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Umberto Grande

Goal functions and the assessment of natural capital and ecosystem services

PhD thesis

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UNESCO Chair “Environment, Resources and Sustainable Development”, Parthenope University of Naples, Italy

Supervisors

dr hab. Agnieszka Piernik, prof. NCU

prof. Pier Paolo Franzese

prof. (ass) Elvira Buonocore

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"Farewell to the harbor, to my old hometown

Let's all sing out with a Don! As the ship sets sail

Waves of gold and silver dissolve to salty spray

As well as sail to the ends of the sea…"

…For my beloved grandmother and father.

Table of contents

ABSTRACT

The Earth System is nowadays facing an unprecedented crisis due to intensifying anthropogenic pressures that are leading to an ecological deficit. By extracting resources at a rate exceeding their natural regeneration and emitting waste beyond ecological carrying capacities, humans are destabilizing the biosphere. Therefore, in a world increasingly impacted by human activities, understanding ecosystem functioning and the condition of Natural Capital stocks is crucial for ensuring human well-being.

Multiple theories and methodological approaches have been proposed for assessing and valuing nature and its services. Among them, notable are the Goal Functions, which can be conceptualized as propensities towards which ecosystem evolution is oriented, providing information about ecosystems, their configurations, and functions over time. GFs may be grouped into three main categories: biotic, network, and thermodynamic. In particular, thermodynamic Goal Functions base their concept on the laws of thermodynamics and the entropy principle, accounting for matter and energy within ecosystems to evaluate the intrinsic worth of natural systems, enabling a comprehensive understanding of their complex dynamics.

The attribution of biophysical and economic value to the benefits ecosystems offer is indispensable. In this regard, the United Nations established the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA) framework, which provides a standardized approach for accounting ecosystem service flows in both biophysical and economic terms, aiming to incorporate their value into decision-making processes.

Within this context, the goal of this doctoral thesis was to apply a biophysical approach to explore the exchange of matter and energy flows in the functioning of ecosystems, with a particular focus on the assessment of natural capital and ecosystem services.

To explore natural capital values, ecological complexity, and efficiency in ecosystems, we investigated three different types of lakes located in the Tuchola Forest UNESCO-MAB Biosphere Reserve (Northern Poland). By jointly applying emergy and eco-exergy Goal Functions, we tested the hypothesis that lakes of different trophies (e.i., oligotrophic, mesotrophic, and eutrophic) differ regarding natural capital value, system complexity and functioning. Moreover, using the eco-exergy / emergy ratio, we assessed the efficiency of the investigated ecosystems, describing the role of matter and energy flows in maintaining the structure of lake ecosystems over time. Our findings revealed that eutrophic lakes showed the highest natural capital measured in terms of emergy and eco-exergy values. However, the mesotrophic and oligotrophic lakes displayed a higher efficiency in maintaining and developing ecosystem structures and organizations.

The second hypothesis assumed that Natural Capital stocks can be affected by environmental parameters and anthropogenic pressures, and their changes can be detected by thermodynamical goal functions. Testing this hypothesis, we studied marine human-affected ecosystems of the Mediterranean Sea, in particular the Strait of Sicily (Italy). By applying the eco-exergy method, we assessed the complexity and dynamic of natural capital stocks over time. Moreover, spatial and hotspot analysis of eco-exergy and diversity indices were performed to identify key areas crucial for conservation strategies and marine spatial planning. Results showed a decline of natural capital stocks

over time, correlated to environmental parameters including temperature and pH. In addition, changes in the structure and complexity of the ecosystems were found. Furthermore, by combining eco-exergy and the Shannon index, two important areas were identified for conservation purposes.

The third hypothesis stated that variation in ecosystem services supply can be caused not only by human activities but also by intense natural disasters. We tested this hypothesis using the SEEA-EA framework, assessing the ecosystem assets and then ecosystem services provided by the forests of Tuchola Forest UNESCO-MAB Biosphere Reserve (Poland). In particular, the ability of the forests to remove air pollutants (PM10, PM2.5, NO2, and O3) and the loss of function caused by a hurricane were assessed. Findings showed the structure and composition of the forest (mainly covered by conifers and broadleaf functional groups) and its ability to highly contribute to air quality amelioration. Overall, removal efficiency revealed variations depending on the vegetation period of trees, phenological and physiological parameters, and the pollutant concentration. The total economic value of the regulating ecosystem services of air pollution removal was estimated in 791 million euros per year. Furthermore, changes in ecosystem services supply due to natural disasters highlighted how climate change and related extreme events can compromise the provision of benefits to humanity, with a loss of 7.4 million euros.

The research conducted within this doctoral study has demonstrated that ecological Goal Functions serve as a valuable tool for assessing natural capital, ecological complexity, and ecosystem dynamics. Furthermore, the evaluation of ecosystem services has emphasized the importance of attributing both biophysical and economic value to ecosystem goods and services in order to integrate their worth into decision-making processes, thereby preserving human well-being.

Keywords:

natural capital, emergy, eco-exergy, ecosystem efficiency, ecosystem complexity, ecosystem dynamic, diversity, fishery resources, air quality amelioration.

1. INTRODUCTION

1.1 Background

Throughout history, human societies have depended on natural systems for sustenance (Liu et al., 2007). For much of this time, human interactions with the biosphere remained within ecological limits, ensuring the continued functioning of ecosystems (Rockstrom et al., 2009; Richardson et al., 2023). However, the Earth System is nowadays facing an unprecedented crisis due to intensifying anthropogenic pressures that are leading to an ecological deficit (Folke et al., 2021). By extracting resources at a rate exceeding their natural regeneration and emitting waste beyond ecological carrying capacities, humans are destabilizing the Biosphere (Wackernagel et al., 2002). Furthermore, rapid urbanization, driven by population growth, exacerbates environmental pressures. With projections indicating a global population increase to 10 billion within the next 50 years, the associated rise in ecological footprint risks causing irreversible damage (Dasgupta and Ehrlich, 2013; Lam, 2024).

The scale and intensity of these phenomena profoundly alter ecological processes and functions (Western, 2001). Manifestations of these disruptions include soil degradation, habitat destruction, biodiversity loss, climate change, pollution, and disturbances in biogeochemical cycles (Rabouille et al., 2001; Jie et al., 2002; Lovett et al., 2009; Pecl et al., 2017; Trenberth, 2018). While ecosystems exhibit dynamic self-regulating capacities, their resilience is not boundless. Once critical thresholds are surpassed, their ability to mitigate anthropogenic pressures diminishes significantly, leading to non-linear changes. Such regime shifts can result in new equilibrium states beyond human adaptability (Capon et al., 2015; Newbold et al., 2020).

In 2005, the Millennium Ecosystem Assessment (MA), a scientific and international initiative to assess ecosystem conditions worldwide, alarmingly reported that approximately 66% of global ecosystems were already degraded or at risk (MA, 2005). The MA also highlighted the indispensable role of natural systems in supporting human well-being, emphasizing the profound threats posed by ecosystem deterioration to mankind (Daguspta, 2001; MA, 2005). The integrity of natural systems is fundamental to ecological stability, human health, and socio-economic security (Neller and Neller, 2009). When ecosystems maintain their inherent processes and function, they provide essential benefits to human well-being (Balmford & Bond, 2005). For example, forests and oceans can absorb CO2 from the atmosphere, helping to reduce greenhouse gas concentrations in the air, thus mitigating the effects of climate change and damage to the population (Nunes et al., 2020). Furthermore, forests act as natural barriers against air pollutants such as SO_2, NO_2, $PM_{2.5}$, and PM_{10} (Escobedo & Nowak, 2009; Han et al., 2020; Jin et al., 2021), abating health disease and hospitalization (Nowak et al., 2018). Still, aquatic ecosystems are able to ensure food supply in terms of fish biomasses (Dugan et al., 2002), or energy through the provisioning of renewable resources (de Assis Especie, 2019). Some marine habitats ensure coastal protection from storms and waves, avoiding coastal erosion and consequently, monetary loss due to the decrement in the tourism sector (Liquete et al., 2013). Both terrestrial and aquatic ecosystems offer nursery areas essential to maintain the trophic web and the generated food supply (Burch, 2005; Liquete et al., 2016).

Recognizing the environmental problems and the risks for society, numerous global initiatives have been launched to address ecosystem degradation and promote sustainability. The United Nations (UN) General Assembly has declared 2021-2030 the UN Decade on Ecosystem Restoration, an effort aimed at preventing, halting, and reversing ecosystem decline worldwide (Patra & Basu, 2021). Concurrently, approaches integrating socio-economic needs with environmental conservation have gained prominence. A pivotal framework in this regard is the UNESCO Man and the Biosphere (MAB) Programme, which seeks to foster sustainable human-environment relationships through an interdisciplinary approach combining natural and social sciences, balancing conservation with sustainable human use (Reed, 2019). Overall, such initiatives aim to integrate ecological, social, and economic dimensions, recognizing natural systems as foundational pillars supporting human well-being (Pool-Stanvliet et al., 2018). Additionally, they promote the biophysical and economic assessment of natural resources and the benefits they provide, endeavouring to incorporate this information into decision-making processes.

1.2 Natural Capital and Ecosystem Services

Since the past century, the relationship between natural and socio-economic systems and their functioning has been extensively explored (Turner, 2000; Kusova et al., 2005; Mata-Lima et al., 2013; Jie et al., 2023).

According to the System Theory of Von Bertalanffy (1968), both ecological and socio-economic systems act as open systems, mutually exchanging material, information and energy flows. According to this concept, ecological systems provide many essential resources and services to the socio-economic domain. Contrarily, they receive anthropogenic waste and emissions, regenerating the impacts our society produces. However, humanity has not adequately considered the limits of the Biosphere (Rockstrom et al., 2009).

In 1973, in the book "Small is Beautiful”, Schumacher and Standpunkt (1973) already emphasized the importance of natural resources and the need to consider their limited nature in economic decision-making. They argued that treating natural resources as mere commodities without recognizing their intrinsic value and the essential services they provide would lead to environmental degradation and unsustainable development. This perspective diverged from the tenets of Neoclassical Economics, which posited the potential for unbounded economic growth. Indeed, neoclassical theories suggested that living standards could be indefinitely elevated through expanded production systems and the assumption of limitless natural resources and consumption (Kneese, 1988). However, in 1980, a domain of economy named Ecological Economics began to affirm the concept that the economy is a subsystem embedded within the broader natural systems (Costanza, 1996). This concept opened up a novel perspective of the human-nature relationship, laying the foundation for a paradigm shift. Indeed, the confluence of all these factors, including growing concerns about environmental degradation, the realization that natural resources are constrained, and the recognition of natural systems as drivers of our society, have contributed to the genesis of the Natural Capital (NC) concept.

NC can be defined as the stock of renewable and non-renewable natural resources that yields a "natural income" by providing ecosystem goods and services (Ignatyeva & Logvinenko, 2020). More broadly, NC encompasses both living and non-living components of ecosystems, which form the basis for producing goods and services that benefit society (Buonocore et al., 2021).

Drawing upon the economic definition of capital as human-made assets that yield flows of goods and services, NC conceptualizes ecological resources as assets that provide analogous valuable flows. However, the core of NC aligns with the perspective of 'strong sustainability' (Neumayer, 1999). Sustainability, as the balance between human needs and the capacity of the Earth's systems to support them is characterized by two main approaches: 'weak sustainability, which posits that NC is substitutable with technological capital, and 'strong sustainability, which asserts that NC is irreplaceable by any form of human intervention and must be preserved. In alignment with the strong sustainability approach, the extraction of NC must be regulated to remain within the bounds of their sustainable yield, thereby securing the enduring sustainability of human populations (Neumayer, 1999). The maintenance of NC, therefore, constitutes a critical prerequisite for the continuous provision of goods and services, which are indispensable for human existence and prosperity.

Goods and services provided by natural systems can be defined as the benefits people obtain from ecosystems (MA, 2005) or, equally, as the contribution of NC to human well-being (TEEB, 2010) and named Ecosystem Services (ES). The Millennium Ecosystem Assessment (MA, 2005) divided the ES into four macro categories: (1) provisioning services, all the direct benefits provided by ecosystems, including food, fibre, drinking water, and timber; (2) regulating services, which represent indirect services such as carbon sequestration, air pollution removal, pollination; (3) cultural services, which represent non-material benefits obtained from ecosystems including aesthetic experience or recreational activities; and (4) supporting services, which are fundamental for sustaining all other ecosystem services. The definition of ES has evolved over time, accompanied by corresponding variations in their classification. A pivotal effort was implemented by The Economics of Ecosystems and Biodiversity (TEEB, 2010) that introduced the economic assessment of the benefits provided by ecosystems, giving value to natural systems and incorporating it in decision-making processes. Nowadays, the Common International Classification of Ecosystem Services (CICES) represents the official classification that divides ES into three macro categories (Haines-Young and Potsching, 2012; 2018): 1) Provisioning, 2) Regulating and maintenance, and 3) Cultural services.

1.3 Unlocking the value of ecosystems

The urgent need to assess the stock of NC, the benefits they provide and their changes over time led scientists to implement strategies to monitor the value of ecosystems and its involvement in decision-making processes. Over the past decades, numerous studies have estimated NC stocks and the associated ES flows through monetary valuation, emphasizing the critical role of natural resources in supporting human economies (Brown et al., 2016; Vassallo et al., 2013; Franzese et al., 2017; Capriolo et al., 2020; Jiang et al., 2021; Addamo et al., 2025). A landmark study by Costanza et al. (1997; 2014) provided one of the first global monetary estimates of NC and ES, concluding that their total economic value exceeded the annual global GDP at the time.

According to TEEB (2010), multiple theories and methodological approaches exist for valuing nature and its services, which can generally be categorized into two main paradigms: preference-based and biophysical approaches. Preference-based methods, widely used in economics, rely on monetary valuation and market-based principles. In contrast, biophysical methods are increasingly applied as complementary tools that capture non-anthropocentric forms of value.

One of the key advantages of monetary valuation lies in its ability to explicitly quantify natural systems to the economy and the costs associated with their loss, using economic metrics that are easily interpretable by decision-makers and stakeholders. However, monetary valuation approaches typically assign value only to services directly contributing to economic productivity. This creates limitations when monetary metrics are inapplicable or insufficient for decision-making. In particular, ES classified as "Commons" public goods without a market price end to be overlooked in monetary assessments, leading to their undervaluation and, in many cases, unsustainable use and overexploitation (Hardin, 1968; Häyhä & Franzese, 2014). Furthermore, another constraint in economic valuation occurs when ecosystems approach critical thresholds, where ecological alterations may be irreversible or require substantial remediation costs. Specifically, as an ecosystem nears a tipping point, minor reductions in the physical provision of ES can precipitate disproportionately with significant increases in their marginal economic value, rendering monetary assessment unreliable in such contexts (Farley, 2012).

Recognizing these limitations, some researchers proposed alternative biophysical methodologies to assess the intrinsic value of the ecosystem, offering an alternative perspective to economic valuation (Odum, 1988, 1996; Brown & Ulgiati, 1999; Wackernagel et al., 1999; Müller, 2005; Jørgensen, 2010; Ulgiati et al., 2011; Müller & Burkhard, 2012).In the biophysical approach, notable is the concept of Goal functions (GF). GFs can be conceptualized as propensities towards which the ecosystems' evolution is oriented, providing information about ecosystems and their configurations and functions over time (Nielsen & Jorgensen, 2013). GF can be used to characterize the state and the functional and structural features of an ecosystem, describing the tendencies of an ecosystem to move towards a certain state, often associated with increased stability, complexity, or efficiency in energy flow (Buonocore et al., 2019). In particular, thermodynamical GFs base their concept on the thermodynamic laws and entropy principle (Nielsen et al., 2020), revolving around the idea of predicting the entity of spontaneous changes in systems and their negative or positive development. This concept is often used in ecological modelling and theoretical ecology to understand and predict ecosystems' dynamics. GFs may be grouped into three main categories: biotic, network, and thermodynamic (Nielsen & Jorgensen, 2013). These functions help determine whether a process will occur naturally and, if so, what the final equilibrium state will be. The application of thermodynamic GF facilitates the evaluation of the intrinsic worth of natural systems, enabling a comprehensive understanding of their complex dynamics and extant environmental conditions (Bendoricchio & Jorgensen, 1997). Among the thermodynamic GFs, Emergy (Paoli & Vassalo, 2008; Picone et al., 2017; Liu et al., 2021; Vassallo et al., 2021) and Eco-exergy (Jorgensen & Nielsen, 2007; Zhang et al., 2010; Dai et al., 2014) have been widely used to unfold the role of matter and energy flows in the functioning of ecological systems. Emergy measures the work of nature to generate natural capital stocks embedded into ecosystems (Picone et al., 2017), while Eco-exergy accounts for the development and the organizational level of an ecosystem (Buonocore et al., 2019).

