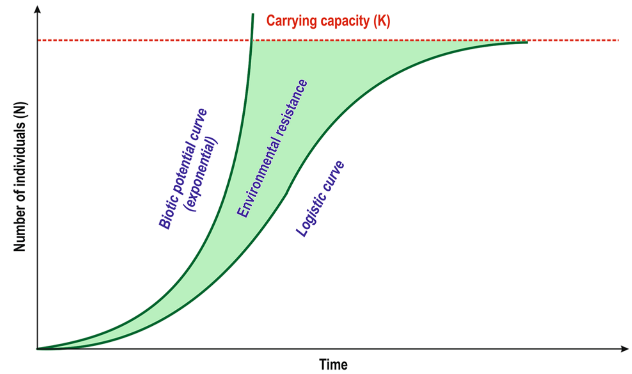

Fig. 4 Theoretical growth curves of a population. The area between the exponential curve and the logistic curve represents the environmental resistance

environment could not sustain. Consequently, the actual growth of populations is typically described by the logistic equation:

$$dN/dt = r \cdot N \cdot (K - N)/K$$

where K represents the carrying capacity, that is the maximum number of individuals that the environment can sustainably support for the given population. As the population size (N) increases, the environment increasingly restrains exponential growth, preventing the population from exceeding its carrying capacity (K). This environmental resistance manifests in many ways:

- Depletion of resources (food, water, shelter, space for activity);
- Habitat degradation (accumulation of waste, alteration of biogeochemical cycles);
- Overcrowding (physiological and reproductive stress);
- Spread of diseases (due to crowding and deteriorated environmental conditions);
- Increase in intraspecific competition and aggression;
- Greater control by other species (predation, parasitism, interspecific competition).

Considering the human population, environmental resistance has apparently been effective throughout prehistory. During the Middle Pleistocene transition, associated with a severe cooling phase, *Homo sapiens* ancestors experienced a significant population bottleneck starting around 930,000 years ago and lasting nearly 120,000 years, leading to a drastic reduction in population and bringing them close to extinction [40]. Throughout the Palaeolithic, the world was likely inhabited by less than a million humans. This number increased in the Neolithic due to technological innovations such as agriculture and livestock farming, with an estimated population of around 8 million individuals about 10,000 years ago. Around the year zero, the human population was approximately 250–300 millions, a number that remained relatively stable throughout the Middle Ages (Fig. 5). After this period, the population began to increase rapidly: the first billion was reached around 1815, three billions by 1960, and seven billions by 2012. Towards the end of 2022, the population reached eight billions [63]. This growth rate surpasses the one described by an exponential curve, and never in Earth's history has a large-sized species been as abundant as are humans today. Projections indicate that the global population could reach 10 to 11 billions by the end of the century. However, this trajectory is not inevitable—socially responsible policies and actions will be essential to shaping a more sustainable demographic future [21].

This frantic growth of human population, often referred to as the "population bomb" [26], has been facilitated by the general improvement in living conditions and the advancement of medicine, which has eradicated many diseases, reduced infant mortality, and increased life expectancy. While these are undoubtedly positive achievements, the current rate of global population growth is clearly unsustainable. Consequently, many experts advocate for a reduction in natality rate through birth control measures. Lower natality should slow the growth of the human population, keeping the number of individuals within more acceptable limits. This is what has been observed in recent decades, particularly in the economically most developed nations: between 1960 and 2022, the global population growth rate halved [83]. However, the downside of reduced birth rates is a distortion of demographic pyramids, which get a "mushroom" shape: the average age increases while the proportion of young people decreases. This demographic shift creates significant socio-economic challenges, especially straining social security systems [37]. Therefore, the governments of many nations

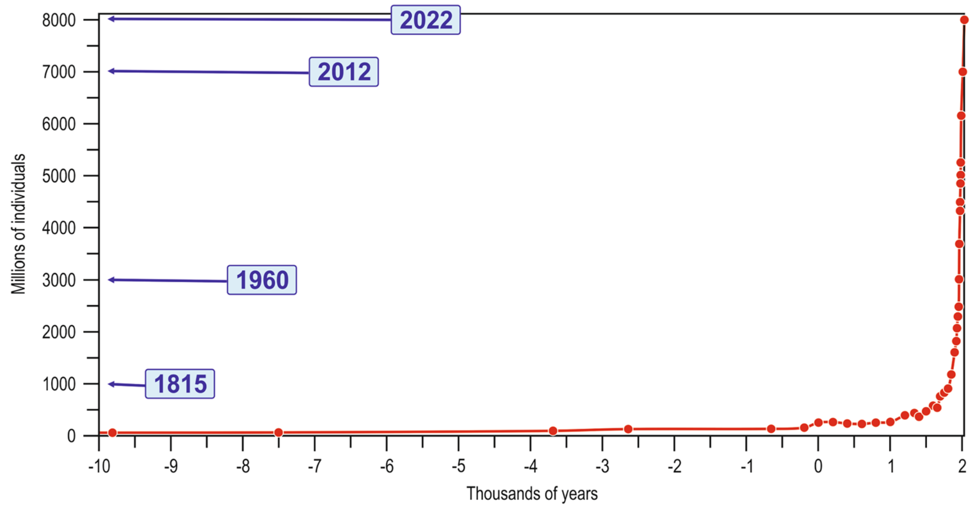

Fig. 5 Growth of the global human population from the Neolithic era to the present day, with emphasis on dates marking major steps in population growth

are promoting initiatives to encourage natality. Yet, an increase in birth rates will inevitably contribute to a further population growth, exacerbating the issue of global overcrowding and creating a vicious cycle that undermines prospects for sustainable development.

4 The ecological footprint

The impact of humanity on our planet stems not only from population size but also from the standards of living, including consumption of resources and waste production [50]. This concept underpins the notion of "ecological footprint" [93]. The ecological footprint is both a conceptual framework and a measurement tool, assessing the extent to which human society strains the Earth by comparing resource consumption to the planet's capacity for regeneration. The ecological footprint can be assessed through various metrics. The ecological backpack represents the total weight of resources required throughout the lifespan of a product: from the extraction of raw materials, through manufacturing, to the final disposal. The water footprint measures the total volume of water used or contaminated directly or indirectly per unit of time or functional unit within a process or the production of a good or service, it includes all the water withdrawn and utilized for system operation, agricultural irrigation, or livestock hydration. The carbon footprint quantifies the amount of CO_2—a primary greenhouse gas—emitted during the lifecycle of a product or activity, from raw material extraction to processing, production, transportation, use, and disposal; the CO_2 footprint is typically expressed as carbon dioxide equivalent (CO_2e) or the land area needed for carbon dioxide absorption via reforestation. The nitrogen footprint quantifies the impact on the nitrogen cycle and its environmental consequences, measuring the amount of reactive nitrogen (such as NO_x, N_2O, NO_3^-, and NH_3) released due to human activities. A broader and more comprehensive measure involves assessing the amount of productive land required to sustain everyone's resource consumption and manage the waste generated—a concept known as biocapacity, measured in global hectares with average biological productivity. Calculation typically considers six primary land-use categories:

1. Area required to absorb CO_2 emissions from fossil fuels;
2. Arable land used for food and goods production;
3. Land designated for livestock breeding;
4. Land allocated for timber production;
5. Urban and built-up areas;
6. Marine surface area dedicated to aquaculture and fishing.

The planetary biocapacity is estimated at 12 billion hectares, which represents only 23% of the total surface area of the planet, amounting to 51 billion hectares. For ecological balance, humanity's ecological footprint should ideally match or be less than this biocapacity. Dividing the 12 billion hectares by the 8 billion individuals on Earth, each person theoretically has approximately 1.5 hectares available, representing the sustainable ecological footprint.

Humanity requires about 20 billion hectares of land, resulting in an actual ecological footprint of around 2.5 hectares per person on average—a 60% excess. This imbalance manifests in functional deficits, such as the Earth's inability to absorb all the carbon dioxide emitted, leading to its accumulation in the atmosphere and exacerbation of the greenhouse effect.

The ecological footprint can be calculated for individuals, enterprises, economic activities, and entire nations. Countries like the USA, Canada, Europe, and Japan typically have large ecological footprints, while most African nations have smaller footprints. If everyone in the world lived at the standard of living of Italians, it would require two and a half planets; living like Americans would necessitate nearly five planets, Australians over nine, and Luxembourgers almost sixteen! Essentially, this means that the world's richest countries can sustain their living standards only because many people worldwide live below the poverty sill.

The disparity between ecological footprint and biocapacity can also be illustrated using a calendar analogy. Dividing the annual footprint by 365 allows each day to represent the gradual consumption of hectares until it exceeds biocapacity. The day when this limit is surpassed is known as Earth Overshoot Day, marking the commencement of using fertile land without replenishment. Ideally, the Overshoot Day should occur at the end of the year, but since the 1970s, this has not been the case. In 1992, the Overshoot Day fell on October 21st; by 2012, it had moved to August 20th, and in 2022, it arrived on July 28th. When the Overshoot Day will coincide with June 30th, it will mean that humanity would require two planets to sustain its consumption rate.

Substantial political and administrative reforms are necessary to reduce the ecological footprint of nations and cities. However, at the individual level, everyday actions can already make a difference. A widely embraced slogan encourages integrating the 'three R' of sustainability into personal lifestyles:

1. Reduce. Decrease consumption to minimize resource usage and waste generation;
2. Reuse. Opt to use materials multiple times in their original form instead of disposing them after the first use. Avoid single-use products whenever possible;
3. Recycle. Transform waste materials into new products through physical and chemical processes, a core principle of the circular economy. While individuals play a role by properly sorting waste, the effectiveness of recycling ultimately depends on administrations establishing and maintaining the necessary industrial infrastructure for processing and transformation.

The personal ecological footprint includes various components: consumption (including clothing, furniture, electronics) accounts for approximately 31%, nutrition (food and beverages) for 28%, housing (water, electricity, gas) for 19%, private mobility (commuting, vacations, travel) for 12%, with the remaining 10% attributed to other items. It may come as a surprise that over a quarter of our ecological footprint is influenced by our dietary choices.

Ecological theory calculates that the efficiency of food chains is approximately 10%, meaning that at each trophic level transition, 90% of biomass is lost through respiration, while only 10% is transferred to the next higher trophic level. This implies that consuming one-hundred grams of veal meat is like consuming a kilogram of vegetables. A predominantly carnivorous diet results in an ecological footprint about ten times larger than a vegetarian diet. However, as long as our diet is based on land products, the ecological impact remains manageable: we predominantly eat vegetables (bread, pasta, rice, legumes, greens, fruits), drawing from the first trophic level, and the comparatively few meat we consume is mostly herbivore meat from the second trophic level. The situation changes radically when we consume seafood. Unlike land-based diets, seafood diets mostly include carnivorous fish, which are usually top predators occupying the fourth or fifth trophic level. For example, consuming one-hundred grams of tuna is like consuming a metric ton of vegetables. Comparing two similar hypothetical menus—one based on land products and the other on sea products—reveals that despite slightly lower caloric intake, the seafood menu requires a consumption of primary (vegetable) production approximately 25 times greater than the land-based menu (Table 1). Thus, from an ecological footprint perspective, a meal based on seafood equates to consuming 25 meals based on land products.