The emergy and eco-exergy GFs were widely applied in previous studies, confirming their extensive efficacy in evaluating ecosystems. Cohen et al. (2006) assessed environmental costs associated with soil erosion at multiple scales in Kenya using emergy GF. Libralato et al. (2006) applied the eco-exergy method to the complex dynamics occurring in a disturbed benthic community during recovery processes in the coastal area of the North Adriatic Sea. Kernegger et al. (2008) applied eco-exergy to assess fisheries landing and aquaculture trends based on FAO data to monitor marine NC stocks from 1950 to 2003 in the main fishing and aquaculture FAO areas. Lu et al. (2015) jointly applied emergy and eco-exergy to assess forest restoration in China. Picone et al. (2017) applied emergy to account for NC in Egadi Island Marine Protected Areas (MPAs), Italy. Zhong et al. (2018) used the emergy accounting method to evaluate the performance and carrying capacity of the Erhai lake and hydrographic basin (China). Buonocore et al. (2019) applied both emergy and eco-exergy to assess NC in MPAs in Italy. Yuan et al. (2022) assessed the effect of artificial reef construction on the nekton community in Dalajia (China) by applying the eco-exergy accounting method. Bastianoni (2002) used emergy, eco-exergy, and the eco-exergy to emergy ratio to assess the ecosystem efficiency of the Figheri basin located in the Lagoon of Venice (Italy), also comparing it with Trasimeno Lake and the Caprolace Lagoon.

Overall, biophysical assessment constitutes a fundamental component for determining the value of natural resources; however, to achieve comprehensive incorporation of ecosystem value into decision-making processes, NC and ES valuation necessitates a multi-methodological approach that accounts for economic and environmental benefits, costs and impacts. In this context, in 2021, the United Nations (UN) established the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA). This framework provides a standardized and comprehensive approach for accounting NC stocks and ES flows in both biophysical and economic terms, aiming to incorporate their value in decision-making processes (United Nations et al., 2021). Although it is a novelty, several studies applied the SEEA-EA framework for the assessment of ES. Farrell et al. (2021) implemented the SEEA-EA framework at the catchment scale to develop ecosystem extent and condition accounts in Ireland. Schenau et al. (2022) assessed ecosystem services and ecosystem assets in the Netherlands using the SEEA-EA framework, only focusing on estimating the economic value of human benefits produced by ecosystems, excluding non-economic values and 'non-human' benefits. Bruzon et al. (2023) used the SEEA-EA framework to monitor forest condition accounts at the national level (Spain). Maes et al. (2023) implemented the SEEA-EA framework accounting for European forest conditions. De Fioravante et al. (2023) implemented the SEEA-EA framework mapping ecosystems extent in Italy and assessing crop provisioning and carbon stock at a national level.

1.4 Objectives of the work and research hypotheses

In the presented above context, the aim of this project was to apply a biophysical approach to exploring the exchange of matter, and energy flows in the functioning of ecosystems, with a particular focus on the assessment of NC and ES. We focused on both aquatic and terrestrial ecosystems.

For assessing ecosystems' natural capital value, ecological complexity and efficiency we choose three different types of lakes located in the Tuchola Forest UNESCO-MAB Biosphere Reserve (Northern

Poland). We jointly applied emergy and eco-exergy to test the hypothesis that lakes of different trophy, e.i. oligotrophic, mesotrophic and eutrophic differ regarding the natural capital value, system complexity and functioning. Moreover, we use the eco-exergy / emergy ratio to define the efficiency of the investigated ecosystems, describing the role of matter and energy flows in maintaining the structure of lake ecosystems over time. While the emergy and eco-exergy methods have been previously applied to investigate natural ecosystems, there are no research specifically assessing the value of biotic natural capital stocks in freshwater lake ecosystems by jointly using the emergy and eco-exergy methods. Therefore, this case study can represent a benchmark for future comparison of interest for an international audience.

The second hypothesis assumes that ecosystem Natural Capital can be affected by human activity and environmental parameters and can change over time. Testing this hypothesis, we studied marine human-affected ecosystems of the Mediterranean Sea, applying the eco-exergy method supplemented by Shannon diversity analysis. We chose the Strait of Sicily (SoS), in the central Mediterranean Sea, as a case study given its ecological significance as a biodiversity hotspot and its socio-economic importance. This area is also increasingly threatened by the overexploitation of demersal fish populations, primarily driven by intensive fishing to harvest valuable shrimp species. We explored the current state of NC's stock of demersal resources and its changes in the last fifteen years. The findings regarding NC and biodiversity were correlated with temporal trends of key environmental factors and fishing efforts within the study area. Moreover, to detect areas of high ecological value, spatial and hotspot analysis of eco-exergy and diversity indices were performed, identifying key areas crucial for conservation strategies and marine spatial planning. This is the first study that aims to implement a multi-methodological framework integrating the use of thermodynamic GF, diversity index, and spatial and hotspot analysis to assess the spatiotemporal trend of NC stock in the SoS.

The third hypothesis stated that variation in ES supply can be caused not only by human activity but also by intense natural disasters. We tested this hypothesis using SEEA-EA methodology as a standardised statistical framework adopted by the United Nations. We implemented the SEEA-EA framework to assess the ecosystem assets and then ES provided by the forests of Tuchola Forest UNESCO-MAB Biosphere Reserve (Poland). We included selected ecosystem extent and condition indicators to focus on the estimation of regulating ES regarding air pollution regulation. Then, we assessed the variation in ES supply caused by an intense hurricane that destroyed a large area of the Biosphere Reserve forests. To the best of our knowledge, this is the first study that aims to implement the SEEA-EA framework within the MAB Biosphere Reserve, assessing variation in ES supply caused by natural disasters.

2. METHODS

2.1 Emergy sinthesys

The emergy accounting method was used in the first case study of this thesis for assessing the biophysical value of NC stocks in three lakes with different trophies in terms of matter and energy flowing in the ecosystems and ecosystems' efficiency. Emergy is a biophysical method useful to assess the cumulative environmental support for NC stocks (Odum, 1988, 1996). Specifically, emergy is defined as "the total amount of solar available energy (exergy) directly or indirectly required to make a given product, to support a given flow or service" (Odum, 1996; Franzese et al., 2020). The emergy method considers free environmental inputs (e.g., solar radiation, wind, rain, and geothermal flow), human-driven material and energy flows, and the indirect environmental support embodied in human labor and services. The first step is creating a system diagram summarizing the main external driving forces supporting the generation of natural capital stocks.

According to the emergy theory, inputs are accounted for through a common unit of measure, the solar equivalent Joule (sej) (Odum, 1996). The solar emergy required to generate one unit of product or service is referred to as Unit Emergy Value (UEV, sej J^{-1}, sej g^{-1}). The UEV reflects the direct and indirect environmental support for generating one unit of product or service: the higher the UEV, the higher the environmental cost (Brown and Ulgiati, 1997). Mass, energy, labour, and money input flows converging to the investigated system are converted into emergy units by using appropriate UEVs and then summed to compute the total emergy supporting the system.

The emergy accounting follows four main steps:

1. Identification of the spatial and temporal boundaries of the investigated lake ecosystems.
2. Inventory of mass and energy flows supporting natural capital stock formation in the lake ecosystems (integration of literature and field data)
3. Conversion of input flows into emergy units by using appropriate UEVs (literature data)
4. Calculation of the total emergy supporting natural capital stocks formation in the lake ecosystems.

2.2 Eo-exergy

The eco-exergy accounting was applied in the first and second case studies to assess NC stocks regarding energy and genetic information. The eco-exergy accounting method aims at quantifying the available energy of all living biotic components in an ecosystem compared to the non-living state (i.e., the detritus). In particular, the eco-exergy method accounts for the chemical energy in organic matter and the genetic information embodied in living organisms, measuring the organization and development stage of an ecosystem (Jørgensen and Mejer, 1979). Broadly, eco-exergy allows us to account for the distance from thermodynamic equilibrium as a measure of the complexity of an ecosystem (Fath et al., 2004; Marchi et al., 2012).

The eco-exergy value for living organisms is calculated according to the following equation:

$$\mathrm{EEx} = \sum_{i}^{n} \mathrm{EEx}_i = \sum_{i}^{n} \beta_i * \mathrm{B}_i * \mathrm{f}_i$$

where, ß is a weighting factor expressing the information content of the organism's genes, B is the organism's biomass (in ash free dry weight), and *f* is the value of work energy per biomass unit. Through appropriate conversion factors ash free dry weight was obtained from wet weight (Ricciardi and Bourget, 1998; Gogina et al., 2022; FishBase, data access 2024). The value of *f* may change among different taxonomic groups: the higher the fat content, the higher the value. The average value of 18.7 kJ/g was used in this study, according to Jørgensen (2015). The ß-value derived from Jørgensen (2015).

The total eco-exergy of an ecosystem is computed as the sum of the eco-exergy values calculated for all the organisms living in that ecosystem.

2.3 Shannon diversity index

In this research, the biomass-based Shannon index was used in the first case study to compare holistic (GF) and conventional (Shannon index) ecological indicators. The Shannon index was also applied in the second case study dealing with marine ecosystems, jointly coupled with GF, in order to detect areas for conservation strategies exhibiting high NC value and high diversity value.

The Shannon index is a widely used metric in ecology to quantify biodiversity within a given ecosystem. It takes into account for both the number of different species (species richness) and their relative abundances and is calculated as follows:

$$\mathrm{H} = - \sum_{i=1}^{s} p_i \ln p_i$$

where H is the Shannon index, S is the total number of species, p_i is the proportion of individuals belonging to the i-th species on the total.

Higher values of the Shannon index indicate greater diversity within the community, with a maximum value occurring when all species are equally abundant. In ecological studies, the Shannon index is often used to compare diversity across communities or to track changes in diversity over time in response to various environmental factors or disturbances (Shannon and Weaver, 1963).

2.4 SEEA-EA framework

In this research, SEEA-EA methodology was applied to assess ecosystem extent, condition, and ES supply in the forest ecosystem before and after a hurricane destroyed hectares of trees, to determine the benefits lost.

In recent decades, a proliferation of methodologies and approaches aimed at assessing the value of ES occurred, each offering unique perspectives (Liquete et al., 2013). In this context, ecosystem accounting seeks to assign both biophysical and economic significance to the benefits that nature provides to mankind, highlighting the strong relationship between ecosystems and human well-being (Edens et al., 2013). One notable model in this field is the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA), established by the United Nations as a standardized statistical framework (United Nations et al., 2021). This framework provides a standardized and comprehensive approach for quantifying and assessing ES provided by NC stocks in both biophysical and economic terms. The SEEA-EA framework emerged as a response to the growing recognition of the critical role that ecosystems play in supporting human well-being and economic development (De Valck et al., 2023). The SEEA-EA facilitates an integrated, spatially explicit methodology that organizes biophysical data, evaluates ES, and monitors changes in ecosystem extent and condition over time (Vallecillo et al., 2022). Significantly, the SEEA-EA framework emphasizes the intricate connection between humans and the environment, linking ecosystem stocks and flows with economic assets in alignment with the principles of the System of National Accounts (SNA) (United Nations, 2021).

Basically, the SEEA-EA framework consists of five main components: (1) ecosystem extent, (2) ecosystem condition, (3-4) ecosystem services flows and use, 5) ecosystem asset account (De Fioravante et al., 2023). **Ecosystem extent and condition,** clustered in the macro category of the "stock account & change in stocks" provide a comprehensive overview of the extent and condition of ecosystems within a specific accounting area. The accounting area can be a nation, province, river basin, protected area, or any other defined geographic boundary composed of different **ecosystem types**. The ecosystem types represented within an accounting area categorize ecosystems based on their biophysical characteristics, aligning with the IUCN Global Ecosystem Typology (Farrell et al., 2021). This hierarchical classification system organizes ecosystems into 108 distinct types, defined by functional groups like tropical forests, seagrass meadows, and annual croplands (Blazquez et al., 2023). By tracking changes in the extent and condition of the ecosystems over time, it is possible to provide valuable information regarding the trends and evolution of natural capital stocks.

The **ecosystem services flow and use,** clustered in the macro category of the "flow account", is the core component of the SEEA-EA framework, allowing the assessment in both biophysical and monetary terms of ecosystem services provided by the accounting area. In these steps, the way that people utilize the service is also assigned: direct use (e.g., harvesting timber), indirect use (e.g., benefiting from air purification), or non-use values (e.g., the value of preserving biodiversity for future generations).

Lastly, the **ecosystem asset account** is the fifth and final step of the SEEA-EA framework. It provides a comprehensive overview of the stock and changes in stocks (additions and reductions) of ecosystem assets, valuing how the extent, condition and monetary value have been changed over time. This step is not mandatory compared to the previous ones (United Nations, 2021).

2.5 Data sources and methodological applications

2.5.1 The lakes ecosystems

Three different lakes, namely Czarne, Zmarle and Laska, located in the Brusy municipality in the Chojnice district (Northest Poland), were investigated. The lakes are embedded in the Zaborski Landscape Park, surrounding the Tuchola Forest National Park. The morphology and trophism of the three lakes differ considerably. Czarne is an oligotrophic and polymictic lake characterized by lobelia colonies which are recorded to a depth of 5 m (Barańczuk & Borowiak, 2010). Zmarle is a young lake without drainage. Due to its water mixing dynamic, it is classified as a dimictic lake, while in terms of trophism it is classified as a mesotrophic lake (Barańczuk & Borowiak, 2010). Laska is a mature lake belonging to the Zubrzyca River Basin. Laska is a polymictic lake characterized by complete mixing of water several times per year. In terms of trophism, it is classified as a eutrophic lake. The nutrient input flow is also raised by a large salmon farm located close to the water body (Barańczuk & Borowiak, 2010).In the case of emergy, environmental input including sun, rain, wind, geothermal flow, nitrogen and phosphorous were accounted for each of the lake, and literature and local data were used (Rejewski, 1981; Rejewskiego et al., 1993; Odum, 1996; Metereological station in Chojnice, 1988-1998; Atlas klimatu Polski, 2005; Global solar atlas, data access, 2021; Global heat flow database, data access, 2021).

Solar radiation was calculated as:

annual solar irradiance*(1-albedo)*lake surface*natural capital formation time (1)

Rain as:

annual rainfall*water density*Gibbs number*lake surface*natural capital formation time (2)

Wind was assessed by:

annual wind energy*unit of surface*lake surface*natural capital formation time (3)

Geothermal flow as:

heat flow*lake surface*natural capital formation time (4)

Nitrogen was assessed as:

annual water flow*unit of surface*catching area*N content in water*natural capital formation time(5)

Phosphorus was calculated as:

annual water flow*unit of surface*catching area*P content in water*natural capital formation time(6)

Natural capital formation time was assumed to be three years. The UEV value to convert the input amount in solar Joule was taken from the literature (Odum, 1996; Brown and Ulgiati, 2010). For the eco-exergy calculation, the biomasses of the main taxonomic groups living in the lakes were accounted and biomasses from field data were used. Literature data were applied to determine the beta value (Jorgensen et al., 2005).

Furthermore, the eco-exergy /emergy ratio was calculated to determine the efficiency of ecosystems in maintaining their NC stocks (Bastianoni, 2002; Lu et al., 2015).

Lastly, the Biomass-Shannon index was assessed to compare holistic and conventional ecological indicators. The biomasses data used to assess the diversity were the same of the eco-exergy calculation.

2.5.2 Marine ecosystem

The eco-exergy assessment based on the Mediterranean International Trawl Survey (MEDITS) dataset was used to assess the demersal NC stock in the timeframe from 2005 to 2021. The MEDITS is a standardized trawl survey program, started in 1994, which aims to collect data on the distribution and abundance of demersal fish and shellfish in the EU Mediterranean Sea (Bertrand et al., 2002). According to the MEDITS protocol, the survey is conducted annually during the spring season. It utilizes a stratified random sampling approach based on five depth strata: 10–50 m, 51–100 m, 101–200 m, 201–500 m, and 501–800 m. The number of sampling stations in each stratum is proportional to the surface area of the respective depth stratum.

Furthermore, to investigate ecological parameters, monthly layers of Sea-Surface Temperature (SST, °C) and Sea-Surface Salinity (SSS, psu) were extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) for the period from 2000 to 2021 (Nigam et al., 2021). Monthly layers of seawater pH and net Primary Production (PP) for each year from 2000 to 2021 were extracted from

Teruzzi et al., 2021. In the case of fishing effort (kW*fishing days) data from the EU Data Collection Framework (DCF) source (Regulation EU 2017/1004) were used.

Lastly, to detect areas for conservation purpose, Georeferenced data on eco-exergy and diversity indices were used to create annual distribution maps through inverse distance-weighted (IDW) deterministic interpolation (Isaaks and Srivastava, 1989). In addition, hotspot analysis, a technique that identifies statistically significant spatial clusters of high values (hot spots) and low values (cold spots), was applied using the Getis-Ord Gi* statistics (Ord and Getis, 1995). Queen's case contiguity was applied to determine grid cells considered spatial neighbours in the cluster analysis. Statistically significant clusters were identified as hotspots based on a z-score greater than 1 and a p-value of 0.05 (Ord and Getis, 1995). Finally, for each of the three defined 5-year time intervals, annual hotspots of eco-exergy and diversity were overlaid. This allowed to identify areas where high values for both indices consistently co-occurred and whether these areas changed through time, highlighting key areas for conservation strategies and marine spatial planning. All the analyses were performed in R software.

In addition, linear models were applied at eco-exergy values to investigate the presence of significant trends in the eco-exergy and diversity indices over the total area and for both the shelf and the slope. Linear regression analysis was conducted to identify significant trends over time in environmental variables and fishing effort data. Anomaly of environmental variables Sea Surface Temperature (SST), Sea Surface Salinity (SSS), pH and Primary Production (PP) in the study area, expressed as a difference from the overall mean divided by the standard deviation between 2000 and 2021. The nominal fishing effort (GT*fishing days) of bottom trawlers registered in the Strait of Sicily was investigated applying a superimposed linear model, along with its 95% confidence interval. Spearman correlations between eco-exergy (EEx), Shannon index (H), environmental variables (SST, SSS, pH, PP) and fishing effort was assessed. The analyeses were performed using R software.

2.5.3 Forest ecosystem

Ecosystem extent evaluation was performed using Quantum Geographic Information System (QGIS) software (version 3.26.3), while Corine Land Cover (CLC) products provided by the Copernicus Land Monitoring Service (CLMS) to establish the land cover classification.

Ecosystem **condition** focused on the assessment of abiotic and biotic indicators. Air pollutant concentrations of (PM_{10}, PM $_{2.5}$, NO_2 and O3) were used as abiotic indicators. European annual air quality (interim) reanalyses at a 0.1-degree (approximately 10 km) spatial resolution from Copernicus Atmosphere Monitoring Service (CAMS) were used and processed in QGIS. Among biotic indicators, the seasonal Leaf Area Index was accounted for. Data from Copernicus Global Land Services (CGLS) and based on Sentinel-3/OLCI with PROBA V with 300 were used. Values were averaged on a seasonal basis using the GRASS GIS software. (v. 7.8.3), according to the tree functional group (FG) and meteorological season classification (NOAA, 2023).

Ecosystem services assessment was performed as a set of regulating ES. In particular, the air pollution removal (PM_{10}, $PM_{2.5}$, NO_2 and O_3) was evaluated before and after a hurricane destroyed hectares of forest. Two different models were applied.

The removal of PM_{10}, and $PM_{2.5}$ was estimated following the equation proposed by Nowak et al. (1994) and Fusaro et al., (2017):

$$Q = F * L * T \tag{7}$$

where Q is the amount of pollutant which is adsorbed; F is the flux of pollutant, defined as the deposition velocity of the pollutant multiplied by the pollutant concentration; L is the LAI for the considered period; T is the vegetative period of the considered FG of vegetation. According to Sebastiani et al. (2021), conifers are considered to provide ESs all year long. Instead, deciduous trees provide it for 275 days per year, according to their different phenology.

In the context of PM_{10}, the deposition velocity (Vd) in this study has a median value of 0.0064 m/s, which is based on a mean annual LAI value of six and then adjusted according to the actual LAI, while a median value of 0.0019 m/s was adopted for $PM_{2.5}$ according to the local wind speed and adjusted according to the actual LAI (Escobedo & Nowak, 2009; Hirabayashi et al, 2012)..

The absorption of NO_2 and O_3 was estimated using a spatially explicit model (Fusaro et al., 2017; Nardella et al., 2024) following the equation:

$$FO_3t = C * gs * Ph * K \tag{8}$$

Where FO3t is the total cumulated O_3 flux (ppb), C is the O_3 concentration (ppb), gs represents the stomatal conductance to water vapour (mol/m2s), and Ph indicates the length of the photoperiod (s). The mean photoperiod was estimated according to the season and the local daylight amount (NOAA, 2023). K is a constant given by the following equation:

$$K = (48 * 0.613 * 0.5) / (0.3 * 109) \tag{9}$$

48 refers to the molecular weight of O_3 (g/mol), 0.613 represents the diffusibility ratio between O_3 and water vapour, 0.5 is a conversion factor from µg/m3 to ppb (assuming an average temperature of

25 °C and pressure of 1 atm), and 109 is a dimensional correction factor (from mol to nmol). The stomatal conductance (gs) values were collected from the literature according to Emberson et al. (2000) and Nardella et al. (2024). Based on previous studies on coniferous and broadleaf forests, 0.3 represents 30% of the total potential O_3 removal of both stomatal and non-stomatal processes. In the case of NO_2 the molecular weight was 46 and the diffusibility ratio 0.62, according to the nitrogen dioxide molecule.

Lastly, the economic value of the air pollution service was determined by applying the externality cost of pollutants (Sebastiani et al., 2021), based on the values reported in the (EEA, 2024).

3. RESULTS

3.1 Paper

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Measuring natural capital value and ecological complexity of lake ecosystems

U. Grande[a,b], A. Piernik[b], A. Nienartowicz[b], E. Buonocore[a,*], P.P. Franzese[a]

[a] Department of Science and Technology, International PhD Programme / UNESCO Chair "Environment, Resources and Sustainable Development", Parthenope University of Naples, Italy

[b] Department of Geobotany and Landscape Planning, Nicolaus Copernicus University in Toruń, Toruń, Poland

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ABSTRACT

Healthy ecosystems are capable of maintaining their structures and functions, ensuring the generation and maintenance of natural capital stocks delivering ecosystem services flows vital for human well-being. The development of ecosystems can be investigated by using different ecological goal functions. Among them, emergy and eco-exergy can be used to unfold the role of matter and energy flow exchanges in the functioning of ecological systems. In this paper, the emergy and eco-exergy accounting methods were integrated to investigate three forest lake ecosystems characterized by a different trophism (oligotrophic, mesotrophic, and eutrophic) and located in the Tuchola Forest UNESCO-MAB Biosphere Reserve (Northern Poland). In particular, emergy was used to account for the work of nature invested to generate natural capital stocks, while eco-exergy was used to characterize the development stage of lake ecosystems reflecting their trophic and health state. The eutrophic lake showed the highest emergy investment ($4.36 \bullet 10^{12}$ sej m^{-2}) for the generation of natural capital stocks, mainly due to the high convergence of nutrient flows. The eutrophic lake also showed the highest value of eco-exergy density ($1.38 \bullet 10^{6}$ KJ m^{-2}) mainly due to the high ß value of macrophyte and aquatic birds. Finally, the eco-exergy / emergy ratio was calculated to assess the efficiency of the three lake ecosystems. The mesotrophic lake showed the highest value of the ratio ($1.43 \bullet 10^{-3}$ J sej^{-1}), highlighting a better efficiency in maintaining and developing ecosystem structure and organization. Overall, the outcomes of this study were consistent with the different trophism of the investigated lakes, confirming how external driving forces can orient the development and complexity of lake ecosystems. In conclusion, integrated assessments adopting an ecosystem and holistic perspective can result in a promising approach to investigate lake ecosystems worldwide, providing useful scientific information to policy makers committed to ensure the sustainable management of surface water ecosystems.

1. Introduction

1.1. Scientific background

Surface water ecosystems include rivers, lakes, and transitional and coastal waters (European Environment Agency, 2019). These ecosystems have always played a crucial role in the history of humanity providing flows of goods and services vital for human well-being (Vári et al., 2022).

Nevertheless, the ever increasing anthropogenic pressures are altering the structure and functioning of these ecosystems, threatening their ecological integrity (Albert et al., 2021; Janse et al., 2015; MA, 2005). According to "The European environment - state and outlook 2020″ report published by the European Environment Agency, currently only 40% of the European surface water bodies achieve good ecological status, thus emphasizing the need to undertake concrete measures to preserve them (European Environment Agency, 2019).

Ensuring the good status of ecosystems means maintaining their ability to store natural capital while generating vital flows of goods and services. Natural capital can be defined as the stocks of natural resources (such as water, soil, and living biomass) generated by matter and energy flows in the ecosystems (Costanza et al., 1997, 2014; Daily, 1997; Folke et al., 2010, 2011; Jones et al., 2016; MA, 2005).

In the last decades, several actions have been undertaken to preserve

* Corresponding author.
E-mail address: elvira.buonocore@uniparthenope.it (E. Buonocore).

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natural capital stocks in aquatic ecosystems. In 2000, the Water Framework Directive (WFD) was adopted establishing a framework for action in the field of water policy for achieving a good qualitative and quantitative status of all European water bodies within 2015. The WFD aimed at enhancing the health of aquatic ecosystems paying attention to groundwater, sustainable water use, pollution, floods, and droughts mitigation (Josefsson and Baaner, 2011). Despite the efforts in restoring the ecological condition of the European waters, the main goals of the WFD have not been fully accomplished (Voulvoulis et al., 2017).

Among the surface waters, lakes hold 98% of all global freshwater ecosystems, although covering only 0.01% of the total area (Hairston and Fussmann, 2012). Lacustrine ecosystems provide a wide range of benefits to human society, among which flood control, climate change mitigation, river flow regulation, hydropower supply, and water purification and storage (Ho and Goethals, 2019).

Ecosystem functions underlying lake ecosystems are driven by metabolic processes (Staehr et al., 2012). Depending on their metabolism and the amount of available nutrients, lakes can be classified in three main categories: oligotrophic, mesotrophic, and eutrophic (Istvanovics, 2010).

Oligotrophic lakes are featured by poor amounts of nutrients and low productivity. They are characterized by scarce populations abundance, low consumption of oxygen, water clarity, few suspended algae and low amount of chlorophyll. Mesotrophic lakes are distinguished by a middle amount of nutrients and organic sediments accumulating on the bottom. The productivity is intermediate between oligotrophic and eutrophic lakes and the oxygen concentration may not fluctuate except near the bottom. Finally, eutrophic lakes are characterized by large amounts of nutrients and high productivity. Eutrophic lakes also imply high quantity of organic sediments, high phytoplankton and zooplankton concentrations, depletion of oxygen from the lower depths, high chlorophyll concentration and low water clarity.

In the case of forest lakes, the metabolism is conditioned by further factors influencing ecological processes (Staehr et al., 2010, 2012). Tree canopy coverage and nutrients inputs by the surrounding forest are the main additional driving forces. The increase in forest coverage corresponds to a decrease in solar radiation which triggers negative feedback on primary production. In addition, a higher shading causes a lower exposure to wind affecting the water circulation and temperature. Forest lakes can also receive nutrients coming from the external environment. The additional contribution of terrestrial organic matter causes a further attenuation of sunlight and an increase of organic carbon oxidation. Thereby, the respiration growth induces a greater oxygen consumption and a higher CO_2 release, mostly in small forest lakes. Such dynamics strongly affect the metabolic system of forest lakes inducing a heterotrophic character (Jankowski et al., 2021; Martinsen et al., 2020; Staehr and Sand-Jensen, 2007; Staehr et al., 2010).

The metabolic rate is a good indicator to describe the state and the evolution of an aquatic ecosystem (Kim and Kim, 2021). Yet, it does not account for the ecosystem complexity through a holistic perspective (Likens, 2010). Ecosystems are open and hierarchically self-organized systems, characterized by complex networks and emergent properties (Jørgensen, 2016; Odum, 1969, 1988). Predicting the behavior of ecological systems involve several challenges due to their complexity. Systems ecology and ecological modeling have attempted to identify those principles able to provide information on the development of ecosystems, accounting for their complexity (Odum, 1994). In this context, Goal Functions (GFs) can be used to characterize the state and the functional and structural features of ecosystems. GFs can be conceptualized as propensities towards which the ecosystems evolution is oriented, providing information related to ecosystems and their configurations and functions over time (Buonocore et al., 2019; Nielsen and Jorgensen, 2013). GFs may be grouped in three main categories: biotic, network, and thermodynamic (Nielsen and Jorgensen, 2013). Among the thermodynamic GFs, Emergy (Odum, 1996) and Eco-exergy (Jørgensen and Mejer, 1977, 1979) have been widely used to unfold the role of matter and energy flows in the functioning of ecological systems (Bastianoni and Marchettini, 1997; Buonocore et al., 2020, 2021). Emergy measures the work of nature to generate natural capital stocks embedded into ecosystems (Brown and Ulgiati, 2004; Picone et al., 2017), while Eco-exergy accounts for the development and the organizational level of an ecosystem (Jørgensen, 2006, 2010; Silow and Mokry, 2010; Vihervaara et al., 2019).

Zhong et al. (2018) used the emergy accounting method to evaluate the performance and carrying capacity of the Erhai lake and hydrographic basin (China). Others studies used the emergy method to assess the sustainability of human activities associated to lacustrine environments as well as the provision of ecosystem services (Li et al., 2018; Pan and Yi-qing, 2011; Zhong et al., 2019). In addition, Zhang et al. (2016) used the eco-exergy method to assess the ecosystem condition of Poyang Lake (China), combining eco-exergy with others ecological indicators such as structural eco-exergy, ecological buffer capacities, biodiversity, trophic level. Xu et al. (2012) used eco-exergy for assessing the ecosystem status and health of the Baiyangdian Lake (China), also assessing structural eco-exergy, ratio of zooplankton biomass to phytoplankton biomass, and phytoplankton biomass. Ludovisi and Poletti (2003) used exergy to assess the development state of three different lakes, comparing the results with the trophic state index.

In addition, several studies suggested the combined use of emergy and eco-exergy and related indices to investigate aquatic ecosystems. In particular, Marchi et al. (2012) assessed the health status of two lake ecosystems in Spain by the joint application of eco-exergy and emergy methods. In Bastianoni and Marchettini (1997), the jointly use of emergy and eco-exergy and related indices were used to assess the organization level of the Caprolace lagoon (Italy). Bastianoni (2002) used emergy, eco-exergy, and the eco-exergy to emergy ratio to assess the ecosystem efficiency of the Figheri basin located in the Lagoon of Venice (Italy), also comparing it with Trasimeno Lake and the Caprolace Lagoon. More recently, the combined use of emergy and eco-exergy was also proposed by Buonocore et al. (2019) to account for the natural capital value of a marine protected area located in Southern Italy.

1.2. Goal and novelty of the study

In this study, emergy and eco-exergy were jointly used to assess natural capital value and the ecological complexity of three different forest lakes located in the Tuchola Forest UNESCO-MAB Biosphere Reserve (Northern Poland). The eco-exergy / emergy ratio was calculated to define the efficiency of the investigated ecosystems, describing the role of matter and energy flows in maintaining the structure of lake ecosystems overtime.