The issue of marine resource consumption is exacerbated by widespread overfishing. Currently, 31% of global seas are overfished, 58% are at their sustainable limits, and only 11% are underfished [27]. In the Mediterranean, over 90% of fish stocks are exploited beyond sustainable levels [15]. Moreover, fishing impacts more than just the targeted fish stocks. Pelagic fishing (Fig. 6a, b), for instance, unintentionally captures cetaceans, turtles, and seabirds. Demersal fishing (Fig. 6c,d) impacts mechanically the seabed, destroying its delicate ecosystems. Divers often encounter lost fishing gears entangled on the seabed (Fig. 6e), where its non-biodegradable materials persist for long. Future fisheries must operate on sustainable principles and actions [80] that minimise environmental impacts, allow for the regeneration of depleted biodiversity, and adapt to climate change.

Table 1 Comparison between caloric intake and equivalent primary (plant) production consumption of two hypothetical menus that are similar but based on land or sea products, respectively

Course	Calories per serving	Equivalent primary production
TASTING MENU: LAND		
Appetizer (cold cuts and pickles)	150	3720
First course (raviolis with meat sauce)	580	3190
Second course (mixed meat grill)	421	13,650
Dessert (lemon sorbet)	132	1320
Total	**1283**	**21,880**
TASTING MENU: SEA		
Appetizer (oysters)	57	570
First course (fish raviolis)	580	290,290
Second course (mixed fish grill)	271	27,100
Dessert (lemon sorbet)	132	1320
Total	**1040**	**563,180**

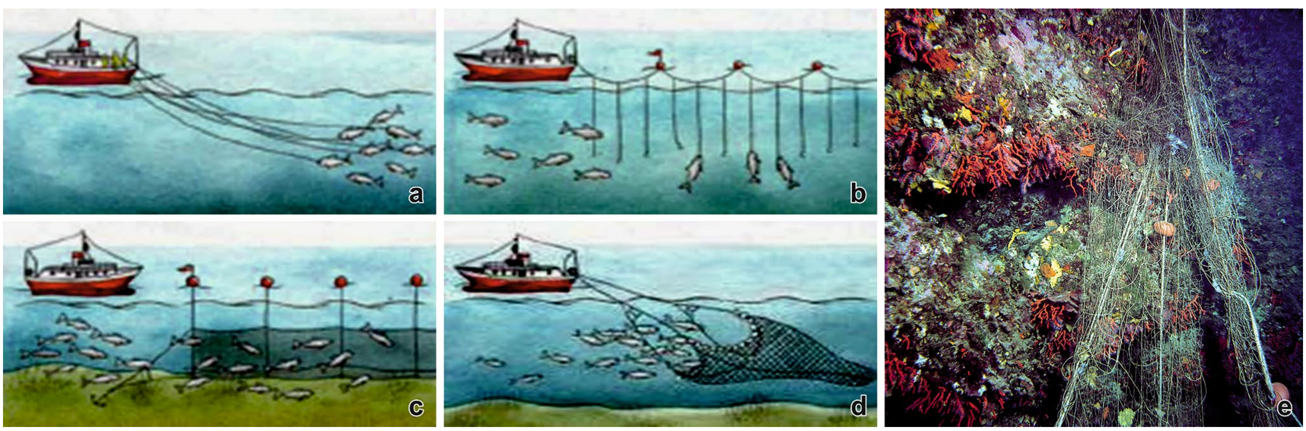

Fig. 6 Environmental impact of fishing: **a** trolling; **b** longline; **c** trammel net; **d** trawl; **e** a lost net entangled on a rocky wall populated by the precious red coral *Corallium rubrum*

5 The importance of ecosystem services

Overfishing serves as a prominent example of resource overconsumption. Classical economists like François Quesnay and the physiocrats, Adam Smith, David Ricardo, and John Stuart Mill, consistently recognized that resource scarcity could hinder economic development [11]. The renowned English economist Lionel Charles Robbins (1898–1984) defined economics as "the science which studies human behaviour as a relationship between ends and scarce means which have alternative uses" [78]. Traditionally, classical economics focused on enhancing efficiency in resource extraction rather than on preservation. Only recently has the economy begun to acknowledge the costs associated with environmental degradation and the resultant decline in ecosystem services [20].

The concept of ecosystem services, intrinsically linked to biodiversity [48], gained attention beyond the academic world thanks to the Agenda 21 (literally: the things to do for the twenty-first century). Agenda 21 is a UN action plan drafted in 1992, which outlines global, national, and local initiatives to be undertaken by United Nations System organizations, governments, and key stakeholders to address human impacts on the environment. This programmatic document explicitly recognized ecosystem services alongside the goods provided by ecosystems. Section 15.2 specifically said: "The essential goods and services provided by the planet's ecosystems depend on the variety and variability of genes, species, populations and ecosystems. The current decline in biodiversity is largely due to human activity and represents a serious threat to human development". Biodiversity is here for the first time clearly defined in a political, not scientific, context.

And it is also the first time that in an international document, signed by many governments and organizations, it is stated that the conservation of biodiversity is necessary for development and not an impediment to the economy, as has often been stated in the not-too-distant past. Similar concepts and goals are now expressed in Agenda 2030 (i.e., Sustainable Development Goals to be achieved by 2030), where sustainable development takes centre stage in the document's goals.

In reality, classical economics has consistently overlooked ecosystem services. Traditional economic calculations for industrial processes typically account for inputs from ecosystems (raw materials), inputs from society (workforce, semi-finished products, transportation), and outputs directed toward society (finished products for the market). Outputs directed toward ecosystems (such as waste and pollutants released into the environment) have historically been disregarded. However, rejects and waste must undergo mineralization through biogeochemical cycles, and contaminated air and water require purification. These ecosystem services are not quantified in terms comparable to economic services and industrial products, thus they are often overlooked and undervalued [23]. The prioritization of production, consumption, and market laws has led economic science to neglect understanding the fate of consumed goods: a product sold is perceived as having vanished, while waste—considered a non-monetary element—is seen as nonexistent. Economic focus is still primarily on market-exchanged goods for monetary value, disregarding any phenomenon that lacks a direct monetary exchange (termed an externality) from economic calculation and evaluation [11].

In contemporary economic and financial evaluations of intervention and development projects, there is an increasing recognition of externalities—the impacts of these projects on natural environment and its capacity to provide ecosystem services. The challenge lies in effectively monetizing environmental assets and the diverse benefits that ecosystems offer humanity. A crucial initial step is to qualify and quantify ecosystem services. In 2005, the United Nations Millennium Ecosystem Assessment identified four categories of ecosystem services [54]:

1. Provisioning services: the products obtained from ecosystems, including food, water, oxygen, drugs, timber, fibre, fuels, and genetic resources;
2. Regulating services: the benefits obtained by ecosystem processes, including air and water purification, waste mineralisation, climate mitigation, flood prevention, storm protection, disease control, and pollination;
3. Cultural services: the non-material benefits people obtain from ecosystems through spiritual enrichment, education and research, cognitive development, recreation, and aesthetic experiences;
4. Supporting services: the services that are necessary to produce all other ecosystem services, such as soil formation, photosynthesis and primary production, biogeochemical cycles, habitat creation and biodiversity maintenance.

It should be noted that provisioning services practically correspond to the goods mentioned in Agenda 21, thus eliminating the distinction between goods and services and unifying the terminology and evaluation. Recently, this classification has also been extended to the marine environment [59, 65]. Among the marine ecosystem assessments, the most comprehensive and detailed have been conducted on seagrass beds, particularly focusing on *Posidonia oceanica*. The ecosystem services they provide include biomass production, oxygenation of waters, and especially coastal protection through wave attenuation and sediment retention. The economic value of these services has been estimated to reach potentially 2 million Euros per hectare per year [92]. However, this estimate applies to meadows in optimal conditions, whereas seagrass beds in the Mediterranean Sea are generally degraded [16]. Based on available data from the Ligurian Sea, estimates for degraded seagrass beds are significantly lower, averaging less than 200,000 Euros per hectare per year [76]—an order of magnitude lower than the theoretical value (Fig. 7).

6 The value of the natural capital

It is now evident that ecosystem services, encompassing both tangible goods and services provided by ecosystems, possess economic value. Consequently, they constitute a genuine natural capital, comparable to human and financial capitals—those exclusively recognized by classical economics. For instance, in calculating Gross Domestic Product (GDP), which serves as the primary indicator derived from national accounts, classical economics employs the following formula:

$$\mathrm{GDP} = \mathrm{C} + \mathrm{I} + \mathrm{E} - \mathrm{M}$$

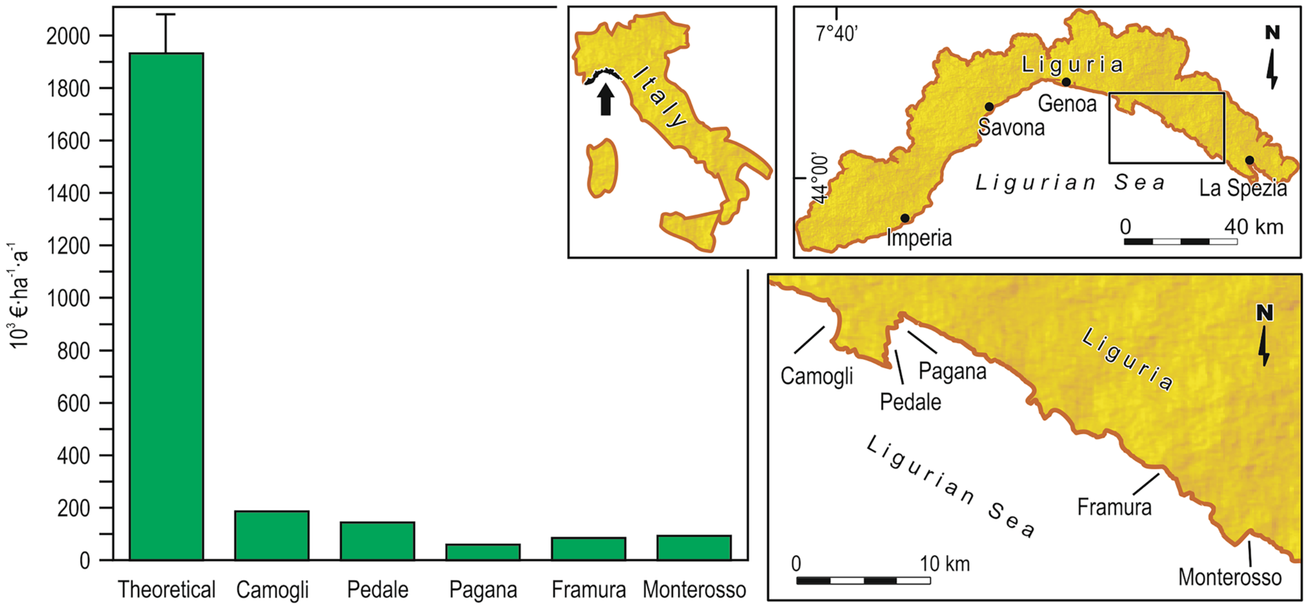

Fig. 7 Economic valuation of ecosystem services provided by *Posidonia oceanica* meadows in the Mediterranean Sea, in the theoretical case of a healthy meadow and in the real case of some Ligurian Sea meadows

where C represents consumption, I denotes investment, E stands for exports, and M indicates imports. In contrast, the green economy advocates for the calculation of an adjusted GDP (GDP*), which incorporates changes in natural capital:

$$GDP^* = C + I + E - M + \Delta Kn$$

where ΔKn measures the net change in natural capital, reflecting alterations in the availability of ecosystem services. If a nation were to clear-cut all its forests to create arable land, grazing areas, or for selling timber and real estate development, GDP would increase, but GDP* would likely decrease. Robert F. Kennedy (1925–1968), a politician, not an ecologist, criticized the conventional GDP measure in a campaign speech for the presidency shortly before his assassination, when the concept of GDP* still had to appear. He argued that GDP accounts for morally, culturally, and socially questionable aspects, yet fails to capture the values that bring dignity to life (the original speech can be retrieved at https://www.jfklibrary.org/learn/about-jfk/the-kennedy-family/robert-f-kennedy/robert-f-kennedy-speeches/remarks-at-the-university-of-kansas-march-18-1968).