While the emergy and eco-exergy methods have been previously applied to investigate natural ecosystems, there are no articles specifically assessing the value of biotic natural capital stocks in freshwater lake ecosystems by jointly using the emergy and eco-exergy methods. Therefore, this case study can represent a benchmark for future comparison of interest for an international audience.

2. Material and methods

2.1. Description of the study area

Three different lakes, namely Czarne (53°54.8′ N - 17°31.0′ E), Zmarle (53°55.4′ N - 17°31.7′ E) and Laska (53°55.9′ N - 17°00.6′ E) located in the Brusy municipality in the Chojnice poviat (Northest Poland) (Fig. 1), were investigated. The lakes are embedded in the Zaborski Landscape Park, a protected reserve covering a surface of 34,026 ha surrounding the Tuchola Forest National Park. The morphology and trophism of the three lakes differ considerably (Fig. 2). Czarne is a very young internal basin with a water table without drainage. The lake surface covers an area of 9 ha, mostly surrounded by pine forests. The arboreal vegetation is also characterized by the

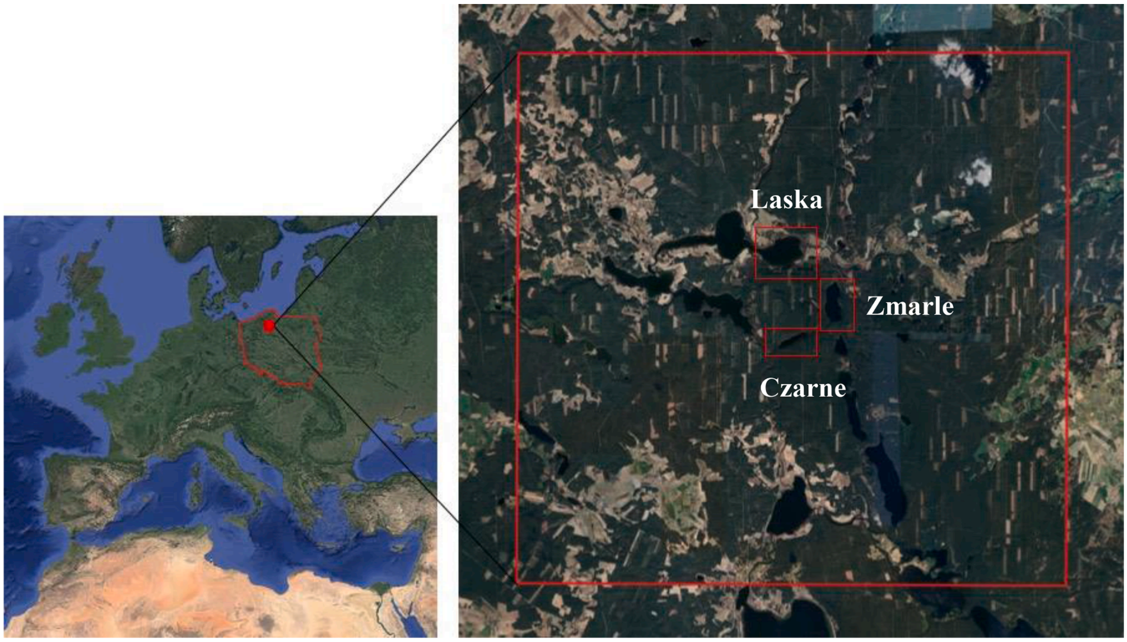

Fig. 1. Czarne, Zmarle and Laska lakes (Poland).

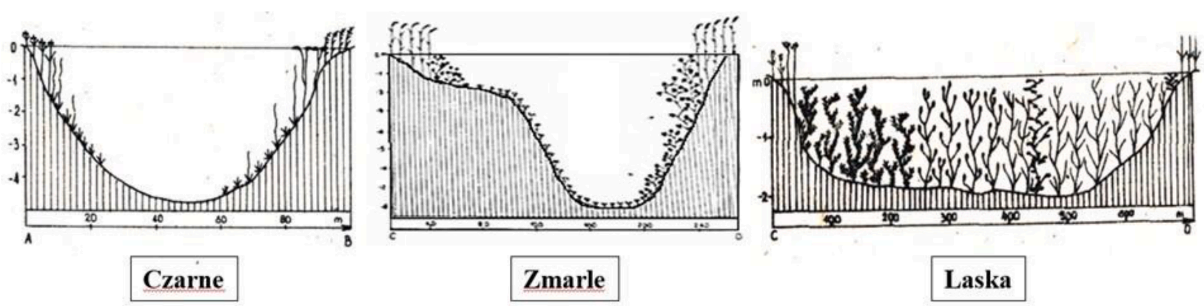

Fig. 2. Lakes investigated in this study.

presence of willows, alders, and birches. Czarne is an oligotrophic and polymictic lake characterized by *lobelia* colonies which are recorded till a depth of 5 m. The average depth is 3.85 m with a maximum depth at 7.3 m (Barańczuk and Borowiak, 2010).

Zmarle is a young lake without drainage with a surface area of 30 ha. Due to its water mixing dynamic, it is classified as a dimictic lake, while in terms of trophism it is classified as a mesotrophic lake. The water body is surrounded by a dense pine forest while its shoreline is occupied by alders and birches. The shallow water is mostly covered by reeds. The average depth is 9.3 m with the deepest point at 19.4 m (Barańczuk and Borowiak, 2010).

Laska is a mature lake belonging to the Zubrzyca River Basin and covering an area of 70 ha. In 1997, Laska was proclaimed a protected reserve being made up of a rich vegetation composed by rushes and sedges, numerous breeding sites of waterfowl and marsh birds. The water drainage is allowed by the Zbryzca river that enters in the east side and gets out in the west side. The littoral zone is densely covered by reeds with a narrow strip of alders and birches. Pine forests mostly surround the water body, even though pastures and wetland occur in the eastern side. Laska is a polymictic lake characterized by complete mixing of water several times per year. In terms of trophism, it is classified as a eutrophic lake. The nutrient input flow is also raised by a large salmon farm located close to the water body. The average depth of the lake is 1.5 m, and the deepest point is 3.6 m (Barańczuk and Borowiak, 2010). The driving forces converging to the investigated lake ecosystems are summarized in Table 1, while Table 2 shows the main features of the three lakes.

Table 1
Driving forces to lake ecosystems.

INPUT	Czarne	Zmarle	Laska
Solar radiation (J)	1.00×10^{15}	3.27×10^{15}	7.77×10^{15}
Rain (J)	7.75×10^{11}	2.52×10^{12}	6.00×10^{12}
Wind (J)	2.40×10^{12}	7.81×10^{12}	1.86×10^{13}
Geothermal flow (J)	4.30×10^{11}	1.40×10^{12}	3.33×10^{12}
N (g)	9.88×10^{5}	6.45×10^{5}	3.66×10^{8}
P (g)	1.17×10^{5}	7.61×10^{4}	3.29×10^{7}

Table 2
Main features of the three investigated lakes.

Lake	Development	Trophism	Mixing	Area (ha)	Average depth (m)
Czarne	Very young	Oligotrophic	Polymictic	9	3.9
Zmarle	Young	Mesotrophic	Dimictic	30	9.3
Laska	Mature	Eutrophic	Polymictic	70	1.5

2.2. Methods

2.2.1. The emergy accounting method

Emergy is an environmental accounting method useful to measure the cumulative environmental support for generating a good or service (Odum, 1988, 1996). Specifically, emergy is defined as "the total amount of solar available energy (exergy) directly or indirectly required to make a given product, to support a given flow or service" (Franzese et al., 2020; Odum, 1996). The emergy method takes into account for free environmental inputs (e.g., solar radiation, wind, rain, and geothermal flow), human-driven material and energy flows, and the indirect environmental support embodied in human labor and services. The systems diagram in Fig. 3 shows the main driving forces supporting the functioning of the three investigated lakes, using the energy systems language (Odum, 1996). The systems diagram highlights the main external driving forces supporting the generation of natural capital stocks. In the case of Laska lake, the input on nutrients coming from a major nearby salmon farm was also accounted for. In addition, the systems diagram shows the main components (producers, consumers, and storages) of the lake ecosystems, and the interactions among them.

According to the emergy theory, inputs are accounted for through a common unit of measure, the solar equivalent Joule (sej) (Odum, 1996). The solar emergy required to generate one unit of product or service is referred to as Unit Emergy Value (UEV, sej J^{-1}, sej g^{-1}). The UEV reflects the direct and indirect environmental support for generating one unit of product or service: the higher the UEV, the higher the environmental cost (Brown and Ulgiati, 1997). Mass, energy, labour, and money input flows converging to the investigated system are converted into emergy units by using appropriate UEVs, and then summed to compute the total emergy supporting the system.

In this study, the emergy accounting method was used for assessing the biophysical value of natural capital stocks in the three investigated forest lakes considering a formation time of 3 years. The maximum value among the turnover time of the different biomass groups (3 years) was chosen considering that all groups are co-products of the total emergy invested. Therefore, in this study, the driving forces converging for the formation of biotic natural capital stocks were multiplied by 3 years that is the average turnover time of the higher trophic level (aquatic birds), while the assessment of the abiotic natural capital stocks was out of the scope of the present investigation.

The emergy accounting was performed through the following main steps:

1 Identification of the spatial and temporal boundaries of the investigated lake ecosystems.
2 Inventory of mass and energy flows supporting natural capital stocks formation in the lake ecosystems.
3 Conversion of input flows into emergy units by using appropriate UEVs.
4 Calculation of the total emergy supporting natural capital stocks formation in the lake ecosystems.

The UEVs used in this study (Table 3) were updated to the $1.20 \bullet 10^{25}$ sej yr^{-1} biosphere emergy baseline calculated by Brown et al. (2016a, 2016b).

2.2.2. The eco-exergy accounting method

The eco-exergy accounting method aims at quantifying the available energy of all living biotic components in an ecosystem compared to the non-living state (i.e., the detritus). In particular, the eco-exergy method accounts for the chemical energy in organic matter and the genetic information embodied in living organisms, measuring the organization and development stage of an ecosystem (Jørgensen and Mejer, 1979). Broadly, eco-exergy allows to account the distance from thermodynamic

Table 3
UEVs used in this study.

INPUT	UEV (sej $unit^{-1}$)	Ref.
Solar radiation	1.00	By definition
Rain	2.31×10^4	After Odum (1996)
Wind	1.90×10^3	After Odum (1996)
Geothermal flow	1.58×10^4	After Brown and Ulgiati (2010)
Nitrogen	5.84×10^9	After Odum (1996)
Phosphorus	2.26×10^{10}	After Odum, (1996)

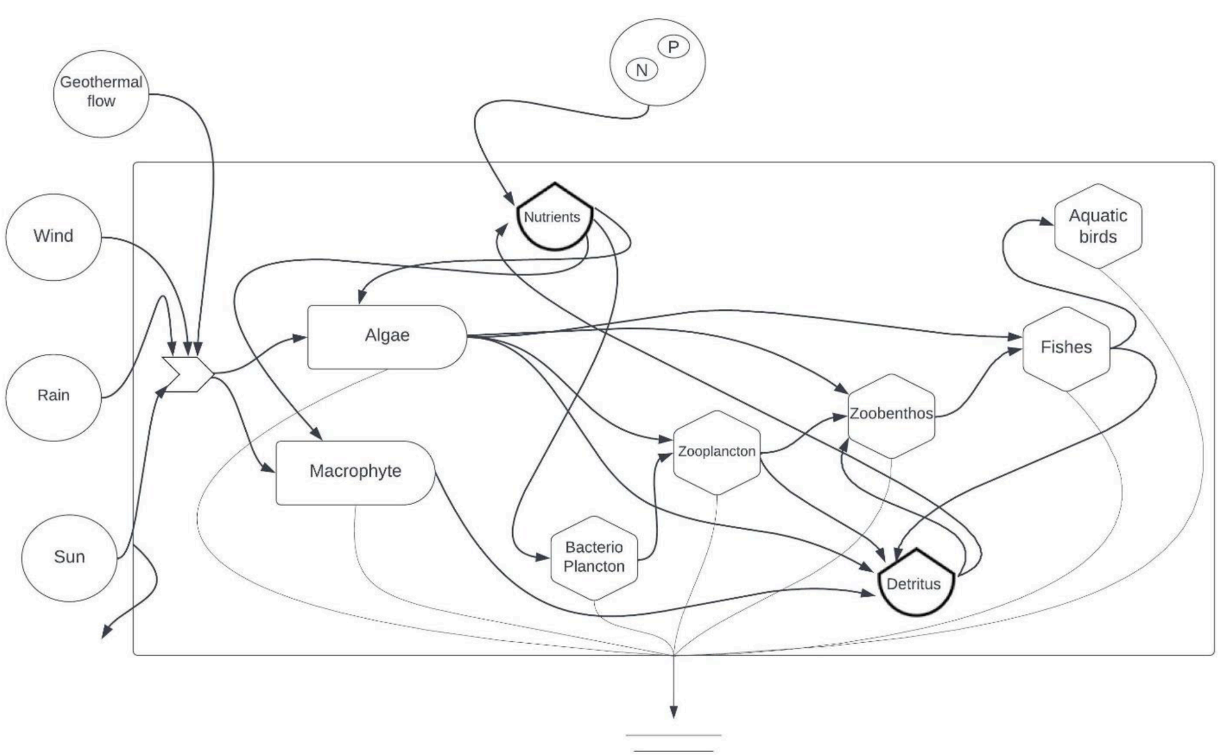

Fig. 3. Systems diagram of lake ecosystems.

equilibrium as a measure of the complexity of an ecosystem (Fath et al., 2004; Marchi et al., 2012).

The eco-exergy value for living organisms is calculated according to the following equation:

$$\textbf{Eco}-\textbf{exergy} = \beta \times \textbf{B} \times f$$

where, ß is a weighting factor expressing the information content of the organism's genes, B is the organism's biomass (in grams), and f is the value of work energy per unit of biomass. The value of f may slightly change among different taxonomic groups; the higher is the fat content, the higher is the value. The average value of 18.7 kJ/g was used in this study, according to Jørgensen (2015).

The total eco-exergy of an ecosystem is computed as the sum of the eco-exergy values calculated for all the organisms living in that ecosystem. In this study, the eco-exergy method was used to quantify natural capital value of the three investigated lakes in terms of chemical energy stored in organic matter and genetic information embodied in biomass stocks.

Ash free dry weights (AFDW) per unit area of the different taxonomic groups embedded into the three lakes were multiplied by the relative ß-values (Table 4). The resulting values were then summed to calculate the total eco-exergy value of each investigated lake ecosystem.

2.2.3. The eco-exergy / emergy ratio

The relation between eco-exergy and emergy has been much debated over time. It was stated that coupling emergy and eco-exergy accounting is complementary and non-competitive (Bastianoni et al., 2007; Sciubba and Ulgiati, 2005). The complementarity is due to the different purpose of the two accounting approaches: emergy accounts for the cumulative work of nature performed over time while eco-exergy focuses on the present state of a system, measuring the level of organization and the information content (Amaral et al., 2016).

In the present study, the eco-exergy / emergy ratio was calculated to assess the ability of lake ecosystems in generating biomass stocks per unit of invested emergy (Bastianoni, 2002; Lu et al., 2015).

3. Results

In this study, matter and energy supporting the generation of autotrophic and heterotrophic stocks in the investigated forest lakes (Czarne, Zmarle, and Laska) were assessed by using the emergy accounting method. In particular, natural flows (solar radiation, rain, wind, geothermal flows) and nutrient flows (N, P) supporting the formation of natural capital stocks were accounted for. In the case of Laska lake, the nitrogen input coming from the nearby Zubrzyca river, which influxes into the lake, was also taken into account. Table 5 shows the emergy value of natural and nutrient flows supporting the three investigated lake ecosystems, the total emergy values and the emergy per unit area (i.e., the emergy density). The total emergy is an extensive measure depending on the area of the lake, while the emergy density is an intensive indicator allowing the comparison among lakes despite their different extent. The Laska lake showed the highest emergy density ($4.36{\cdot}10^{12}$ sej m^{-2}) and total emergy value ($3.07{\cdot}10^{18}$ sej), while the Zmarle lake showed the lowest emergy density value ($2.90{\cdot}10^{11}$ sej m^{-2}).

Table 6 shows the main autotrophic and heterotrophic groups embedded into the three lake ecosystems together with the relative biomass density calculated by using local data gathered through field sampling activities and expressed as ash free dry weight (AFDW) per unit area.

Flowering plants and aquatic birds in the Laska lake were the groups with the highest biomass value: $6.59{\cdot}10^{10}$ mg m^{-2} and $2.39{\cdot}10^{10}$ mg m^{-2}, respectively.

The biomass values represented the basic information for the implementation of the eco-exergy accounting. Table 7 shows the eco-exergy value of the main taxonomic groups, the total eco-exergy and the eco-exergy density. The Laska lake showed the highest values of total eco-exergy ($9.71{\cdot}10^{11}$ kJ) and eco-exergy density ($1.38{\cdot}10^{6}$ kJ m^{-2}). The lowest value of eco-exergy density was calculated for Zmarle lake, while the lowest total eco-exergy resulted for Czarne lake.

Finally, the eco-exergy/emergy ratio was calculated as a measure of efficiency of the three investigated lakes (Table 8). The highest value of

Table 4
ß-values used in this study (from et al.,Jørgensen et al., 2005).

Groups	ß-values
Planctonic bacteria	8.5
Algae	20
Macrophytes	
Algae	20
Ferns	158
Mosses	174
Flowering plants	393
Zooplancton	
Rotatoria	163
Cladocera	232
Copepoda	232
Zoobenthos	183
Fishes	499
Acquatic birds	980

Table 5
Emergy values of natural capital stocks of the three lake ecosystems.

INPUT	Emergy (sej) Czarne	Zmarle	Laska
Solar radiation	1.00×10^{15}	3.27×10^{15}	7.77×10^{15}
Rain	1.79×10^{16}	5.83×10^{16}	1.39×10^{17}
Wind	4.57×10^{15}	1.49×10^{16}	3.54×10^{16}
Geothermal flow	6.80×10^{15}	2.21×10^{16}	5.26×10^{16}
N	5.77×10^{15}	3.77×10^{15}	2.14×10^{18}
P	2.63×10^{15}	1.72×10^{15}	7.44×10^{17}
Total emergy (sej)	$\mathbf{3.31 \times 10^{16}}$	$\mathbf{8.59 \times 10^{16}}$	$\mathbf{3.07 \times 10^{18}}$
Emergy density (sej m^{-2})	$\mathbf{3.64 \times 10^{11}}$	$\mathbf{2.90 \times 10^{11}}$	$\mathbf{4.36 \times 10^{12}}$

Footnotes: calculation procedures.
Solar radiation = annual solar irradiance x (1 - albedo) x lake surface x natural capital formation time.
Rain = annual rainfall x water density x Gibbs number x lake surface x natural capital formation time.
Wind = annual wind energy per unit of surface x lake surface x natural capital formation time.
Geothermal flow = heat flow x lake surface x natural capital formation time.
N (nitrogen) = annual water flow per unit of surface x catching area x N content in water x natural capital formation time.
P (phosphorus) = annual water flow per unit of surface x catching area x P content in water x natural capital formation time.

Table 6
Biomass density of the main taxonomic groups embedded in the three lake ecosystems.

Biomass (mg AFDW m^{-2}) Groups	Czarne	Zmarle	Laska
Planktonic bacteria	1.33×10^{9}	1.44×10^{10}	4.68×10^{9}
Algae	5.03×10^{8}	1.81×10^{9}	3.08×10^{9}
Macrophytes			
Algae	0.00	2.73×10^{9}	8.85×10^{10}
Ferns	1.15×10^{9}	2.71×10^{8}	0.00
Mosses	7.79×10^{7}	0.00	0.00
Flowering plants	4.74×10^{9}	1.10×10^{10}	6.59×10^{10}
Zooplankton			
Rotatoria	6.16×10^{6}	7.07×10^{8}	1.55×10^{8}
Cladocera	1.21×10^{9}	5.17×10^{9}	5.99×10^{8}
Copepoda	7.23×10^{6}	2.69×10^{8}	2.59×10^{8}
Zoobenthos	4.28×10^{7}	3.35×10^{7}	9.06×10^{8}
Fishes	3.83×10^{7}	2.66×10^{8}	7.37×10^{8}
Aquatic birds	3.55×10^{7}	4.43×10^{8}	2.39×10^{10}

Table 7
Eco-exergy value of natural capital stocks of the three lake ecosystems.

Groups	Eco-exergy (kJ m^{-2}) Czarne	Zmarle	Laska
Planktonic bacteria	2.11×10^8	2.29×10^9	7.44×10^8
Algae	1.88×10^8	6.79×10^8	1.15×10^9
Macrophytes			
Algae	0.00	1.02×10^9	3.31×10^{10}
Ferns	3.39×10^9	8.00×10^8	0.00
Mosses	2.54×10^8	0.00	0.00
Flowering plants	3.48×10^{10}	8.12×10^{10}	4.84×10^{11}
Zooplankton			
Rotatoria	1.88×10^7	2.15×10^9	4.73×10^8
Cladocera	5.23×10^9	2.24×10^{10}	2.60×10^9
Copepoda	3.14×10^7	1.17×10^9	1.12×10^9
Zoobenthos	1.46×10^8	1.15×10^8	3.10×10^9
Fishes	3.57×10^8	2.48×10^9	6.88×10^9
Aquatic birds	6.50×100^8	8.12×10^9	4.37×10^{11}
Total eco-exergy (kJ)	$\mathbf{4.53 \times 10^{10}}$	$\mathbf{1.22 \times 10^{11}}$	$\mathbf{9.71 \times 10^{11}}$
Eco-exergy density (kJ m^{-2})	$\mathbf{4.98 \times 10^5}$	$\mathbf{4.14 \times 10^5}$	$\mathbf{1.38 \times 10^6}$

Table 8
Values of eco-exergy and emergy density, and eco-exergy/emergy rati.

Lake	Eco-exergy density (J m^{-2})	Emergy density (sej m^{-2})	Eco-exergy/Emergy ratio (10^{-3} J sej^{-1})
Czarne	4.98×10^8	3.64×10^{11}	1.37
Zmarle	4.14×10^8	2.90×10^{11}	1.43
Laska	1.38×10^9	4.36×10^{12}	0.32

the eco-exergy/emergy ratio resulted for the Zmarle lake ($1.43 \cdot 10^{-3}$ J/sej) and Czarne ($1.37 \cdot 10^{-3}$ J/sej), while the lowest value was obtained for the Laska lake ($0.32 \cdot 10^{-3}$ J/sej).

4. Discussion

In this study, the emergy and eco-exergy accounting methods were jointly used to assess the value of natural capital stocks of the investigated lake ecosystems adopting two different perspectives: the cumulative work of nature invested for natural capital formation and the organization and development state of the three lake ecosystems.

The total emergy and the emergy density values resulted higher for the Laska lake compared to the other investigated lakes (Table 5). Fig. 4 shows the contribution of the emergy inputs driving the development of the lake ecosystems. The highest emergy investment for the generation of natural capital stocks resulted in the case of the eutrophic Laska lake, mainly due to the high convergence of nitrogen and phosphorus flows contributing for 70% and 24% to the total emergy value. The high share of the nitrogen influx in the Laska lake is mainly due to the large amount of wastewater deriving from a nearby large salmon farm. Instead, the highest emergy input contributing to natural capital formation in the Czarne and Zmarle lakes was the chemical potential energy in the rain flow.

The eco-exergy method allowed for the assessment of the development state, the information content, and the complexity of the three investigated lakes. The highest value of total eco-exergy and eco-exergy density resulted for the Laska lake (Table 7). These outcomes are mainly due to the high biomass value of macrophytes and aquatic birds characterizing the Laska lake, and their related high ß value, reflecting the evolutionary history of organisms that acquired key adaptations for successful colonization. Macrophytes also showed the highest eco-exergy value in both the Czarne and Zmarle lakes, followed by the zooplankton. Fig. 5 shows the contribution of the different taxonomic groups to the eco-exergy value of natural capital.

Overall, the obtained results are consistent with the different trophism (oligotrophic, mesotrophic, eutrophic) of the investigated lakes, highlighting how external driving forces are capable to orient the development and complexity of lake ecosystems.

Furthermore, the eco-exergy/emergy ratio was used to assess the lakes' efficiency in transforming natural inputs flows into ecosystem components. The eco-exergy/emergy ratio was higher for the Zmarle lake compared to Czarne and Laska lakes (Fig. 6). The ratio resulted similar for Czarne and Zmarle lakes that are only supported by natural input flows compared to the Laska lake which receives human-driven input flows due to nearby aquaculture activities. Therefore, despite the highest eco-exergy value of natural capital calculated for the Laska lake, the results highlighted the better efficiency of the Zmarle lake in maintaining and developing ecosystem structures and organization. In fact, the large amount of nutrients coming from the nearby salmon farm outweighed the carrying capacity of the Laska lake, resulting in a lower efficiency of the ecosystem. Indeed, the excess of biomass generated in

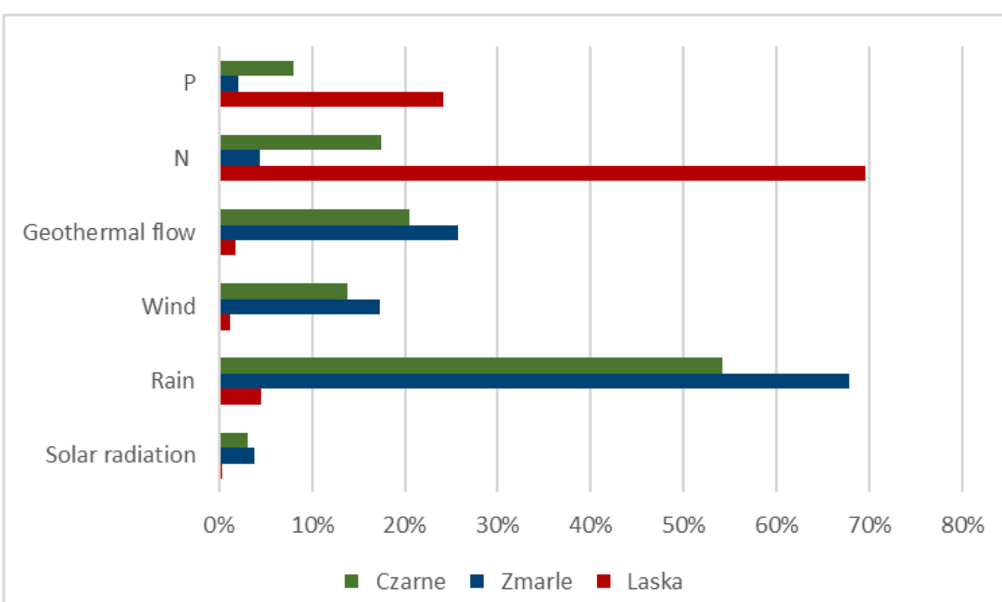

Fig. 4. Contribution of input flows to the emergy value natural capital.

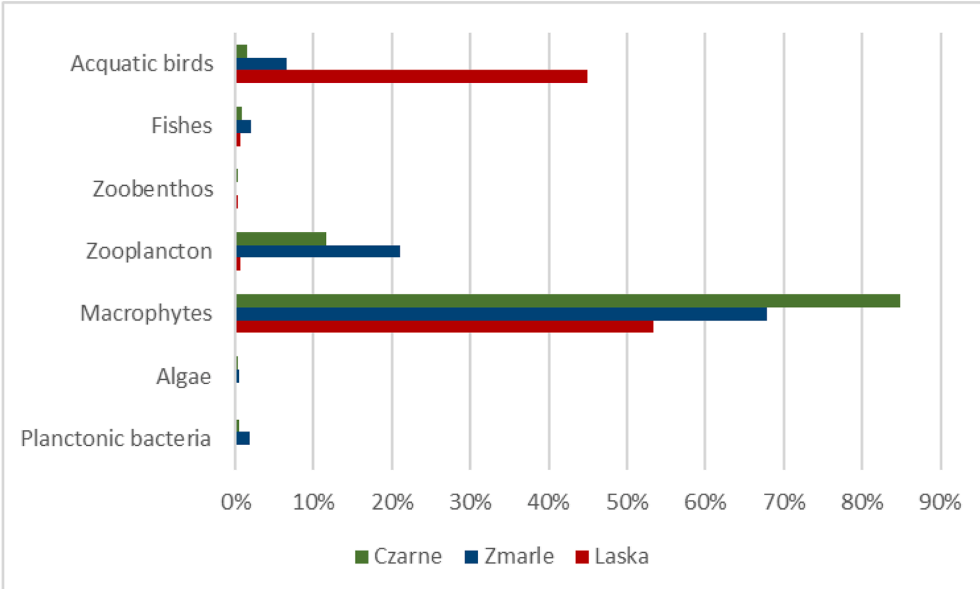

Fig. 5. Contribution of taxonomic groups to the eco-exergy value of natural capital.

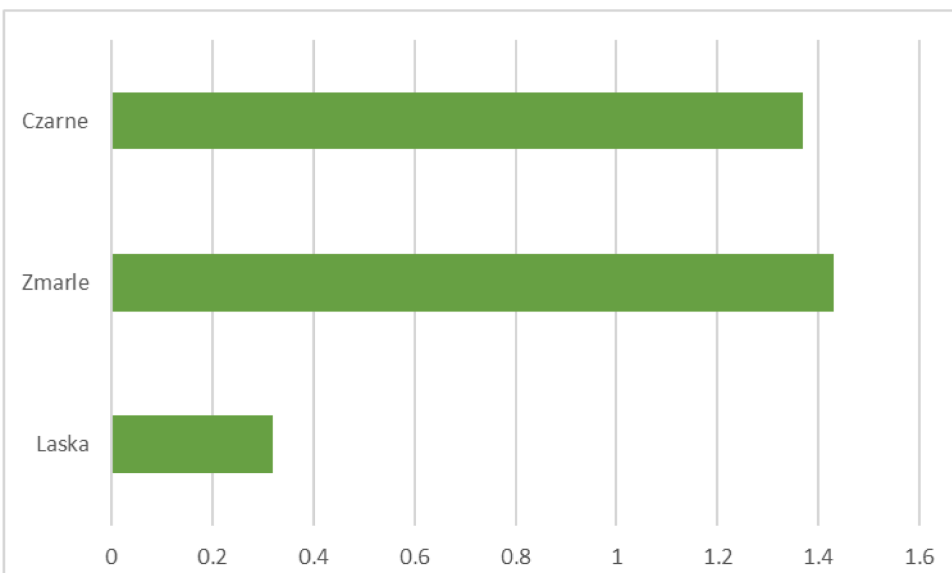

Fig. 6. Eco-exergy/Emergy ratio (KJ/sej) calculated for the three lakes.

the Laska lake does not flow into the food chain enhancing natural capital stocks. These outcomes are also in line with the eco-exergy/emergy ratio calculated by Bastianoni (2002) highlighting that natural lakes are characterized by higher eco-exergy/emergy ratio compared to lakes affected by human activities.

Finally, to compare the results of the study with a conventional ecological indicator, a biomass-based Shannon diversity index was calculated. Fig. 6 shows that the values of the eco-exergy/emergy ratio are in line with the calculated biomass-based Shannon diversity index (Fig. 7). The highest diversity resulted in the case of the Zmarle lake, showing a positive correlation between the lake ecosystems efficiency and their capability of building biodiversity.

Therefore, the results of this study highlight that undisturbed lake ecosystems show a higher efficiency in transforming natural inputs into biomass stocks and biodiversity that decreases when anthropogenic stress factors increase. The eco-exergy and emergy indicators integrated with the biomass-based Shannon diversity index can be useful to inform local managers and policy makers on the importance of monitoring and managing human activities and related environmental impacts in order to preserve natural capital stocks in lake ecosystems.