Since 2016, Italy—among other nations—has embraced the ESW (Equitable and Sustainable Wellbeing) as part of its State Budget, marking a significant departure from traditional economic measures like GDP. Unlike GDP, which only quantifies economic balance, ESW evaluates development through a broader lens that includes social and environmental dimensions. The ESW framework is underpinned by 12 indicators, including health, education and training, work-life balance, economic wellbeing, social relationships, governance and institutions, security, subjective wellbeing, landscape and cultural heritage, environment, research and innovation, and quality of services [64]. In recent years, another innovative approach is the Happy Planet Index (HPI), which diverges from traditional economic metrics by prioritizing efficiency alongside wellbeing. This index integrates subjective assessments with ecological considerations such as the ecological footprint [91]. It operates on a multidimensional basis across four pillars: (i) cultural foundation for development, (ii) socio-economic progress, (iii) environmental stewardship, and (iv) good governance. HPI further elaborates on nine dimensions, including psychological wellbeing, time use, cultural diversity and resilience, community vitality, education, health, governance quality, ecological diversity and resilience, and living standards [88]. Where GDP traditionally places humanity and the planet at the service to economic growth, the HPI reorients economic activity to serve society within the boundaries of planetary constraints. This paradigm-shift challenges conventional economic wisdom by promoting individual capability development for collective well-being, advocating for non-exploitative practices of both people and nature, and prioritizing ecological integrity over economic expansion. The HPI thus seeks a balanced approach that harmonizes human prosperity with sustainable ecological practices, offering a robust alternative to GDP-centric economic paradigms. Extensive research has demonstrated that well-preserved and biologically diverse ecosystems offer numerous benefits, not only to physical health but also to mental and emotional well-being. These environments provide a natural refuge that fosters relaxation, reduces stress, and enhances cognitive functioning. Moreover, a growing body of evidence highlights a significant positive relationship between biodiversity and self-reported happiness, suggesting that greater exposure to diverse natural settings can elevate individuals' overall life satisfaction and sense of connection to the world around them [96]. These findings emphasize the critical role of nature in promoting holistic human well-being, while also reinforcing the importance of conserving biodiversity to sustain these invaluable benefits.

The prosperity and well-being of humanity thus hinge crucially on healthy environments, with the ocean being a cornerstone. Encompassing 71% of Earth's surface and hosting 95% of the biosphere, the ocean provides a vast array of goods and services essential for human survival and advancement [86]. It plays a pivotal role in climate regulation, supplies water, and sustains biodiversity critical for food security and livelihoods, particularly for coastal communities and island nations. The ecological functions of the ocean underpin human well-being and socio-economic progress. Recognizing the imperative of sustainable ocean management, the High Level Panel for a Sustainable Ocean Economy [85] underscores that this responsibility is shared globally—a collective duty of humanity. This imperative has gained significant traction in international political and economic agendas, culminating in initiatives like the Sustainable Blue Economy. The United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030) further underscores this commitment [86], focusing on advancing transformative ocean science solutions. Its mission is to foster the conservation and sustainable use of oceans, seas, and marine resources, connecting people with the ocean to achieve sustainable development goals [72]. This concerted effort reflects a global commitment to safeguarding the ocean's health, recognizing its pivotal role in sustaining human life and fostering resilient, equitable, and prosperous societies.

Certainly, the challenge lies in accurately defining and monetarily valuing natural capital, but collaboration between economists and ecologists in recent decades has yielded promising developments.

There are primarily two approaches to assigning a monetary value to natural capital: the user-side approach and the donor-side approach [70]. Under the user-side approach, typical of exergoeconomics, the value is determined by how much the users (i.e., humans) are willing to pay for a specific natural capital. In contrast, the donor-side approach, characteristic of emergoeconomics, values natural capital based on the energy spent by nature (the donor) to accumulate it. To illustrate these concepts, consider a simplified example: what is the cost of a fish to those who catch it? For the user, costs include bait price, fishing equipment amortization, travel expenses, and time spent, while the fish itself has no cost. In contrast, for the donor (nature), the cost is the energy invested in producing the fish. Solar energy is assimilated by phytoplankton, which—with an efficiency of approximately 10%—is consumed by zooplankton; the latter will be eaten—again with an efficiency of 10%—by small fish, which will be predated by the fish in question with a 10% efficiency. By quantifying the energy costs and measuring the energy contained in the fish biomass (expressed in solar joule equivalents), emergy analysis provides a more objective valuation of the natural capital represented by the fish. Without such an approach, it would be akin to valuing a car solely based on the cost of picking it up, without considering the extensive manufacturing processes involved. This emergy-based evaluation offers a comprehensive perspective, bridging economic valuation with ecological reality, thus enhancing our understanding and stewardship of natural resources.

We are currently beginning to estimate the monetary value of the natural capital across various ecosystems, both terrestrial and marine. For instance, coral reefs, among the most valuable ecosystems on Earth, can be valued at over a million dollars per hectare annually. In a pioneer study, Costanza et al. [20] revealed that the annual value of the global natural capital exceeds 33 trillion dollars per year, nearly double the world's GDP, estimated at 18 trillion dollars per year.

The ability to estimate the value of natural capital is crucial for comparing, in monetary terms, the benefits of economic activities with the loss of natural capital caused by their impacts. For example, constructing a marina might involve destroying a portion of seagrass meadow. The economic benefits brought by the marina (tourism revenue, job creation, related industries, etc.) can be quantified. If these benefits outweigh the value of the natural capital lost, it might be concluded that building the marina is economically justified. This perspective aligns with the concept of "weak sustainability", which posits that natural capital can be replaced by human-financial capital of equivalent economic value, as long as their sum remains constant [45]. In contrast, the "strong sustainability" principle argues that the natural capital has an intrinsic value that cannot be fully replaced by the human-financial capital. Essential ecosystem services vital for our survival, such as fertile soils, clean air, and pure water, are primarily provided by healthy ecosystems. A well-known native American saying underscores this perspective: "When the last tree is cut down, the last fish eaten, and the last stream poisoned, you will realize that you cannot eat money". This adage emphasizes the irreplaceable importance of preserving natural capital for our mere survival, not just for our socio-economic development.

7 Are there limits to economic development?

Being able to monetize natural capital provides us with the opportunity to understand the consequences of our development and assess how financial capital may increase at the expense of natural capital. Natural resources are finite and do not regenerate at the same pace as the growth of the human population [39]. All ecosystems are open systems, exchanging energy and matter with the outside world. However, our planet, along with its biosphere, operates as a closed system, receiving energy from the sun but possessing a finite amount of matter that must be continually recycled.

The developmental model based on the assumption that technological advancements can overcome the constraints imposed by nature has now faltered in the face of evident environmental and economic crises, revealing its impracticality. The first discussions about the limits to human population and civilization development arose in the 1970s, paradoxically initiated by economists and technocrats rather than ecologists. A significant milestone was the study commissioned by the Club of Rome and conducted by the Massachusetts Institute of Technology (MIT), employing the World3 model to simulate a wide array of socio-economic factors [39, 52]. The study forecasted that economic growth could not perpetually expand due to finite natural resources and the Earth's limited capacity to absorb pollutants. It predicted a crisis in global society by the early decades of the twenty-first century.

While the MIT report received substantial media attention and public interest, it also faced scepticism, as predictive modelling was still a novelty at that time, and doubts persisted about its accuracy versus real-world dynamics. However, an updated study about 30 years later [53], on the base of more sophisticated computational tools and additional data, reaffirmed the 1972 predictions. It underscored the temporal trends of population, food, resources, services, industrial output, and pollution, warning of a potential global crisis around 2030 (Fig. 8). Throughout subsequent years, international scientific bodies, including Nobel laureates, published two "warnings to humanity" [77, 87], reiterating the predictions of the MIT studies and highlighting the inadequate response to alter the status quo. This wealth of information, with data, models, and graphs, has prompted scientists to contemplate whether we have reached a tipping point as far as our lifestyle and socio-economic systems are concerned [82]. Globalization has had profound impacts on the Earth, yet environmental policies often lag behind scientific warnings about these threats. This gap exists largely because, while science is global and unified, environmental policy remains fragmented across countries, regions, and continents [28]. Strengthening international cooperation between science and policy is therefore essential to address these challenges effectively. Addressing these challenges requires not only stronger cooperation but also a deeper understanding of how natural systems respond to pressures. Ecological principles offer hope through the concept of resilience, which denotes the capacity of ecosystems to rebound when pressures are alleviated or reduced. If recovery is possible, thereby allowing for a return to healthier states, then the feared tipping point might still be avoidable.

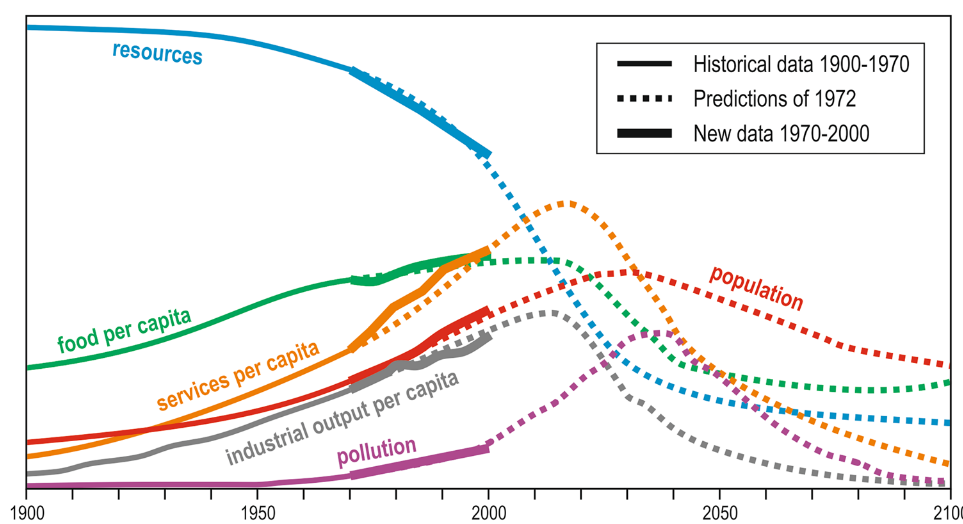

Fig. 8 Observed and projected socio-economic trends based on the reports of the Massachusetts Institute of Technology (MIT) in 1972 and 2004

8 The role of resilience

Resilience has recently got considerable media attention. The term originates from the Latin verb *resilire*, meaning to jump back, return quickly, bounce. The diffusion of this term in physics and engineering dates to the mid-nineteenth century, denoting the ability of a material not to break under stress. Resilience has subsequently been adopted in psychology to refer to the capacity to respond to trauma. In ecology, it denotes how swiftly an ecosystem can revert to its original state following disruption by external forces. The broader application of the term across diverse fields—from politics to sports, and from economics to commerce—began in journalistic circles during the 1980s.