5. Concluding remarks

In this study, the integration of the emergy and eco-exergy accounting methods resulted a promising approach to explore lake ecosystems adopting a holistic and ecosystem perspective. The complementarity of the methodologies allowed a comprehensive assessment of natural capital value of three lake ecosystems with a different trophism, capturing both the work of nature for generating biomass stocks as well as their structure, functioning, and complexity.

The emergy and eco-exergy density values resulted higher for the eutrophic lake receiving human-driven input flows due to nearby aquaculture activities. Nonetheless, the eco-exergy/emergy ratio, calculated to assess the efficiency of the lake ecosystems in transforming

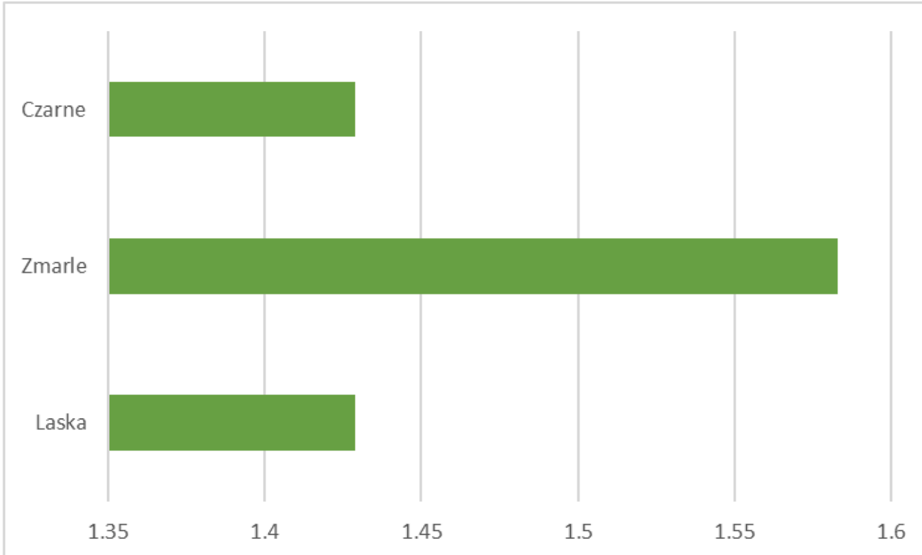

Fig. 7. Biomass-based Shannon diversity index of the three lake ecosystems.

natural and human inputs into biomass stocks, showed that the undisturbed lakes are characterized by higher values. In addition, the biomass-based Shannon diversity index calculated for the three investigated lakes highlighted the linkage between ecosystems efficiency and biodiversity.

A future development of this study could focus on the assessment of ecosystem services flows generated by the investigated lake ecosystems to further evaluate how their health state affects the capability of providing benefits for human well-being.

In conclusion, integrated assessments adopting an ecosystem and holistic perspective can result in a promising approach to investigate lake ecosystems worldwide, providing useful scientific information to policy makers committed to ensure the sustainable management of surface water ecosystems.

CRediT authorship contribution statement

U. Grande: Investigation, Data curation, Software, Writing – original draft. **A. Piernik:** Conceptualization, Methodology, Writing – review & editing, Supervision. **A. Nienartowicz:** Conceptualization, Methodology, Supervision. **E. Buonocore:** Conceptualization, Methodology, Writing – review & editing, Supervision. **P.P. Franzese:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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3.2 Manuscript 2

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APPLYING GOAL FUNCTIONS FOR NATURAL CAPITAL STOCK CHANGE ASSESSMENTS IN MARINE ECOSYSTEMS

U. Grande [1,2,5], E. Buonocore [2], F. Fiorentino [1,3], P.P. Franzese [2], V. Lauria [1], A. Piernik[5], E. Sabatella [4], D. Scannella [1,6], S. Vitale [1], G. Garofalo [1]

[1] Istituto per le Risorse Biologiche e le Biotecnologie Marine, SS di Mazara del Vallo, Consiglio Nazionale delle Ricerche, Via Luigi Vaccara 61, 91026 Mazara del Vallo (TP).

[2] International PhD Programme / UNESCO Chair "Environment, Resources and Sustainable Development", Department of Science and Technology, Parthenope University of Naples, Centro Direzionale Isola C4 (80143), Naples, Italy.

[3] Stazione Zoologica Anton Dohrn, Department of Integrative Marine Ecology, Lungomare Cristoforo Colombo 4521, Palermo, Italy.

[4] Istituto di Ricerche sulla Popolazione e le Politiche Sociali, SS di Fisciano, Consiglio Nazionale delle Ricerche, Corso San Vincenzo Ferreri 12, 84084 Fisciano (SA).

[5] Department of Geobotany and Landscape Planning, Nicolaus Copernicus University, ul. Lwowska 1, 87-100, Toruń, Poland.

[6] Institute for Environmental Protection and Research (ISPRA), Lungomare Cristoforo Colombo n. 4521 (ex complesso Roosevelt) Località Addaura, 90149, Palermo, Italy.

Keywords: marine ecology, biodiversity, environmental accounting, Shannon index, Eco-exergy.

ABSTRACT

Marine ecosystems are invaluable reservoirs of biodiversity and natural resources, providing several essential ecosystem services. Preserving and monitoring marine Natural Capital (NC) is crucial to ensure the sustainable management of marine ecosystems. However, NC evaluation in marine ecosystems remains challenging due to their dynamics and complexity. Systems ecology and ecological modelling provide Goal Functions (GFs) to characterize ecosystems' health and functional and structural features. This study aimed to assess changes in NC of demersal fishery resources. The Strait of Sicily (SoS), in the central Mediterranean Sea, was chosen because of its ecological significance and socio-economic importance. We tested the hypothesis that environmental parameters and anthropogenic pressures affect marine Natural Capital stocks, and thermodynamic goal functions can detect their changes. We applied the eco-exergy and Shannon diversity index to assess NC and ecosystem complexity from 2005 to 2021. Moreover, we analysed selected environmental parameters to detect the main drivers of NC change. We based our research on biomass data from the Mediterranean International Trawl Survey and environmental parameters from the Copernicus Marine Environment Monitoring Service. We noted a decrease in eco-exergy over time mainly correlated to the decrease in

marine water pH and an increase in surface water temperature. Eco-exergy has proved to be a more sensitive indicator for detecting changes in ecosystem functioning and complexity than Shannon diversity, which was not significantly related to time and environmental factors. However, two important areas were identified for conservation by combining eco-exergy and the Shannon index. Our results provide helpful scientific information to policymakers in support of strategic conservation efforts.
Keywords: eco-exergy, Shannon index, ecosystem ecology, biodiversity, environmental accounting.

1. INTRODUCTION

Marine ecosystems are invaluable reservoirs of biodiversity and natural resources, providing several essential ecosystem services (UNEP, 2006; Irfan et al., 2019). According to Costanza et al. (1997), the marine environment represents over 60% of the global economic value generated by the biosphere, providing a wide range of benefits, such as seafood supply, climate regulation, coastline protection, water quality preservation, and cultural and spiritual benefits. However, several studies emphasized the global threat that marine ecosystems are facing due to human impacts (Halpern et al., 2008; Christie et al., 2015; Coll et al., 2016). Anthropogenic pressures on marine ecosystems cause biodiversity loss, undermining their ability to benefit humans (Halpern et al., 2008; Haines-Young and & Potschin, 2010). Among the greatest threats to marine ecosystems is the overexploitation of marine resources, which refers to the unsustainable extraction beyond their capacity for renewal. In fact, in the last decades, the continuing and increasing demand for seafood, minerals, and other commodities has led to the depletion of key species and habitats, altering the functioning of marine ecosystems (Arthington et al., 2016).

In the Mediterranean Sea, considered an important hotspot of biodiversity and an area of high socio-economic value (Hilmi et al., 2021; Piroddi et al., 2017), ever-increased evidence highlights the negative environmental impacts caused by human pressures (Tanhua et al., 2013; Colloca et al., 2017). Urbanization, marine traffic, overfishing and pollution are among examples of human impacts that are leading the Mediterranean Sea to become one of the most degraded marine ecosystems worldwide (Claudet & Fraschetti, 2010). Regarding fisheries, about 74 % of the commercial species in the Mediterranean Sea are overexploited (FAO, 2022), undermining the socio-economic welfare at local and global scales. Current fisheries management in the Mediterranean Sea operates at the level of Geographical Sub-areas (GSAs) (GFCM, 2007), focusing mainly on regulating fishing capacity, effort and selectivity across different areas and times (Fiorentino and & Vitale, 2021). Nevertheless, considering the perceived inefficiency of the current management system (Cardinale et al., 2017), mainly due to ineffectiveness in controlling fishing mortality, the continuous non-adherence to the scientific advice, and inadequacies of existing national management plans, urgent strategies are required to preserve Natural Capital (NC) stocks of the Mediterranean Sea.

NC refers to the stocks of natural resources embedded in natural ecosystems generating, through ecological processes and functions, flows of goods and services (Costanza et al., 1997; Daily, 1997; MA, 2005; Folke et al., 2011; Costanza et al., 2014; Jones et al., 2016). Healthy, resilient, and diverse ecosystems can generate NC stocks, guaranteeing benefits for current and future generations (Smith et al., 2017). In the last years, scientific research on NC has grown considerably (Buonocore et al., 2018), driven by major international initiatives such as the Millennium Ecosystem Assessment (MA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB, 2010). The need to preserve biodiversity as an essential component of NC has become increasingly recognized by European Union environmental policies and biodiversity conservation strategies, which explicitly refer to NC accounting (Blasi et al., 2017; Cordella et al., 2022).

In marine environments, preserving and monitoring NC is crucial to ensure the sustainable management of marine ecosystems (Buonocore et al., 2021; UN, 2021). However, NC evaluation in marine ecosystems remains challenging due to their dynamics and complexity, posing ever-increasing challenges in the assessment (Townsend et al., 2018; Manea et al., 2019).

In this context, systems ecology and ecological modelling have attempted to identify those principles able to provide information on the development and complexity of natural ecosystems through a holistic approach (Odum, 1994). In particular, Goal Functions (GFs) can be used to characterize the health, and functional and structural features of ecosystems. GFs can be conceptualized as propensities towards which the ecosystem evolution is oriented, providing information related to about ecosystems and their configurations and functions over time (Nielsen & Jorgensen, 2013; Buonocore et al., 2019). GFs may be grouped into three main categories: biotic, network, and thermodynamic (Nielsen and & Jorgensen, 2013). Among the thermodynamic GFs, eco-exergy (Jørgensen and Mejer, 1977, 1979) has been widely used to unfold the role of matter and energy flows in the functioning of ecological systems, providing a measure of NC stocks and complexity. Several applications of the eco-exergy accounting method have been implemented for marine ecosystems. Vassallo et al. (2012) aimed to investigate the state of benthic ecosystems across the Ligurian coast (Northern Italy) by applying eco-exergy and network analyses. Tang et al. (2015) proposed using a set of ecological indicators, including the eco-exergy indicator, to determine the ecosystem health in the Yangtze River in the Jiangsu coastal area (China). Buonocore et al. (2019, 2020) combined the eco-exergy and emergy methodologies to account for NC value in Italian marine protected areas. Libralato et al. (2006) applied the eco-exergy method to the complex dynamics occurring in a disturbed benthic community during recovery processes in the coastal area of the North Adriatic Sea. Kernegger et al. (2008) applied eco-exergy to assess fisheries landing and aquaculture trends based on FAO data to monitor marine NC stocks from 1950 to 2003 in the main central fishing and aquaculture FAO areas. Lastly, Yuan et al. (2022) assessed the effect of artificial reef construction on the nekton community in Dalajia (China) by applying the eco-exergy accounting method.

Considering the urgent need to find promising strategies to monitor marine biodiversity and manage the overexploitation of the Mediterranean under climate change, this study aimed at assessing changes in NC stocks of demersal fishery resources by implementing an integrated multi-methodological approach. The Strait of Sicily (SoS), in the central Mediterranean Sea, was chosen as a case study given its ecological significance as a biodiversity hotspot and its socio-economic importance (Di Lorenzo et al., 2018). This area is also increasingly threatened by the overexploitation of demersal fish populations, primarily driven by intensive fishing to harvest valuable shrimp species (Fiorentino et al., 2024). In particular, we aimed to explore the current state of NC stock of demersal resources in the SoS and its changes in the last fifteen years, adopting a holistic and ecological perspective. Recognizing the inherent complexity of marine systems, we applied the thermodynamic eco-exergy GF coupled with the Shannon diversity index to quantify NC and biodiversity in the investigated area. Moreover, spatial and hotspot analysis of eco-exergy and diversity indices were performed to identify key areas crucial for conservation strategies and marine spatial planning.

We tested the hypothesis that environmental parameters and anthropogenic pressures affect marine Natural Capital stocks, and thermodynamical goal functions can detect their changes.

Specifically, we expect a decline of demersal stock over time, according to environmental drivers and overexploitation.

This is the first study that aims to implement a multi-methodological framework integrating the use of thermodynamic GF, diversity index, and spatial and hotspot analysis to assess the spatiotemporal trend of NC stock in the SoS.

2. MATERIAL AND METHODS

2.1 STUDY AREA

The SoS is the central transition zone between the eastern and western basins of the Mediterranean Sea, encompassing the marine areas between Italy, Malta, Tunisia, and the western coast of Libya (Figure 1). Its complex oceanographic dynamics involve the interplay of colder Atlantic waters from the west and warmer Levantine Intermediate Waters from the east, fostering high productivity (Jarboui et al., 2022).

Geomorphologically, the SoS has a diverse topography, including sea mountains and volcanic islands, contributing to significant upwelling phenomena and enhancing overall biodiversity (Vega Fernandez et al., 2012; Civile et al., 2016). Noteworthy features include deep coral assemblages, pockmark fields and fossil cold seep communities, habitats for rare or endemic species, and essential spawning and nursery grounds for species of both commercial and conservation interest. (Di Lorenzo et al., 2018).

Recognized as a Mediterranean biodiversity hotspot, the SoS has been earmarked for conservation efforts, with several sites proposed for inclusion in marine protected areas. In addition, it was designated as an Ecologically or Biologically Significant Area (EBSA) in 2014 (Bax et al., 2016), and, more recently, recognized as an Important Shark and Ray Area (ISRA) in 2023 (Jabado et al., 2023). Beyond its ecological significance, the SoS also has an important socio-economic value. Fisheries are the main activities taking place in the region, but the SoS also provides several goods and services such as recreational activities, tourism and oil extraction. It is also a major shipping route for cargo vessels, oil tankers, and container ships (Patruno et al., 2008; FAO, 2016). The Food and Agriculture Organization (FAO) recognized the SoS as one of the most productive areas for demersal fisheries in the Mediterranean Sea (Jarboui et al., 2022). However, the region faces multiple anthropogenic pressures, particularly from maritime traffic, oil drilling, mining activities, and overfishing.

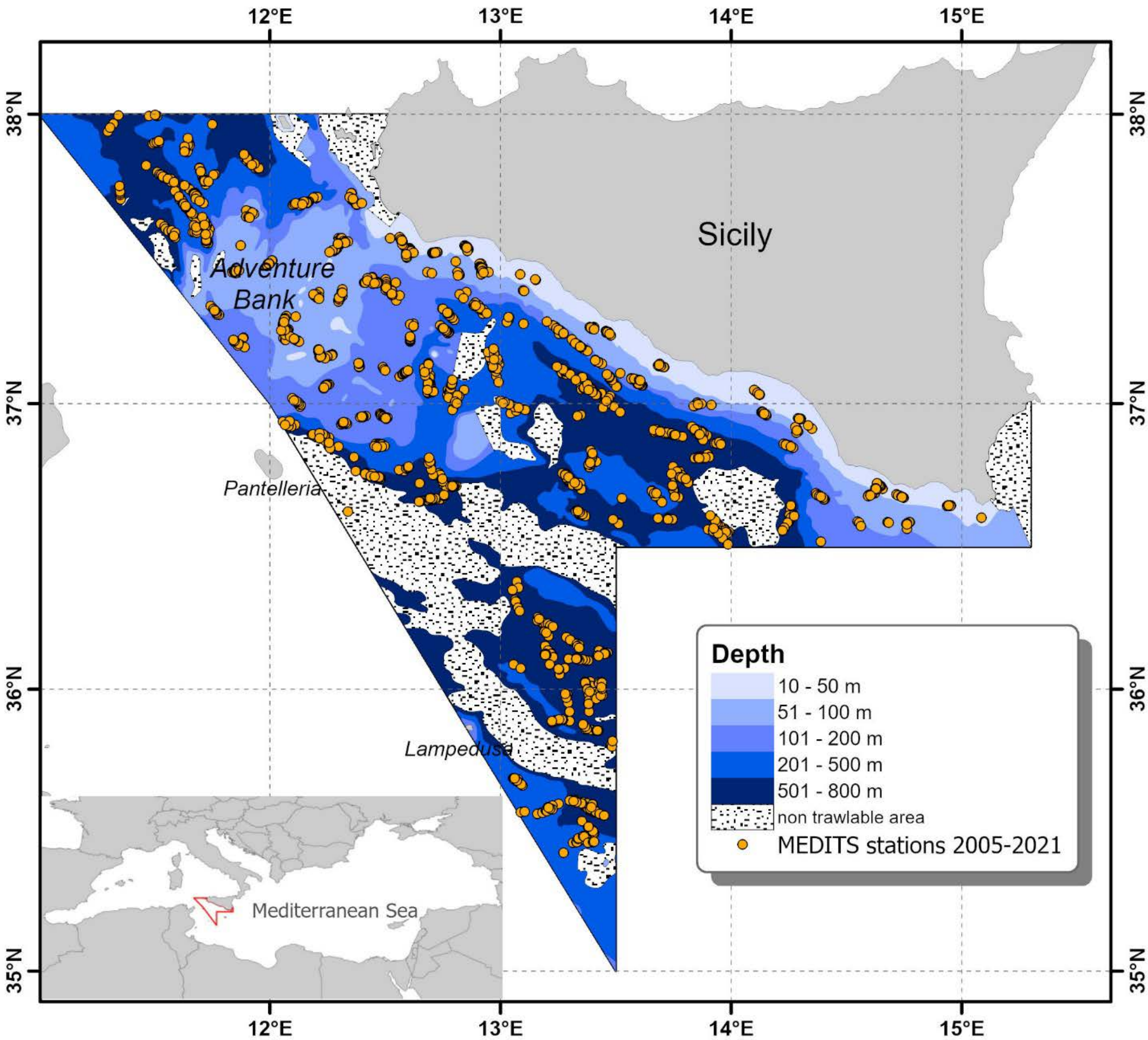


Figure 1 – Location of the study area within the Mediterranean Sea. The area corresponds to the Geographical Sub Area (GSA) 16. Orange dots represent the stations sampled during the Mediterranean International Trawl Survey (MEDITS) from 2005 to 2021.

2.2 THE SOURCES OF DATA

In this study, the Mediterranean International Trawl Survey (MEDITS) dataset referred to Geographical Sub-area 16 (GSA16), extending in the northern sector of the SoS, was used to assess the demersal NC stock in the timeframe from 2005 to 2021. The MEDITS is a standardized trawl survey program, started in 1994, which aims to collect data on the distribution and abundance of demersal fish and shellfish in the EU Mediterranean Sea (Bertrand et al., 2002). According to the MEDITS protocol, the survey is conducted annually during the spring season. It utilizes a stratified random sampling approach based on five depth strata: 10–50 m, 51–100 m, 101–200 m, 201–500 m, and 501–800 m. The number of sampling stations in each stratum is proportional to the surface area of the respective depth stratum. In this study, the historical series starting from 2005 was used because from that year onwards the number of planned stations remained constant at 120 throughout GSA 16. However, due to exceptional circumstances, less than 90% of the stations were sampled in 2014 and 2020. Consequently, data from those years were excluded from the analysis. At each trawl station, all species were sorted, weighed and counted. The relative abundance of each species was expressed in terms of number of individuals per km^2 (N/km^2) and biomass per km^2 (kg/km^2). Finally, the generalised groups of demersal and necto-benthonic species belonging to the cartilaginous fish (Chondrichthyes), bony fish (Osteichthyes), crustaceans (Decapoda and Stomatopoda) and cephalopods taxonomic categories were included in the analysis. In contrast, pelagic species and megabenthos were excluded because of the low catchability of these species by the trawl gear.

To assess long-term changes in the environmental parameters as potential environmental drivers of NC variations, we extracted monthly layers of Sea-Surface Temperature (SST, °C) and Sea-Surface Salinity (SSS, psu) from the Copernicus Marine Environment Monitoring Service (CMEMS) period from 2000 to 2021 (Nigam et al., 2021). Additionally, we obtained monthly layers of seawater pH and net primary production (PP) for each year from 2000 to 2021 (Teruzzi et al., 2021). We included a more extended timeframe than in the case of MEDITS species data. Due to the significant variability within the marine environment, accounting for an extended period allowed us to better analyze the trend of environmental changes in investigated marine areas. Fishing effort data were obtained from the EU Data Collection Framework (DCF) source (Regulation EU 2017/1004). Specifically, the annual average of nominal fishing effort (kW*fishing days) of bottom trawlers registered in GSA 16 was used.

2.3 DATA ANALYSIS

2.3.1 Natural Capital complexity assessments

We applied the thermodynamic eco-exergy GF coupled with the Shannon diversity index to quantify both NC and biodiversity in the investigated area and then to compare the changes within a given timeframe. The eco-exergy accounting method aims at quantifying the available energy of all living biotic components in an ecosystem compared to the non-living state (i.e., the detritus). In particular, the eco-exergy method accounts for the chemical energy in organic matter and the genetic information embodied in living organisms, measuring the organization and development stage of an ecosystem (Jørgensen & Mejer, 1979). Broadly, eco-exergy allows us to account for the distance from thermodynamic equilibrium as a measure of the complexity of an ecosystem, thus providing a measure of NC stocks (Marchi et al., 2012; Vihervaara et al., 2019). The larger the eco-exergy, the higher the NC embedded in the investigated ecosystem. The eco-exergy value of an ecosystem is computed by summing the eco-exergy values for all components within that ecosystem, as follows:

$$\mathrm{EEx} = \sum_i^n \mathrm{EEx}_i = \sum_i^n \beta_i * \mathrm{B}_i * \mathrm{f}_i \qquad (1)$$

where n is the number of the ecosystem components, $ß_i$ is a weighting factor that expresses the information stored in the genes of the i^{th} component, B_i is the i^{th} component's biomass, and f_i is the value of chemical work energy per unit of biomass. The unit of measurement of eco-exergy is Joules.

In this study, to standardize the eco-exergy value of natural capital per unit area, we calculated eco-exergy density by multiplying the biomass in ash-free dry weight (AFDW, kg/km^2) of each of the four different taxonomic groups by their respective ß-value and f. AFDW was obtained through appropriate conversion factors from fresh biomass (Ricciardi & Bourget, 1998; Gogina et al., 2022; FishBase, data access 2024). Factor f can slightly differ between groups. The higher the fat content, the higher the value. We used a standardized value for all groups 18.7 kJ/g (Jørgensen, 2015). The ß-value differs based on the taxa. We followed Jørgensen (2012), as is presented in Table 1. The eco-exergy (GJ/km^2) of the taxonomic groups was then summed to calculate the total eco-exergy density of the demersal component of the investigated ecosystem (equation 1).

Table 1. β values used in this study for the different taxonomic groups.

Taxonomic groups	β value	Reference
Fish	499	Jørgensen, 2012
Crustaceans	232	Jørgensen, 2012
Cephalopods	310	Jørgensen, 2012

Shannon diversity index as biotic GF (Nielsen & Jorgensen, 2013) was calculated according to the formula (Shannon and Weaver, 1963):

$$H = - \sum_{i=1}^{s} p_i \ln p_i \qquad (2)$$

Where H is the Shannon index, S is the total number of species in the sample, p_i is the proportion of individuals belonging to the i^{th} species to the total. Higher values of the Shannon index indicate greater diversity within the community, with a maximum value occurring when all species are equally represented.

We estimated annual indices of eco-exergy and Shannon diversity across the entire depth range of 10- 800 m within the GSA 16. Further, we deepened our assessment by analyzing the shelf (10-200 m) and the slope (201-800 m) regions separately to gain a more comprehensive understanding of the dynamics of the demersal community.

The eco-exergy signature, i.e. the contributions of taxonomic groups (bony fish, cartilaginous fish, crustaceans and cephalopods) to the eco-exergy value of NC, was assessed over time. To smooth out interannual variations, the computation was performed averaging over three 5-year intervals: time 1 (2005–2009), time 2 (2010–2013, 2015), and time 3 (2016-2019, 2021). Specifically, for each time interval and depth range (shelf and slope), we calculated the average eco-exergy for each of the four taxonomic groups. We expressed it as a percentage of the total eco-exergy value.

2.3.2 Time series analysis

We investigated trends in time for NC and for potential drivers of NC change. Significant trends in time in the eco-exergy and diversity indices over the total area and for both the shelf and the slop were investigated by linear models. Since the survey was conducted in the autumn in some years (deviating from the regular late spring/early summer season for MEDITS), the time series were standardized using a linear regression model with a dummy variable for the season, a factor controlling for the seasonal effect. This effectively standardized the time series to the spring season, allowing a more consistent analysis.

To describe long-term variations of environmental parameters in the study area, the yearly average values across the GSA16 were calculated, and an anomaly analysis was performed. Anomaly analysis allows the detection of variations in environmental parameters over time that could affect the ecosystem dynamics. Indeed, noteworthy is their cascade effect on the trophic chain and the consequences on ecosystem stability (Friedland et al., 2019; Lowe et al., 2019; Dahunsi et al., 2023). For each parameter, the anomaly was expressed as a difference from the overall mean over the time series 2000-2021, divided by the standard deviation.

The annual average nominal fishing effort (GT*fishing days) of bottom trawlers registered in GSA 16 was calculated across a time span extending from 2005 to 2021 as an additional factor potentially affecting NC. Significant trends over time in environmental variables and fishing effort data were identified by linear regression analysis.

The relationship between eco-exergy and the Shannon index and potential drivers of change was examined using Spearman's correlation coefficient. All the analyses were processed in the R software.

2.3.3 Spatial analysis

Eco-exergy and Shannon diversity index were analyzed to find spatial variability of ecosystem complexity within the investigated timeframe. Georeferenced data on eco-exergy and diversity indices were used to create annual distribution maps through inverse distance-weighted (IDW) deterministic interpolation (Isaaks & Srivastava, 1989). In addition, hotspot analysis, a technique that identifies statistically significant spatial clusters of high values (hot spots) and low values (cold spots), was applied using the Getis-Ord Gi* statistics (Ord & Getis, 1995) in R software. Queen's case contiguity was applied to determine grid cells considered spatial neighbours in the cluster analysis. Statistically significant clusters were identified as hotspots based on a *z-score* greater than 1 and a *p-value* of 0.05 (Ord & Getis, 1995). Finally, annual hotspots of eco-exergy and diversity were overlaid for each of the three defined 5-year time intervals (as described in section 2.3.2). This allowed us to identify areas where high values for both indices consistently co-occurred and whether these areas changed through time, highlighting key areas for conservation strategies and marine spatial planning.

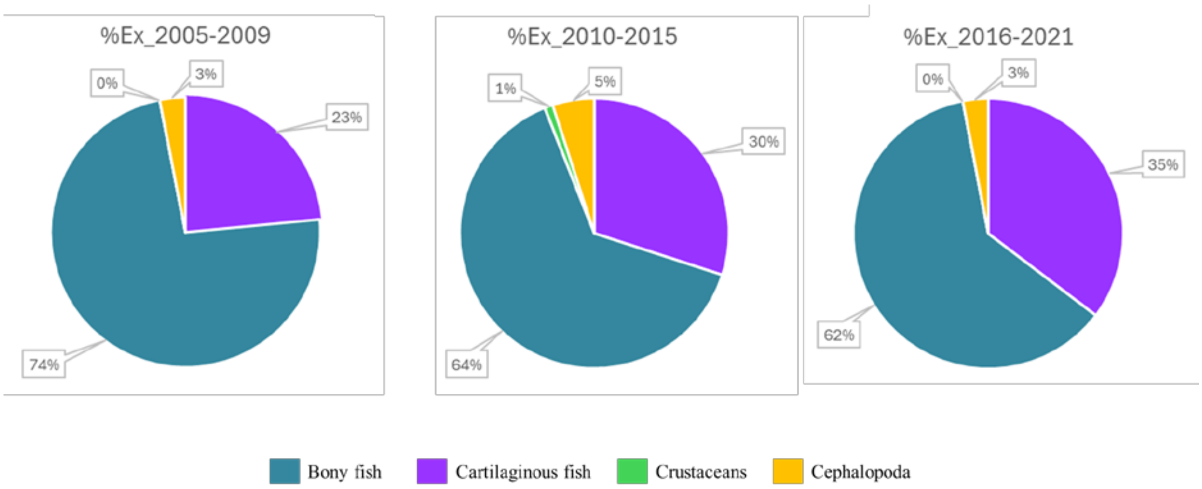
3. RESULTS

3.1 NATURAL CAPITAL AND CHANGES IN STOCKS

The relative taxonomic groups' biomass density per unit area (kg/km2) is presented in supplementary Table S1. These biomasses values represent the essential information for implementing eco-exergy accounting.

The NC presented as the eco-exergy signature, referring to the contribution of each taxonomic group to NC values, shows that bony fish represent the highest contribution to total eco-exergy, ranging between 62% and 74% (Figure 2). However, this contribution decreased over time (-11%) on the shelf (Figure 2a), along with the increase in the contribution of cartilaginous fish (+12%) that, in general, reflects an increase in the biomass of these species group. In contrast, no differences occurred on the slope (Figure 2b) with the eco-exergy signature remaining similar over time. Crustaceans and cephalopods contributed less than 5% to the total eco-exergy (Figure 2a, b).

[a]



[b]

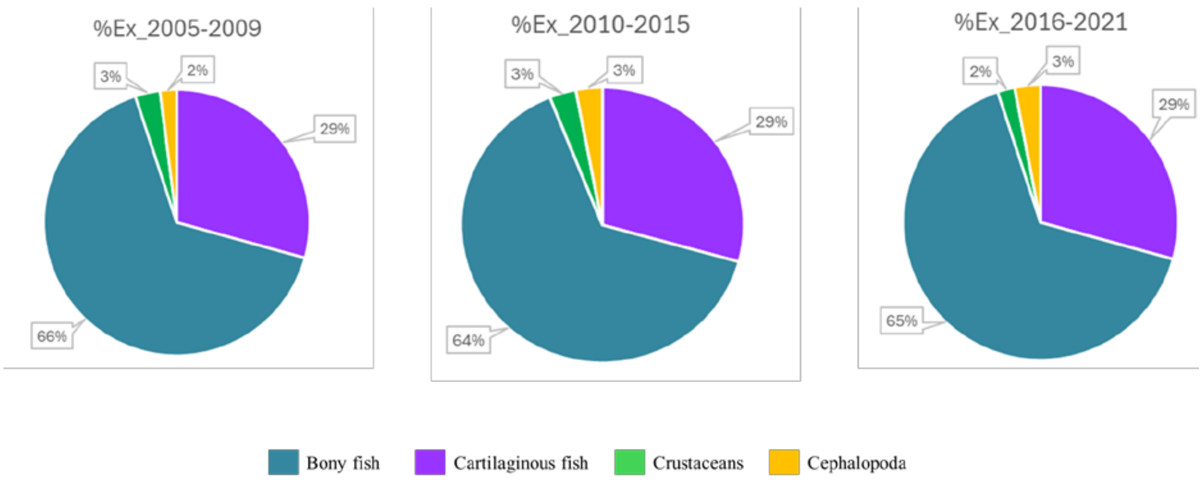


Figure 2 – Average relative contribution of taxonomic groups to the eco-exergy value of natural capital [a] on the shelf and [b] slope in each of three 5-year time intervals: years 2005–2009 (left), years 2010- 2015 (middle), years 2016-2021 (right).