In ecology, resilience is one of the two components of an ecosystem's overall stability—the ability to maintain or return to normal conditions over time. The other component is resistance, which gauges an ecosystem's ability to withstand external disturbances and maintain its state in the face of changing environmental conditions [60]. Resilience is measured temporally (e.g., in years), while resistance is quantified as a variation (typically a percentage) in some benchmark ecosystem function (Fig. 9a). A retrospective study conducted on a *Posidonia oceanica* meadow in the Ligurian Sea showed that after a beach nourishment in 1993, leaf production of the seagrass decreased by approximately 15% (thus indicating 85% resistance) before recovering to previous levels within four years [35]. While occasional nourishment may not severely impact the meadow, frequent or extensive interventions could hinder its ability to recover fully, threatening its long-term health and ecological function. This example underscores the detrimental impact of frequent or large-scale nourishment on seagrass meadows, the only natural defences against beach erosion, and the importance of understanding both resistance and resilience in ecosystem management practices to ensure sustainable conservation efforts.

When discussing ecosystem stability, it is important to differentiate between homeostasis and homeoresis. Homeostasis refers to maintaining or restoring the structure (from the Greek *omeo* = identical, and *stasis* = immobility), while homeoresis pertains to maintaining or restoring flows (from the Greek *reo* = to flow). Experience suggests that ecosystem resilience primarily involves the recovery of flows, such as production, rather than the structural aspects like the qualitative and quantitative composition of the community. This has led to consider resilience a concept fraught with ambiguity [2]. Consider a seabed abundant with clams, providing various services including the culinary delight of spaghetti with clams. Now imagine a disturbance, such as a severe storm or the outbreak of a pathogen, causing a massive die-off of clams. Over time, the ecosystem rebounds, but polychaete worms come to dominate instead of clams, fulfilling a similar ecological role. Functionally, the ecosystem appears restored, yet spaghetti with worms does not offer the same services to humans as spaghetti with clams: we have not included worms in our culinary tradition—at least not yet.

We increasingly recognize that altering community composition in response to changing environmental conditions is a strategy that ecosystems employ to maintain their functionality largely unchanged [6]. At the end of the Cretaceous period, dinosaurs disappeared, giving way to mammals, yet ecosystems continued to operate as they did before. A modification of contemporary ecosystems' composition, potentially leading to a loss of services for humanity, has been observed in numerous marine ecosystems worldwide, both pelagic and coastal [60]. This phenomenon is named "phase

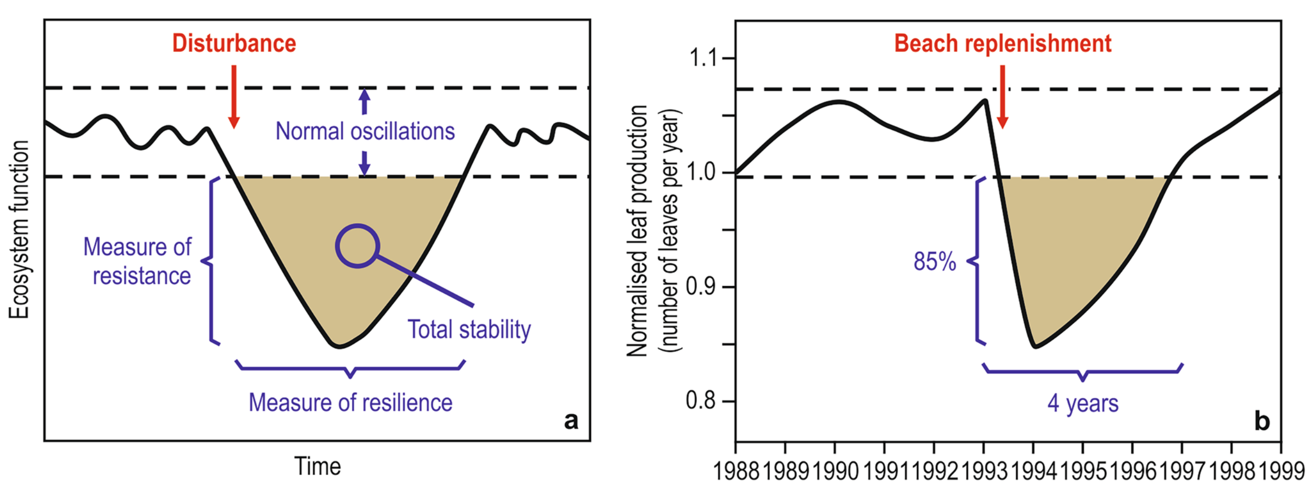

Fig. 9 Resistance and resilience of ecosystems to disturbance events. **a** theoretical scheme, as can be found in most ecology textbooks; **b** a real case, the impact of a beach nourishment on the *Posidonia oceanica* meadow in the Ligurian Sea [35]

shift" (from Greek *phasis* = aspect, appearance, and Anglo-Saxon *sciftan* = to arrange, reorder): a marked transition in species diversity, abundance, and/or trophic organization within the community, resulting in a fundamentally altered structural state of the ecosystem.

Understanding a phase shift requires access to long-term datasets that span sufficient periods to reconstruct temporal dynamics accurately. Such datasets are notably scarce in the marine realm [4]. Fortunately, in the Ligurian Sea, comprehensive data series have been available since 1956 for Portofino [30] and since 1961 for Punta Mesco [31]. This wealth of data owes much to the pioneering efforts of Enrico Tortonese (1911–1987) and Lucia Rossi (1913–2006), who collaborated with the sport divers Duilio Marcante (1914–1985) and Gianni Roghi (1927–1967) to accomplish *ante litteram* what is today known under the name of citizen science [8]. Studies at Punta Mesco, in particular, revealed that its rocky reef community remained stable for about thirty years, underwent a sudden compositional change (phase shift) between 1990 and 1996, and subsequently stabilized in a different configuration with notable species losses, reduced complexity, biotic homogenization, and increased alien species dominance. Concurrently, changes in the Ligurian Sea climate and intensified local anthropogenic pressures have been observed [5]. These studies bring a critical lesson: altering the driving factors that govern ecosystem dynamics, that is inducing a regime shift (from the Latin *regere* = to govern), inevitably leads to a phase shift. Presuming to conserve ecosystems in their current states while continuing to alter their regimes with human pressures is illusory. Ecosystem resilience is further complicated by hysteresis (from the Greek *husterein* = to lag behind), whereby an ecosystem's state depends on its previous history, often exhibiting delayed effects when causes diminish or cease in intensity [68]. Just as healing from injury (assuming you manage to heal perfectly) takes longer than the initial harm, achieving full ecosystem recovery proves similarly challenging.

Among the most well-documented phase shifts are those affecting seagrass meadows in the Mediterranean Sea [58, 61]. A striking example of prolonged phase shift, characterized by extreme hysteresis, can be found in the *Posidonia oceanica* meadow of Prelo Cove, in the Ligurian Sea (Fig. 2e). In the early twentieth century, the owners of a villa on the beach constructed a mooring pier and slipway to facilitate boat access directly under their house—a seemingly innocent convenience and luxury at the time. However, the seagrass obstructed the vessel draft, necessitating excavation of the meadow, which, coupled with pier construction, altered the morphodynamics of the entire inlet, disrupting sedimentary balance and causing the meadow to lose over 50% of its original extent. This environmental damage far outweighed the marginal benefit to a few individuals [46].

When an ecosystem undergoes degradation, efforts can be made towards restoration. In recent decades, initiatives to reforest *Posidonia oceanica*, planting cuttings in areas where meadows have disappeared due to human impacts (Fig. 2f), have shown promising initial success, with survival rates exceeding 75% after one year [79]. However, the endeavour remains costly, especially for achieving densities comparable to healthy meadows (hundreds of cuttings per square metre), and the long-term success is uncertain given the seagrass's low resilience [73]. The underlying message is that investing in conservation is to be preferred to restoration after destruction.

9 The intermediate disturbance hypothesis

The experience acquired to date suggests that the accumulation of disturbances—predominantly from human activities—inevitably leads to ecosystem degradation [67]. This degradation persists despite the inherent resistance and resilience capabilities of these ecosystems. As ecosystems deteriorate, their ability to provide services, essential to our economy and social systems, diminishes. This degradation not only threatens biodiversity but also undermines the very resources and processes that support human life and economic stability. Given this stark reality, it is becoming increasingly evident that the current model of socio-economic development, which often prioritizes short-term gains over long-term sustainability, is untenable. Many experts argue that we cannot continue this path without risking severe ecological and economic consequences [81]. They advocate for a paradigm shift towards more sustainable practices, emphasizing the need to retrace our steps and adopt development models that harmonize economic growth with environmental stewardship. This call for change is not merely about preserving nature for its own sake but recognizing that human well-being and prosperity are inextricably linked to the health of our natural environment. Embracing sustainable development practices, reducing our ecological footprint, and investing in the conservation and restoration of ecosystems are critical steps towards ensuring a viable future for both the planet and humanity.

Some ecologists have proposed the rather radical concept of "prosperous slowdown" [42], also known as "happy degrowth" [13]. It challenges the traditional economic lexicon, which equates growth with positive outcomes and stagnation or recession with negative ones. This concept is highly debated, attracting both staunch advocates and fierce critics. Supporters argue that it represents a necessary shift towards sustainability, envisioning a society where well-being is not tied to perpetual economic growth [43]. They believe that, by focusing on quality of life rather than the quantity of consumption, humanity can achieve a more equitable and environmentally sustainable future. Detractors, on the other hand, dismiss the prosperous slowdown as a utopia [34]. They argue that the complexities of modern economies and societies cannot be resolved by simply reducing consumption and growth. These critics contend that innovation and technological advancement, rather than degrowth, are the keys to overcoming the limits of development. They emphasize that economic growth has historically been linked to improvements in health, education, and overall living standards, and fear that slowing growth could reverse these gains. Despite the heated debate and the considerable amount of literature on both sides, concrete examples of successful implementation of prosperous slowdown are not available yet. While theoretical discussions abound, practical applications are still largely untested. This gap between theory and practice highlights the challenges of transitioning from a growth-oriented economy to one that prioritizes well-being and sustainability. Nonetheless, the concept of prosperous slowdown continues to inspire discussions on alternative pathways to a sustainable future, emphasizing the need for a profound rethinking of our relationship with economic growth and environmental stewardship [38].

Since ecosystem degradation has become inevitable, efforts must now focus on mitigating its impact, restoring damaged ecosystems where possible, and adapting socio-economic systems to the new environmental realities and to the new disturbance regime. Even in this case, ecological theory can provide some insights. The intermediate disturbance hypothesis, which has gained prominence in recent decades, offers an alternative to the notion that disturbances caused by human activities inevitably lead to ecosystem degradation. Disturbance, derived from the Latin *dis-* (intensifying) and *turbare* (to upset or spoil), refers to an unpredictable and/or episodic event caused by an external agent that alters ecosystem state, leading to mortality and hence biomass subtraction [60]. This concept has become central in ecology, leading to a distinction between equilibrium ecology, which dominated until the 1970s, and the emerging disturbance ecology or new ecology of recent decades [6]. The central paradigms of equilibrium ecology likely stem from the idea of the "balance of nature", a concept that has characterized philosophical thought since ancient times. Although somewhat vague, this notion implies that nature, if left undisturbed, is ordered and harmonious. Herodotus (484–430 BC) was among the first to seek an explanation for this balance, believing that divine providence had created predators with lower reproductive rates than their prey, thus maintaining their respective populations. This idea, little modified over centuries, has influenced common thinking to this day. Even Darwin, who revolutionized the natural sciences, did not question the idea of nature's balance: he merely replaced divine providence with natural selection. Equilibrium ecology posits that biodiversity, and consequently ecosystem functionality, is maximized in stable situations that are in harmony with the local climate and free from disturbance. This perspective asserts that "physically controlled" communities (i.e., those disturbed by external agents) exhibit low levels of biodiversity, whereas "biologically accommodated" communities (where species themselves regulate ecosystem functioning by performing different roles) exhibit high biodiversity.

The intermediate disturbance hypothesis suggests that ecosystems experiencing moderate levels of disturbance can support greater biodiversity than those with very high or very low disturbance levels. In stable conditions (at the equilibrium), the dominance of the most competitive species often excludes less competitive species from the community (Fig. 10). The central idea of the new ecology is that disturbances—varied in space, time, intensity, and duration—keep real communities far from equilibrium, creating a mosaic of different states that are intrinsically richer in species. This hypothesis implies that not all disturbances are detrimental; some can enhance biodiversity and ecosystem resilience by preventing any single species from becoming overly dominant. This perspective challenges the traditional view that disturbances are inherently harmful and highlights the complexity of ecosystem dynamics. By considering the potential benefits of moderate disturbances, we may find new ways to manage ecosystems sustainably, balancing human activities with ecological health.

The comparison between ecosystem functioning and the game of Monopoly is quite illustrative. In Monopoly, the expected outcome is not the harmonious coexistence among players, each in their specialized niche—owning houses, hotels, utility companies, or transportation. On the contrary, a superior competitor (the most skilled or lucky player) typically appears, eventually excluding the others. It is the contingencies and probabilities chest cards (analogous to disturbances) that keep the game dynamic and engaging. These elements, comparable to unexpected events in ecosystems, are thus, in a certain sense, the quintessence of the game.

Equilibrium ecology suggests an inverse relationship between biodiversity and disturbance, often represented as a straight line (Fig. 10a). This perspective implies that human activities, which inevitably increase disturbance, always lead to a loss of biodiversity and, consequently, ecosystem functionality. This view offers little hope for sustainability. In contrast, the new ecology posits that the relationship between biodiversity and disturbance is better represented by a

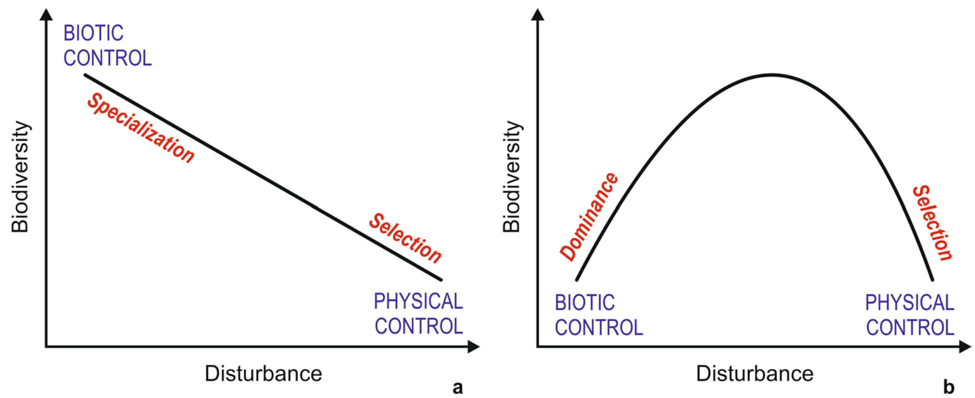

Fig. 10 The relationship between biodiversity and disturbance is depicted differently in equilibrium ecology and the intermediate disturbance hypothesis. In equilibrium ecology (**a**), physical control, due to strong selection pressures, leads to a reduction in biodiversity, while biotic control results in high biodiversity. The intermediate disturbance hypothesis (**b**) agrees that physical control still reduces biodiversity but suggests that biotic control leads to low biodiversity due to dominance phenomena. This hypothesis posits that moderate levels of disturbance can foster greater biodiversity by preventing any single species from becoming overly dominant

curve (Fig. 10b). At the peak of this curve, there is a "window" where moderate disturbances do not lead to significant biodiversity loss or diminished ecosystem functionality. Understanding the normal disturbance regime of ecosystems can help us modulate human-induced disturbances to remain within this optimal range, potentially reconciling development with ecosystem health. The Italian marine biologist Umberto D'Ancona (1896–1964) anticipated this concept: analyzing the effects of reduced fishing during the First World War, D'Ancona [24] noted that "there must be an optimum of fishing intensity. By fishing less, the most voracious species are favoured to the detriment of others… by fishing more, all species are reduced, leading to a tendency towards depopulation of the sea". D'Ancona essentially recognized that fishing impacts should fall within the disturbance regime of the marine ecosystem where it occurs.

It is possibly not a coincidence that, in the same years when the intermediate disturbance hypothesis was becoming established in ecology, environmental impact assessment (EIA) procedures took place. These procedures are intended to precede and accompany the implementation of engineering projects that may impact the environment, providing a comprehensive environmental framework of the project area and assessing the state of the ecosystems present [12]. Until the late 1970s, the idea of evaluating environmental impacts did not exist, leading to many environmental operations being carried out without any analysis of potential risks to ecosystems. Numerous examples from that years illustrate interventions at sea conducted with little to no consideration of their potential harmful effects on ecosystems. An illustrative case is the construction of the so-called "artificial reef" off the coast of Varazze (NW Italy, Ligurian Sea). Following the devastating flood in Genoa in 1970, which caused many casualties and extensive damage—including the destruction of 1,300 vehicles beyond repair—a decision was made to dispose these cars by sinking them into the sea, with the aim of creating a habitat for marine life. The cars, still holding tyres, oil, fuel, batteries, electrical systems, and other components, were submerged without any prior environmental assessment in a triangular area of 15,000 m^2 at depths ranging from 35 to 50 m. Subsequent underwater observations revealed that the car wrecks had deteriorated into rusting masses covered with slime (Fig. 11). There was virtually no colonization by marine organisms, apart from some encrustations of serpulid worms on chromium-plated parts [1], see also Fig. 2B in [59]. Rather than becoming an oasis of life, the artificial reef of Varazze turned out to be an additional source of marine pollution.

However, towards the end of the 1970s, the situation began to change, and the concept of environmental impact assessment started to take hold as a regulatory tool used worldwide in the name of sustainable development [94]. For instance, during the construction of a thermoelectric power plant in the Po River delta (NE Italy, Adriatic Sea), a series of ecological studies were initiated, which provided novel information about this brackish water ecosystem [7, and references therein]. Construction was completed in 1980, but unfortunately, the studies did not continue. The power plant began operations in 1984, with an installed capacity sufficient to cover nearly 8% of the electricity needs of Italy. However, it was soon deemed uneconomical and was shut down in 2009. Decommissioned in 2015, it now stands as an industrial monument, with a 250-m-high chimney. There are plans to repurpose the power plant for tourism.

Today, EIA procedures have become standard practice for mainstreaming environmental concerns into decision-making. For example, the expansion of a tourist port in Ventimiglia (NW Italy, Ligurian Sea) between 2010 and 2013 was expected to impact two adjacent submerged marine caves. Consequently, a series of investigations were launched before,

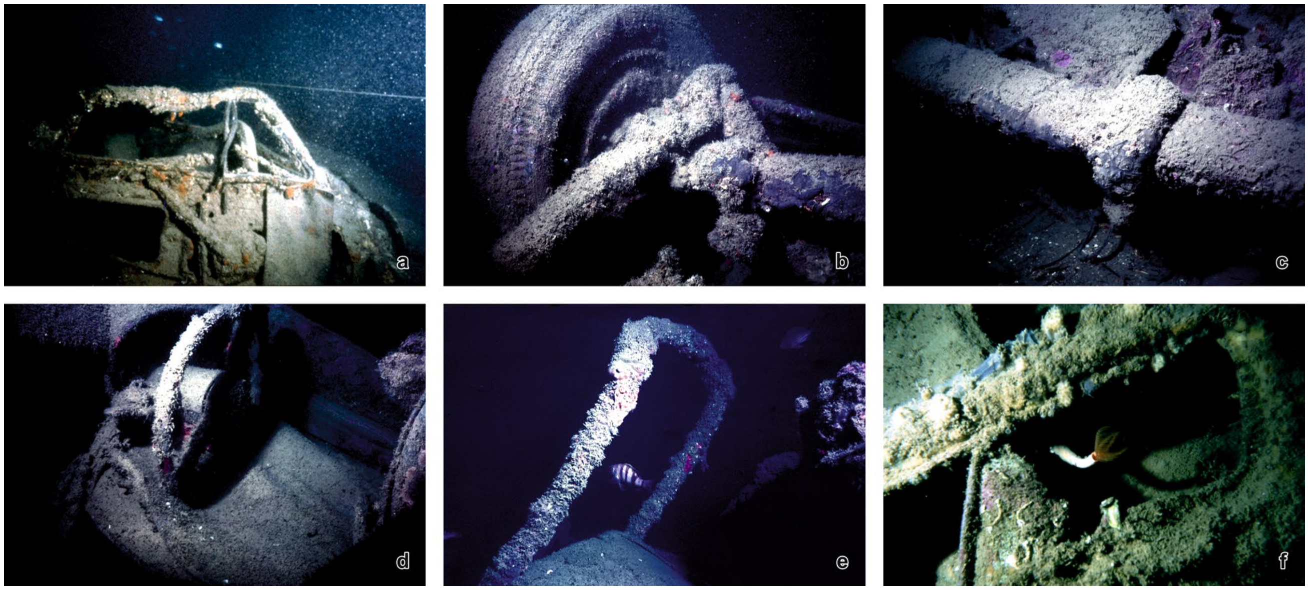

Fig. 11 Underwater images of the car wrecks that form the so-called 'artificial reef' of Varazze, taken a few years after their submersion

during, and after the construction to measure any potential impact. Marine caves are ecologically important habitats, hosting unique fauna [32]. These habitats are considered of conservation interest under various European directives and international agreements signed by many Mediterranean countries [74]. Prior to the studies conducted for the EIA related to the port expansion, no data were available for the caves of Ventimiglia. The EIA studies revealed that the benthic community in these caves changed during the construction and then stabilized in a different ecological state post-construction [62]. This represents the first unequivocal documentation of a phase shift in marine caves following local human impacts related to coastal interventions (Fig. 12).

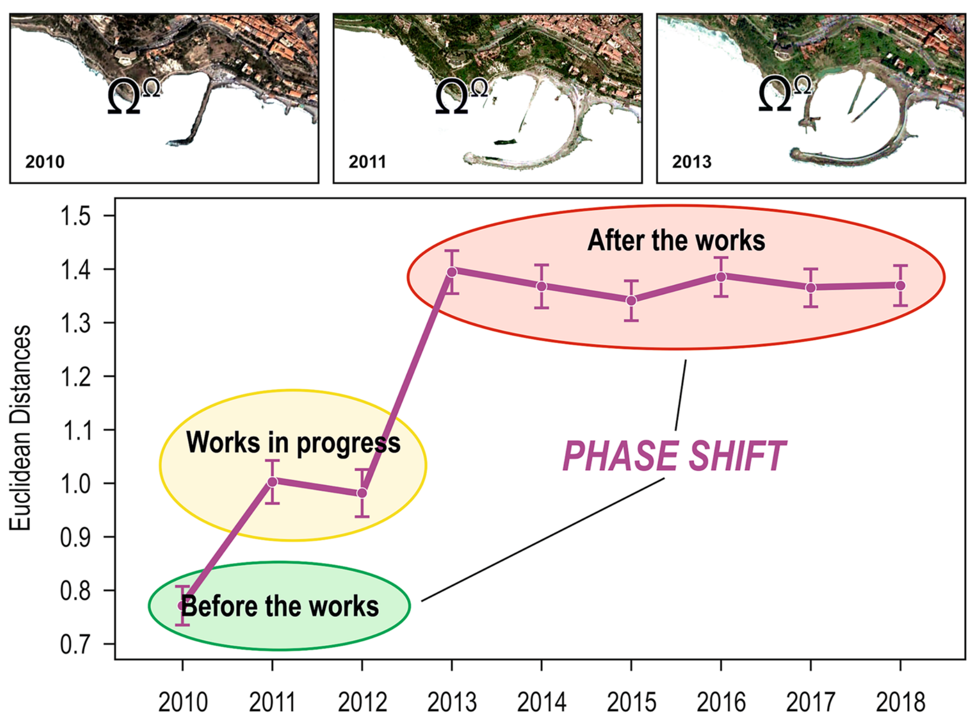

Fig. 12 The expansion of the Ventimiglia marina between 2010 and 2013 resulted in significant change of the benthic communities of two adjacent caves (Ω) of different size, clearly indicating a phase shift

We should fundamentally rethink environmental impact assessment, shifting towards a strategic environmental assessment [94] or a comprehensive sustainability assessment. This transformation is crucial to ensure that impact assessments play a more decisive role in shaping development and decision-making, effectively guiding them towards truly sustainable outcomes.

10 Concluding remarks

This review serves as a warning to policymakers, stakeholders, and ecology professionals alike, and it delivers three key cautions. First, driven by imperialism, extractive capitalism, and growing population, we are exceeding Earth's material boundaries, devastating critical ecosystems, and triggering irreversible changes in the biophysical systems that have sustained the Holocene's climatic stability and, by extension, human civilization [29]. These actions disproportionately impact vulnerable populations, further exacerbating global inequalities. Meanwhile, both marine and terrestrial biomes are nearing critical tipping points, and escalating challenges related to food and water security undermine global stability [44]. In light of these dangerous developments, we call for a global response that pivots immediately away from exploitative, profit-driven capitalism toward an economic model that prioritizes sustainability, resilience, and justice.

Established pathways towards sustainability, emphasizing intergenerational equity and adherence to biophysical limits, encompass the "green and blue economies" advocating for economic reform, technological innovation, and revised performance metrics. Concurrently, "nature protection" stresses biodiversity preservation through expanded protected areas, while "Earth stewardship" promotes local autonomy, solidarity, and biocultural conservation practices. Lastly, socially and ecologically sustainable "degrowth" prioritizes on limiting overconsumption and overproduction [69], while also reducing resource extraction and minimizing waste generation, particularly in industrialized nations. At the same time, it calls for more efficient resource management strategies to prevent depletion in both high- and low-income countries. A fundamental shift away from the current linear economic model toward a circular system—one that is more equitable, resource-conscious, and respectful of both the environment and all living beings—has already been envisioned [50].

The second warning is that concrete progress toward achieving the 17 United Nations Sustainable Development Goals (SDGs) by 2030 remains severely off track. Despite global and regional crises like the COVID-19 pandemic and recent emerging conflicts contributing to setbacks, the inaction of governments is the primary cause. Many countries face hurdles due to insufficient financial resources and weak administrative capacities. Moreover, entrenched habits and lifestyles, bolstered by sophisticated marketing campaigns, pose significant barriers to adopting sustainable diets, transportation, and consumption patterns. Simply extending the deadline by a decade or two will not suffice, and current trends suggest that none of the SDGs will be met even by 2050. It is imperative for scientists to collaborate closely with policymakers and stakeholders to reimagining institutions, systems, and practices [49]. The role of non-governmental environmental organizations, from natural history societies to green parties, must also be strengthened. However, their efforts should be guided by a rigorous and evolving scientific perspective—one that moves beyond a narrow focus on a few charismatic species ("deluxe biodiversity") and instead adopts a holistic, ecosystem-based approach that fully integrates humanity's place within nature. This means recognizing the vital role of lesser-known species ("obscure biodiversity") in sustaining ecosystem functions and providing essential services and goods [14].

The third warning is that two critical endeavours essential for achieving the Sustainable Development Goals have been largely overlooked. First, there is an urgent need to re-evaluate our relationship with nature by adopting a perspective that recognizes the intrinsic value of natural systems and promotes a more harmonious interaction between humans and the environment. Second, our collective scientific culture—especially our ecological literacy—remains insufficiently developed, hindering our ability to address effectively environmental challenges. Without significant progress in these areas, our efforts toward sustainable development will continue to fall short.

When examining the relationship between humanity and nature, we can identify three distinct conceptions that have emerged and gained prominence at various times throughout our civilization's history. The naturalist conception views humans as alien to nature, believing nature to be perfect only in the absence of human intervention. This view advocates for identifying untouched environments and establishing reserves where human activity is prohibited, like to "no-take zones" in marine protected areas. In contrast, the imperialist conception asserts that humans were divinely ordained as masters of nature, endowed with the right to exploit it for their own benefit. This perspective regards wild nature as antagonistic and in need of conquest and domination. The Arcadian conception derives its name from Arcadia, an ancient Greek region symbolizing an idyllic land where humans and nature coexist harmoniously. This vision is rooted in a pastoral and utopian idealism. To realize the contemporary concept of sustainable development, efforts must be directed towards transforming utopian ideals into tangible realities. This aspiration is reflected in the vision of an "ecological civilization", which imagines a future where human flourishing occurs in harmony with a regenerated Earth [47]. Achieving this requires a profound shift in our current economic, political, and cultural paradigms, fostering a civilization based on different values, goals, and collective behaviours. An ecological civilization would model human society on nature wisdom, incorporating principles that have sustained health and resilience of natural ecosystems for millions of years.

Throughout human history, regardless of the conception adopted, the imperative to understand nature has consistently emerged. This persistent drive underscores our intrinsic connection with the natural world and highlights the necessity of deep, integrative knowledge to navigate today's environmental challenges. Epicurus (341–271 BC), in "On Nature", wrote that humans are an integral part of nature, asserting that true inner peace can only be achieved through a deep understanding of it. Lucretius (98–53 BC), in "*De Rerum Natura*", echoed this sentiment, emphasizing that awareness of our interconnectedness with all living beings is essential for reaching a serene existence. Even during the Humanism and Renaissance eras, literature often underscored the need of understanding nature. François Rabelais (1483–1553) conveyed this in the "Letter from Gargantua to Pantagruel" (1532), urging his son to eagerly pursue knowledge of every sea, river, and fountain, along with their inhabitants. Even proponents of dominating nature highlighted the necessity of knowing it. In "*Cogitata et Visa*", Francis Bacon (1561–1626) asserted that human dominion hinges solely on knowledge, arguing that nature can only be effectively harnessed through understanding and obedience. The "Baconian method", derived from 15th-century Italian thinkers like Leonardo da Vinci, exemplifies this approach: it begins with observing nature to gain mastery and derive practical applications beneficial to humanity, a hallmark of the industrial age. During Romanticism (late eighteenth century—nineteenth century), nature was often understood as a mirror of human spirituality: to know nature is a means to know oneself. Regrettably, despite over two thousand years of wise counsel, contemporary society suffers from a glaring deficiency in naturalistic culture [36]. The natural sciences, including ecology, receive little attention in compulsory education, even in scientific high school. Moreover, we have witnessed a concerning rise in anti-scientific thinking, ranging from climate denialism to flat Earth beliefs. We advocate for the integration of natural sciences, particularly ecology, starting from primary school. Education must be a central strategy for fostering the behavioural changes needed to address the environmental change highlighted in the scientists' warnings. Environmental issues are not solely the concern of scientists, they require the support of multiple spheres, including the humanities, arts, social sciences, and the broader society [75].

At the 1968 General Assembly of the International Union for Conservation of Nature (IUCN) in New Delhi, Senegalese forestry engineer Baba Dioum famously declared "In the end, we will conserve only what we love; we will love only what we understand; and we will understand only what we have been taught." It is imperative that politicians, administrators, economists, and engineers master the fundamentals of ecology. Without this foundational knowledge, decisions made by our societal leaders may inadvertently undermine ecological principles and impede progress toward sustainable development. Understanding the natural disturbance regimes of ecosystems is essential, as is promoting more conscientious individual behaviour. In the Anthropocene, much work remains to do, and the responsibility extends beyond ecologists alone. This warning urges humanity not to fear or retreat from change, but to embrace the promising future that sustainable development can engender.

Acknowledgements Annalisa Azzola, Silvia Cocito, Camilla Garofalo, Paolo Guidetti, Ilaria Mancini, Alice Oprandi, Andrea Peirano, Ottaviano Serlupi Crescenzi and Maurizio Wurtz have made information deriving from their research and studies available to us. Some of the images contained in the figures that illustrate this text were provided by Fabio Barbieri, Fabio Benelli, Marcello Di Francesco, Alice Oprandi, Sergio Sgorbini, and Armando Tommei.

Author contributions All authors contributed equally to the study conception, data collection, review, and analysis, and to the preparation of the first draft of the manuscript. All authors read and approved the final manuscript.

Funding Researches were partially funded by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree No. 3175 of 18 December 2021 of the Italian Ministry of University and Research funded by the European Union—NextGenerationEU, Project code CN_00000033, Spoke 1, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, Project title "National Biodiversity Future Center—NBFC".

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent to publication Not applicable.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

References

1. Bianchi CN. Serpulidae (Annelida, Polychaeta) della scogliera artificiale di Varazze (Savona). Atti Soc Ital Sci Nat Museo Civ Storia Nat Milano. 1980;121(1–2):83–93.
2. Bianchi CN. Climate change and biological response in the marine benthos. Proc Italian Assoc Oceanol Limnol. 1997;12(1):3–20.
3. Bianchi CN, Azzola A, Bertolino M, Betti F, Bo M, Cattaneo-Vietti R, Cocito S, Montefalcone M, Morri C, Oprandi A, Peirano A, Bavestrello G. Consequences of the marine climate and ecosystem shift of the 1980–90s on the Ligurian Sea biodiversity (NW Mediterranean). Eur Zool J. 2019;86(1):458–87.
4. Bianchi CN, Azzola A, Cocito S, Morri C, Oprandi A, Peirano A, Sgorbini S, Montefalcone M. Biodiversity monitoring in Mediterranean marine protected areas: scientific and methodological challenges. Diversity. 2022;14(1):43.
5. Bianchi CN, Azzola A, Parravicini V, Peirano A, Morri C, Montefalcone M. Abrupt change in a subtidal rocky reef community coincided with a rapid acceleration of sea water warming. Diversity. 2019;11(11):215.
6. Bianchi CN, Boero F, Fonda US, Morri C, Vacchi M. Successione e cambiamento negli ecosistemi marini. Biol Mar Mediterr. 1998;5(1):117–35.
7. Bianchi CN, Morri C. *Ficopomatus* 'reefs' in the Po River Delta (Northern Adriatic): their constructional dynamics, biology, and influences on the brackish-water biota. PSZN I Mar Ecol. 1996;17(1–3):51–66.
8. Bianchi CN, Morri C. Training scientific divers—Italian style. Ocean Chall. 2000;10(1):25–9.
9. Bianchi CN, Morri C, Chiantore M, Montefalcone M, Parravicini V, Rovere A. Mediterranean Sea biodiversity between the legacy from the past and a future of change. In: Stambler N, editor. Life in the Mediterranean Sea: a look at habitat changes. New York: Nova Science Publishers; 2012. p. 1–55.
10. Bianchi CN, Peirano A. Atlante delle fanerogame marine della Liguria: *Posidonia oceanica* e *Cymodocea nodosa*. ENEA, Centro Ricerche Ambiente Marino, La Spezia. 1995: 146 pp (+ 44 maps).
11. Bianchi CN, Zattera A. Alcune considerazioni sulla gestione della fascia costiera. Notiziario Soc Ital Biol Mar. 1986;10:25–9.
12. Bianchi CN, Zurlini G. Criteri e prospettive di una classificazione ecotipologica dei sistemi marini costieri italiani. Acqua Aria. 1984;8:785–96.
13. Bilancini E, D'Alessandro S. Long-run welfare under externalities in consumption, leisure, and production: A case for happy degrowth vs. unhappy growth. Ecol Econ. 2012;84:194–205.
14. Boudouresque CF, Berland B, Blanfuné A, Cheinet P, Pellicani C, Perret-Boudouresque M, Thibaut T. Long-term change in human impact and environmental perceptions: a 40-year case study of an environment-focused Non-Governmental Organization. Ecol Divers. 2024;1(1):10006.
15. Boudouresque CF, Bianchi CN. Une idée neuve: la protection des espèces marines. In: Le Diréach L, Boudouresque CF, editors. GIS Posidonie: plus de 30 ans au service de la protection et de la gestion du milieu marin. Marseille: GIS Posidonie; 2013. p. 85–91.
16. Boudouresque CF, Bernard G, Pergent G, Shili A, Verlaque M. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: a critical review. Bot Mar. 2009;52:395–418.
17. Brundtland GH. Report of the World Commission on environment and development: our common future. United Nations World Commission on Environment and Development. 1987.http://www.un-documents.net/our-common-future.pdf.
18. Burgos E, Montefalcone M, Ferrari M, Paoli C, Vassallo P, Morri C, Bianchi CN. Ecosystem functions and economic wealth: trajectories of change in seagrass meadows. J Clean Prod. 2017;168:1108–19.
19. Burgos-Juan E, Montefalcone M, Ferrari M, Morri C, Bianchi CN. A century of change in seagrass meadows of Liguria. Biol Mar Mediterr. 2016;23(1):78–81.
20. Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M. The value of the world's ecosystem services and natural capital. Nature. 1997;387(6630):253–60.
21. Crist E, Ripple WJ, Ehrlich PR, Rees WE, Wolf C. Scientists' warning on population. Sci Total Environ. 2022;845: 157166.
22. Crutzen PJ, Stoermer EF. The 'Anthropocene.' Glob Change Newsl. 2000;41:17–8.
23. Daily GC. Nature's services: societal dependence on natural ecosystems. Washington DC: Island Press; 1997. p. 392.
24. D'Ancona U. Dell'influenza della stasi peschereccia 1914–18 sul patrimonio ittico dell'Alto Adriatico. Memorie Reg Com Talassogr Italiano. 1926;126:1–91.

25. de Los Santos CB, Krause-Jensen D, Alcoverro T, Marbà N, Duarte CM, Van Katwijk MM, Pérez M, Romero J, Sánchez-Lizaso JL, Roca G, Jankowska E, Pérez-Lloréns JL, Fournier J, Montefalcone M, Pergent G, Ruiz JM, Cabaço S, Cook K, Wilkes RJ, Moy FE, Muñoz-Ramos TG, Seglar AX, de Jong DJ, Fernández-Torquemada Y, Auby I, Vergara JJ, Santos R. Recent trend reversal for declining European seagrass meadows. Nat Commun. 2019;10(1):3356.
26. Ehrlich PR. The population bomb. New York: Ballantine Books; 1968. p. 226.
27. FAO. The state of world fisheries and aquaculture 2020: sustainability in action. Rome: Food and Agriculture Organization of the United Nations; 2020. p. 244. https://doi.org/10.4060/ca9229en.
28. Faragó T. Our common environment and globalization—shadows and hopes. Budapest: Akadémiai Kiadó Publisher; 2024. p. 236.
29. Fletcher C, Ripple WJ, Newsome T, Barnard P, Beamer K, Behl A, Bowen J, Cooney M, Crist E, Field C, Hiser K, Karl DM, King DA, Mann ME, McGregor DP, Mora C, Oreskes N, Wilson M. Earth at risk: an urgent call to end the age of destruction and forge a just and sustainable future. PNAS Nexus. 2024;3(4):106.
30. Gatti G, Bianchi CN, Montefalcone M, Venturini S, Diviacco G, Morri C. Observational information on a temperate reef community helps understanding the marine climate and ecosystem shift of the 1980–90s. Mar Pollut Bull. 2017;114(1):528–38.
31. Gatti G, Bianchi CN, Parravicini V, Rovere A, Peirano A, Montefalcone M, Massa F, Morri C. Ecological change, sliding baselines and the importance of historical data: lessons from combining observational and quantitative data on a temperate reef over 70 years. PLoS ONE. 2015;10(2): e0118581.
32. Gerovasileiou V, Bianchi CN. Mediterranean marine caves: a synthesis of current knowledge. Oceanogr Mar Biol Annu Rev. 2021;59:1–88.
33. Gibson RB, Hassan S, Holtz S, Tansey J, Whitelaw G, Morrison-Saunders A. Sustainability assessment—criteria and processes. JEAPM. 2006;8(3):399–401.
34. Gordon DM. The rise and fall of American growth: the U.S. standard of living since the civil war. Princeton: Princeton University Press; 2016. p. 784.
35. Guidetti P. Detecting environmental impacts on the Mediterranean seagrass *Posidonia oceanica* (L.) Delile: the use of reconstructive methods in combination with 'beyond BACI' designs. J Exp Mar Biol Ecol. 2001;260(1):27–39.
36. Guidetti P, Parravicini V, Morri C, Bianchi CN. Against nature? Why ecologists should not diverge from natural history. Vie Milieu Life Environ. 2014;64(1):1–8.
37. Harper S. Economic and social implications of aging societies. Science. 2014;346:6209.
38. Hickel J, Kallis G, Jackson T, O'Neill DW, Schor JB, Steinberger JK, Victor PA, Ürge-Vorsatz D. Degrowth can work—here's how science can help. Nature. 2022;612(7940):400–3.
39. Higgs K. Collision course: endless growth on a finite planet. Cambridge: The MIT Press; 2014. p. 416.
40. Hu W, Hao Z, Du P, Di Vincenzo F, Manzi G, Cui J, Fu YX, Li H. Genomic inference of a severe human bottleneck during the early to middle Pleistocene transition. Science. 2023;381(6661):979–84.
41. Issel R. Biologia marina: forme e fenomeni della vita nel mare. Milan: Hoepli; 1918. p. 696.
42. Jackson T. Prosperity without growth: economics for a finite planet. London: Routledge; 2009. p. 288.
43. Jackson T. Post-growth: life after capitalism. Cambridge: Polity Press; 2017. p. 256.
44. Jalil S. Toward an international grundnorm for climate change: ensuring sustainability away from the traditional notion of security. Sustainability. 2025;17(3):1034.
45. Kasperowicz R. Weak vs. strong sustainability: a new perspective. Sustainability. 2017;9(12):2324.
46. Lasagna R, Montefalcone M, Albertelli G, Corradi N, Ferrari M, Morri C, Bianchi CN. Much damage for little advantage: field studies and morphodynamic modelling highlighted the environmental impact of an apparently small coastal mismanagement. Estuar Coast Shelf Sci. 2011;94:255–62.
47. Lent J. Setting the coordinates for an ecological civilization. Ecopoiesis. 2024;5(1):36–44.
48. Mace GM, Norris K, Fitter AH. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol Evol. 2012;27(1):19–26.
49. Malekpour S, Allen C, Sagar A, Scholz I, Persson Å, Miranda JJ, Bennich T, Dube OP, Kanie N, Madise N, Shackell N, Montoya JC, Pan J, Hathie I, Bobylev SN, Agard J, Al-Ghanim K. What scientists need to do to accelerate progress on the SDGs. Nature. 2023;621:250–4.
50. Marín-Beltrán I, Demaria F, Ofelio C, Serra LM, Turiel A, Ripple WJ, Sharif AM, Costa MC. Scientists' warning against the society of waste. Sci Total Environ. 2022;811:151359.
51. McCormick R, Kapustka L, Stahl C, Fava J, Lavoie E, Robertson C, Sanderson H, Scott H, Seager T, Vigon B. Exploring SETAC's roles in the global dialogue on sustainability—an opening debate. Integr Environ Assess Manag. 2013;9(1):7–11.
52. Meadows DH, Meadows DL, Randers J, Behrens WW III. The limits to growth: A report for the club of Rome's project on the predicament of mankind. New York: Universe Books; 1972. p. 205.
53. Meadows DH, Meadows DL, Randers J, Behrens WW III. Limits to growth: The 30-year update. White River Junction VT: Chelsea Green Publishing; 2004. p. 368.
54. Millennium Ecosystem Assessment. Ecosystems and human well-being: synthesis. Washington DC: Island Press; 2005. p. 155.
55. Montefalcone M. Ecosystem health assessment using the Mediterranean seagrass *Posidonia oceanica*: a review. Ecol Ind. 2009;9(4):595–604.
56. Montefalcone M, Albertelli G, Morri C, Bianchi CN. Patterns of wide-scale substitution within meadows of the seagrass *Posidonia oceanica* in NW Mediterranean Sea: invaders are stronger than natives. Aquat Conserv Mar Freshwat Ecosyst. 2010;20:507–15.
57. Montefalcone M, Albertelli G, Morri C, Parravicini V, Bianchi CN. Legal protection is not enough: *Posidonia oceanica* meadows in marine protected areas are not healthier than those in unprotected areas of the northwest Mediterranean Sea. Mar Pollut Bull. 2009;58:515–9.
58. Montefalcone M, Morri C, Peirano A, Albertelli G, Bianchi CN. Substitution and phase shift within the *Posidonia oceanica* seagrass meadows of NW Mediterranean Sea. Estuar Coast Shelf Sci. 2007;75:63–71.
59. Montefalcone M, Oprandi A, Azzola A, Morri C, Bianchi CN. Serpulid reefs and their role in aquatic ecosystems: a global review. Adv Mar Biol. 2022;92:1–54.
60. Montefalcone M, Parravicini V, Bianchi CN. Quantification of coastal ecosystem resilience. In: Wolanski E, McLusky DS, editors. Treatise on Estuarine and coastal science, vol. 10. Waltham: Elsevier; 2011. p. 49–70.
61. Montefalcone M, Vassallo P, Gatti G, Parravicini V, Paoli C, Morri C, Bianchi CN. The exergy of a phase shift: ecosystem functioning loss in seagrass meadows of the Mediterranean Sea. Estuar Coast Shelf Sci. 2015;156:186–94.

62. Nepote E, Bianchi CN, Morri C, Ferrari M, Montefalcone M. Impact of a harbour construction on the benthic community of two shallow marine caves. Mar Pollut Bull. 2017;114(1):35–45.
63. Norrman KE. World population growth: a once and future global concern. World. 2023;4(4):684–97.
64. OECD. How's life in your region? Measuring regional and local well-being for policy making. Paris: OECD Publishing; 2014. p. 172. https://doi.org/10.1787/9789264217416-en.
65. Paoli C, Montefalcone M, Morri C, Vassallo P, Bianchi CN. Ecosystem functions and services of the marine animal forests. In: Rossi S, Bramanti L, Orejas C, editors. Marine animal forests: the ecology of benthic biodiversity hotspots. Cham: Springer International Publishing; 2017. p. 1271–312.
66. Paoli C, Morten A, Bianchi CN, Morri C, Fabiano M, Vassallo P. Capturing ecological complexity: OCI, a novel combination of ecological indices as applied to benthic marine habitats. Ecol Ind. 2016;66:86–102.
67. Parravicini V, Micheli F, Montefalcone M, Morri C, Villa E, Castellano M, Povero P, Bianchi CN. Conserving biodiversity in a human-dominated world: degradation of marine sessile communities within a protected area with conflicting human uses. PLoS ONE. 2013;8(10): e75767.
68. Parravicini V, Thrush SF, Chiantore M, Morri C, Croci C, Bianchi CN. The legacy of past disturbance: chronic angling impairs long-term recovery of marine epibenthic communities from acute date mussel harvesting. Biol Cons. 2010;143:2435–40.
69. Pascual U, Balvanera P, Anderson CB, Chaplin-Kramer R, Christie M, González-Jiménez D, Martin A, Raymond CM, Termansen M, Vatn A, Athayde S, Baptiste B, Barton DN, Jacobs S, Kelemen E, Kumar R, Lazos E, Mwampamba TH, Nakangu B, O'Farrell P, Subramanian SM, van Noordwijk M, Ahn SE, Amaruzaman S, Amin AM, Arias-Arévalo P, Arroyo-Robles G, Cantú-Fernández M, Castro AJ, Contreras V, De Vos A, Dendoncker N, Engel S, Eser U, Faith DP, Filyushkina A, Ghazi H, Gómez-Baggethun E, Gould RK, Guibrunet L, Gundimeda H, Hahn T, Harmáčková ZV, Hernández-Blanco M, Horcea-Milcu AI, Huambachano M, Lutti Hummel Wicher N, Aydın Cİ, Islar M, Koessler AK, Kenter JO, Kosmus M, Lee H, Leimona B, Lele S, Lenzi D, Lliso B, Mannetti LM, Merçon J, Monroy-Sais AS, Mukherjee N, Muraca B, Muradian R, Murali R, Nelson SH, Nemogá-Soto GR, Ngouhouo-Poufoun J, Niamir A, Nuesiri E, Nyumba TO, Özkaynak B, Palomo I, Pandit R, Pawłowska-Mainville A, Porter-Bolland L, Quaas M, Rode J, Rozzi R, Sachdeva S, Samakov A, Schaafsma M, Sitas N, Ungar P, Yiu E, Yoshida Y, Zent E. Diverse values of nature for sustainability. Nature. 2023;620(7975):813–23.
70. Pearce DW, Turner RK. Economics of natural resources and the environment. Baltimore: Johns Hopkins University Press; 1990. p. 392.
71. Peirano A, Damasso V, Montefalcone M, Morri C, Bianchi CN. Effects of climate, invasive species and anthropogenic impacts on the growth of the seagrass *Posidonia oceanica* (L.) Delile in Liguria (NW Mediterranean Sea). Mar Pollut Bull. 2005;50:817–22.
72. Pelke N, Simonn FC. Ocean-human relations in the Anthropocene: mapping trends in sustainability-related marine social sciences articles. Front Mar Sci. 2023;10:1210133.
73. Pergent G, Bazairi H, Bianchi CN, Boudouresque CF, Buia MC, Clabaut P, Harmelin-Vivien M, Mateo MA, Montefalcone M, Morri C, Orfanidis S, Pergent-Martini C, Semroud R, Serrano O, Verlaque M. Mediterranean seagrass meadows: resilience and contribution to climate change mitigation. Gland: IUCN; 2012. p. 40.
74. Rastorgueff PA, Bellan-Santini D, Bianchi CN, Bussotti S, Chevaldonné P, Guidetti P, Harmelin JG, Montefalcone M, Morri C, Perez T, Ruitton S, Vacelet J, Personnic S. An ecosystem-based approach to evaluate the ecological quality of Mediterranean undersea caves. Ecol Ind. 2015;54:137–52.
75. Reid A, Dillon J, Ardoin N, Ferreira JA. Scientists' warnings and the need to reimagine, recreate, and restore environmental education. Environ Educ Res. 2021;27(6):783–95.
76. Rigo I, Paoli C, Dapueto G, Pergent-Martini C, Pergent G, Oprandi A, Montefalcone M, Bianchi CN, Morri C, Vassallo P. The natural capital value of the seagrass *Posidonia oceanica* in the North-Western Mediterranean. Diversity. 2021;13:499.
77. Ripple WJ, Wolf C, Newsome TM, Galetti M, Alamgir M, Crist E, Mahmoud MI, Laurance WF, 15,363 scientist signatories from 184 countries. World scientists' warning to humanity: a second notice. Bioscience. 2017;67(12):1026–8.
78. Robbins LC. An essay on the nature and significance of economic science. 2nd ed. London: Macmillan & Company; 1935. p. 175.
79. Robello C, Acunto S, Leone LM, Mancini I, Oprandi A, Montefalcone M. Large-scale re-implantation efforts for *Posidonia oceanica* restoration in the Ligurian Sea: progress and challenges. Diversity. 2024;16(4):226.
80. Roberts C, Béné C, Bennett N, Boon JS, Cheung WWL, Cury P, Defeo O, De Jong Cleyndert G, Froese R, Gascuel D, Golden CD, Hawkins J, Hobday AJ, Jacquet J, Kemp P, Lam ME, Le Manach F, Meeuwig JJ, Micheli F, Morato T, Norris C, Nouvian C, Pauly D, Pikitch E, Amargos FP, Saenz-Arroyo A, Sumaila UR, Teh L, Watling L, O'Leary BC. Rethinking sustainability of marine fisheries for a fast-changing planet. Ocean Sustain. 2024;3:41.
81. Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes TP, Van der Leeuw S, Rodhe H, Sörlin S, Crutzen P, Foley JA, Kosten S. A safe operating space for humanity. Nature. 2009;461(7263):472–5.
82. Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Summerhayes C, Barnosky AD, Cornell SE, Crucifix M, Donges JF, Ehrlich PR, Gerten D, Heinke J, Kaptue A, Kautsky N, Liu J, de Vries W, Schellnhuber HJ. Trajectories of the Earth system in the Anthropocene. Proc Natl Acad Sci. 2018;115(33):8252–9.
83. Taagepera R, Nemčok M. World population growth over millennia: ancient and present phases with a temporary halt in-between. Anthropocene Rev. 2024;11(1):163–83.
84. Telesca L, Belluscio A, Criscoli A, Ardizzone G, Apostolaki ET, Fraschetti S, Gristina M, Knittweis L, Martin CS, Pergent G, Alagna A, Badalamenti F, Garofalo G, Gerakaris V, Pace ML, Pergent-Martini C, Salomidi M. Seagrass meadows (*Posidonia oceanica*) distribution and trajectories of change. Sci Rep. 2015;5(1):12505.
85. The High Level Panel for a Sustainable Ocean Economy, 2020. The human relationship with our ocean planet. Washington DC: World Resources Institute. P. 80. https://oursharedseas.com/wp-content/uploads/2020/10/
86. United Nations. The second world ocean assessment. New York: United Nations publication; 2021. vol I 570 pp.; vol II 520 pp. https://www.un.org/regularprocess/woa2launch.
87. Union of Concerned Scientists. Warnings to humanity: a statement of the Union of Concerned Scientists. Cambridge: Union of Concerned Scientists; 1992. p. 3.

88. Ura K, Alkire S, Zangmo T. GNH and GNH index: a short guide to Gross National Happiness Index. Thimphu: The Centre of Bhutan Studies; 2012. p. 5.
89. Vacchi M, De Falco G, Simeone S, Montefalcone M, Morri C, Ferrari M, Bianchi CN. Biogeomorphology of the Mediterranean *Posidonia oceanica* seagrass meadows. Earth Surf Proc Land. 2017;42:42–54.
90. Vacchi M, Montefalcone M, Parravicini V, Rovere A, Vassallo P, Ferrari M, Morri C, Bianchi CN. Spatial models to support the management of coastal marine ecosystems: a short review of best practices in Liguria, Italy. Mediterr Mar Sci. 2014;15(1):189–97.
91. Van Norren DE. The sustainable development goals viewed through Gross national happiness, Ubuntu, and Buen Vivir. Int Environ Agreem Polit Law Econ. 2020;20(3):431–58.
92. Vassallo P, Paoli C, Rovere A, Montefalcone M, Morri C, Bianchi CN. The value of the seagrass *Posidonia oceanica*: a natural capital assessment. Mar Pollut Bull. 2013;75:157–67.
93. Wackernagel M, Rees W. Our ecological footprint: reducing human impact on the Earth. Philadelphia: New Society Publishers; 1996. p. 160.
94. Weaver A, Pope J, Morrison-Saunders A, Lochner P. Contributing to sustainability as an environmental impact assessment practitioner. Impact Assess Project Apprais. 2008;26(2):91–8.
95. World Commission on Environment and Development (WCED). Our common future. Oxford: Oxford University Press; 1987. p. 416.
96. Zhang Y, Xue Y, Guo K, Ji Q, Zhang D. Biodiversity and happiness: exploring the value of nature. Sustain Sci. 2024. https://doi.org/10.1007/s11625-024-01599-y.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.