Figure 3 shows the time series of the annual average value of the eco-exergy index (GJ/km^2) and the Shannon diversity index in the investigated period. A negative significant trend for eco-exergy over time was observed for the total area and the slope (Figure 3a; Table 3). Conversely, no significant trend was found for the Shannon index (Figure 3b; Table 3).

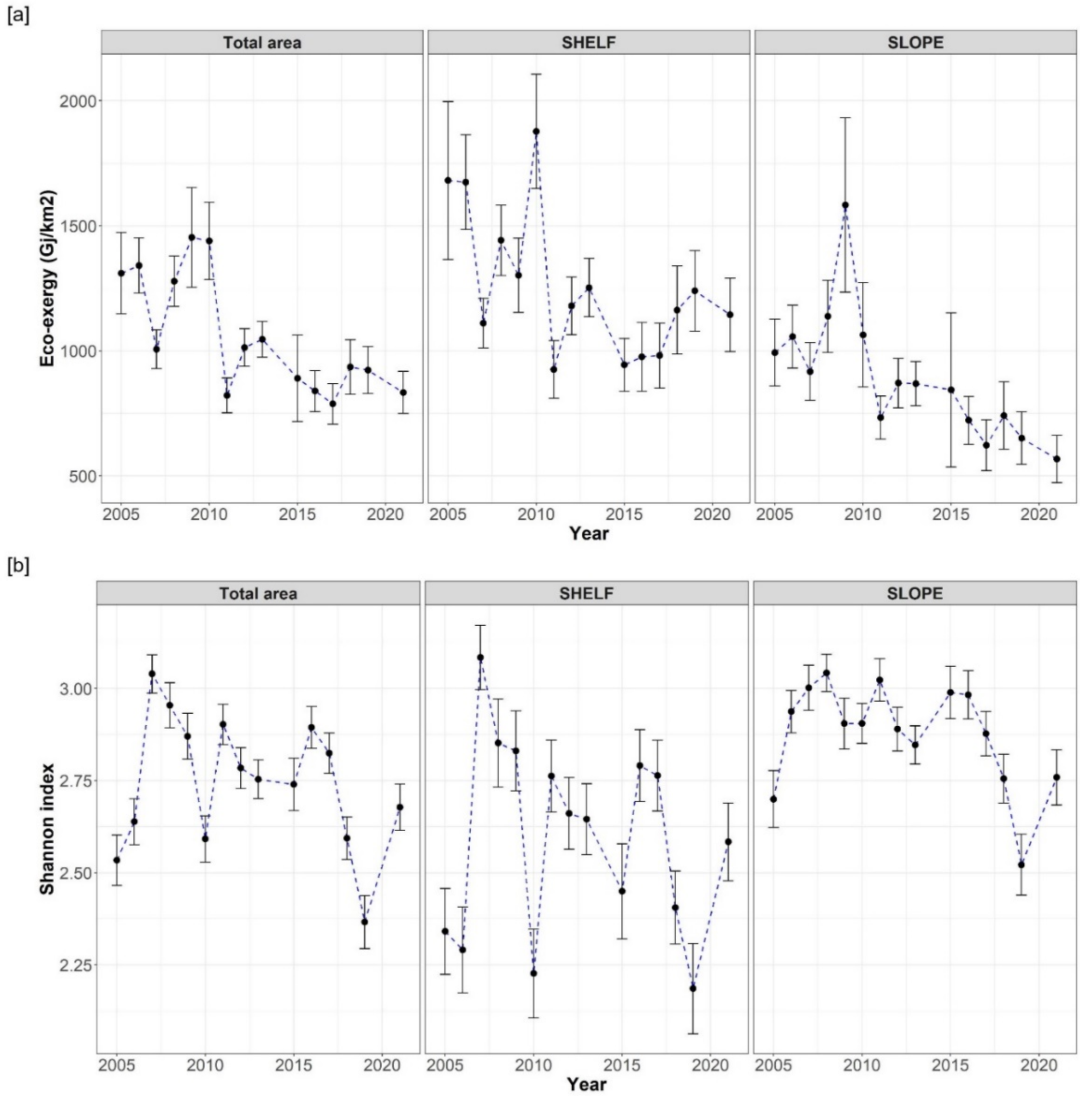


Figure 3 – Time series of average values (2005-2021) of [a] Eco-exergy (GJ/km²) and [b] Shannon diversity index, along with their standard deviations, for the total area, the continental shelf (10-200 m), and the continental slope (201-800 m).

Table 3. Estimates from linear regression models of changes in time for eco-exergy (EEx), Shannon diversity index (H) and fishing effort from 2005 to 2021 and for environmental variables (SST, SSS, pH, and PP) from 2000 to 2021 (***=p<0.001, **=p<0.01, *=p<0.05, ns=not significant).

Variable			Intercept		Slope		R^2
Eco-exergy	-	Total area	72058	**	-35.27	**	0.54
		Shelf	75477	*	-36.85	ns	0.33
		Slope	69147	*	-33.93	*	0.5
Shannon	-	Total area	27.04	ns	-0.01	ns	0.08
		Shelf	29.5	ns	-0.01	ns	0.04
		Slope	24.93	ns	-0.01	ns	0.2

3.2 THE ENVIRONMENTAL DRIVERS OF NATURAL CAPITAL CHANGE

Figure 4a shows the anomaly trends for the selected environmental variables from 2000 to 2021. It is worth noting that all variables, except PP, exhibited a consistent pattern, with a persistent change in anomaly signs between 2011 and 2012. Specifically, SST and SSS recorded values above the mean after 2011, while pH consistently exhibited values below the mean starting from 2012. In contrast, PP did not exhibit a consistent change in anomaly signs. These observations were confirmed by the results of the linear regression models, which showed a significant and positive trend for SST and SSS, a significant and negative trend for pH, and no significant trend for PP (Table 4). The fishing effort has significantly reduced by 75% in 16 years, decreasing from 2.8 $*10^8$ GT*fishing days in 2005 to 6.9 $*10^7$ GT*fishing days in 2021 (Figure 4b, Table 4).

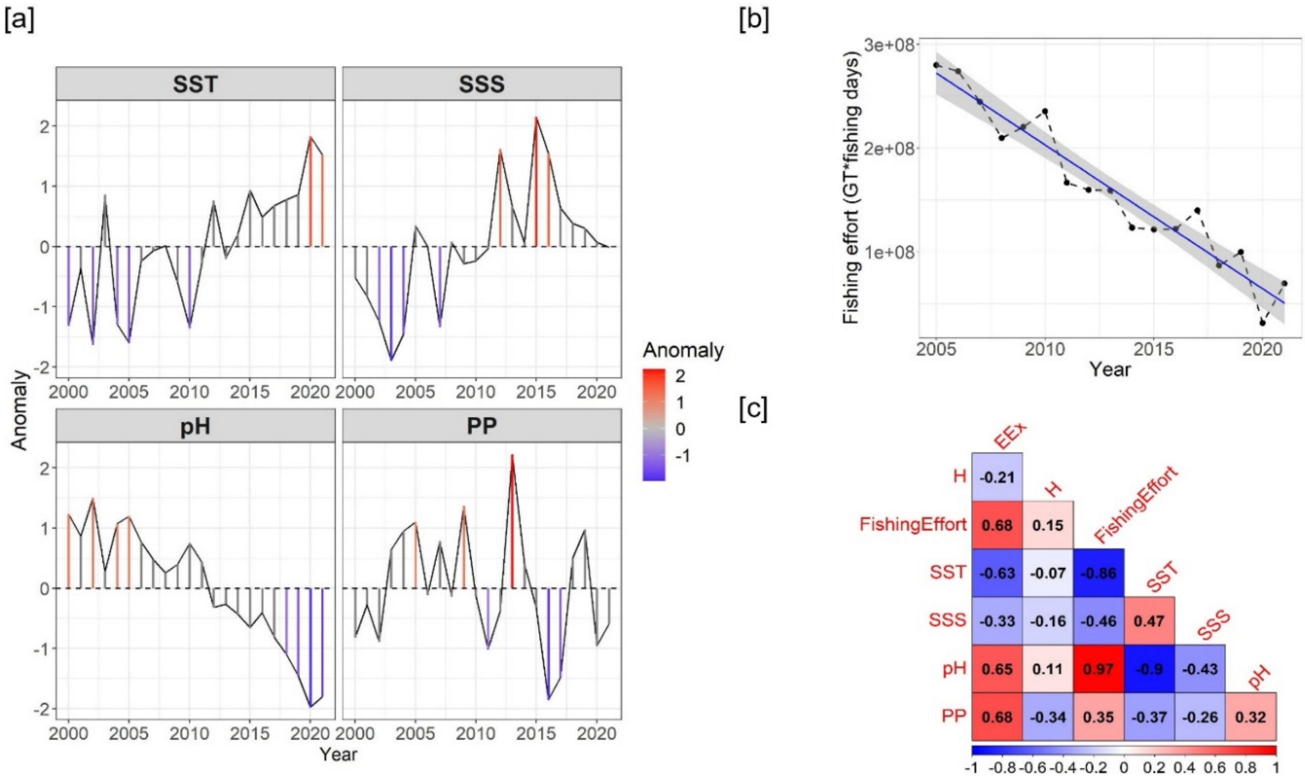


Figure 4 – [a] Anomaly of environmental variables sea surface temperature (SST), sea surface salinity (SSS), pH and primary productivity (PP) in the study area, expressed as the difference from the overall mean divided by the standard deviation between 2000 and 2021; [b] nominal fishing effort (GT*fishing days) of bottom trawlers registered in Geographical Sub Area (GSA) 16. A linear model (blue line) is superimposed, along with its 95% confidence interval (shaded area); [c] Heatmap visualizing Spearman correlations between eco-exergy (EEx), Shannon diversity index (H), environmental variables SST, SSS, pH, PP and fishing effort. Colours ranging from red to blue indicate positive and negative correlations, respectively.

Table 4. Estimates from linear regression models of changes in time for fishing efforts from 2005 to 2021 and for environmental variables (SST, SSS, pH, and PP) from 2000 to 2021 (***=p<0.001, **=p<0.01, *=p<0.05, ns=not significant).

Variable	Intercept		Slope		R^2
Fishing efforts	2.81E+10	***	-1.39E+07	***	0.92
Sea surface Temperature (SST)	-49.62	**	0.034	***	0.58
Sea Surface Salinity (SSS)	12.14	ns	0.013	**	0.37
pH	10.16	***	-0.001	***	0.87
Primary production (PP)	26.16	ns	-0.009	ns	0.02

The correlation analysis of the Eco-exergy with environmental parameters showed significant positive correlations with pH, PP and fishing effort and a negative correlation with SST (Figure 4c). Conversely, the Shannon index showed no significant correlation with the examined variables.

3.3 HOTSPOT ANALYSIS OF ECO-EXERGY AND BIODIVERSITY INDICES

Spatial distribution maps for both eco-exergy and Shannon diversity index are presented in Figure 5. The highest values of eco-exergy were consistently observed over the Adventure Bank throughout the time series, starting from the shallower waters of the coastal area and central part of the Bank (up to 100 m), and extending to the depths of 200 m along its southwest border (Figure 5). Additionally, high eco-exergy density were observed in the southernmost region of GSA 16, near Lampedusa Island. In the other areas, a certain degree of variability in eco-exergy was observed. Notably, observing the temporal sequence of the maps, it appears that the areas affected by high eco-exergy density decreased in extent over time. For the Shannon index, the lowest values were found along the Sicilian coast and in the area extending east of the Adventure Bank (Figure S1). Unlike eco-exergy, the Shannon index did not display a clear temporal trend but exhibited variability from year to year.

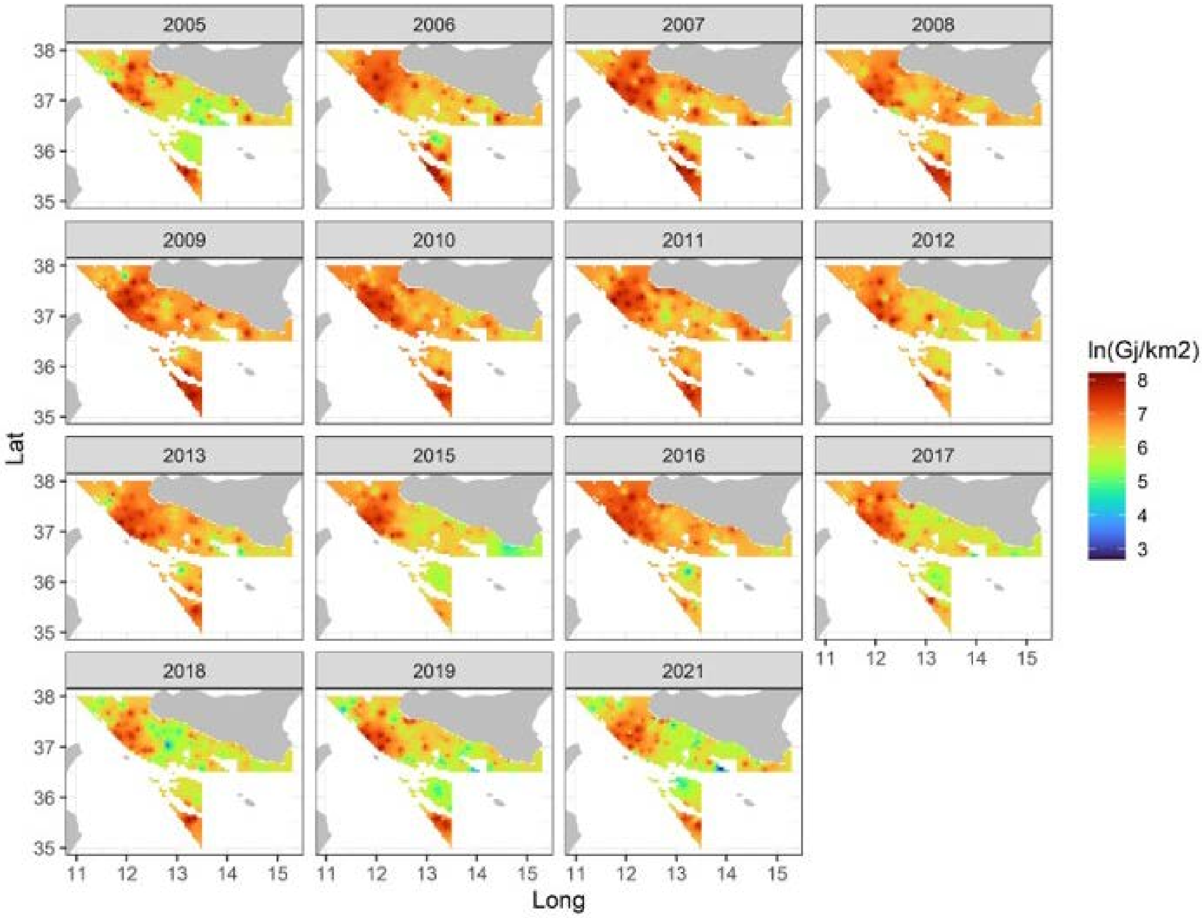


Figure 5 – Annual distribution maps of the eco-exergy index in Geographical Sub Area (GSA) 16.

Spatialization of eco-exergy and Shannon indices facilitated hotspot analysis, identifying significant areas exhibiting high natural capital and biodiversity values (Figure 6 and Figure S2). Regarding eco-exergy, two well-defined hotspot areas were identified in the SoS consistently over time. The primary and most persistent hotspot was localized in the north-western sector of the study area (Figure 6). This hotspot encompassed the shallow western bottoms of Adventure Bank and extended towards the deepest bottoms west of the Bank. A minor hotspot was identified in the South, close to Lampedusa Island. In the case of the Shannon diversity index, the analysis highlighted the persistence of a large coldspot area, whose extent shows remarkable annual variability, and which extends east of the Adventure Bank and along the coastal area of Sicily (Figure S2). This area is known to be a nursery area for several commercially important species (Garofalo et al., 2011; Colloca et al., 2015).

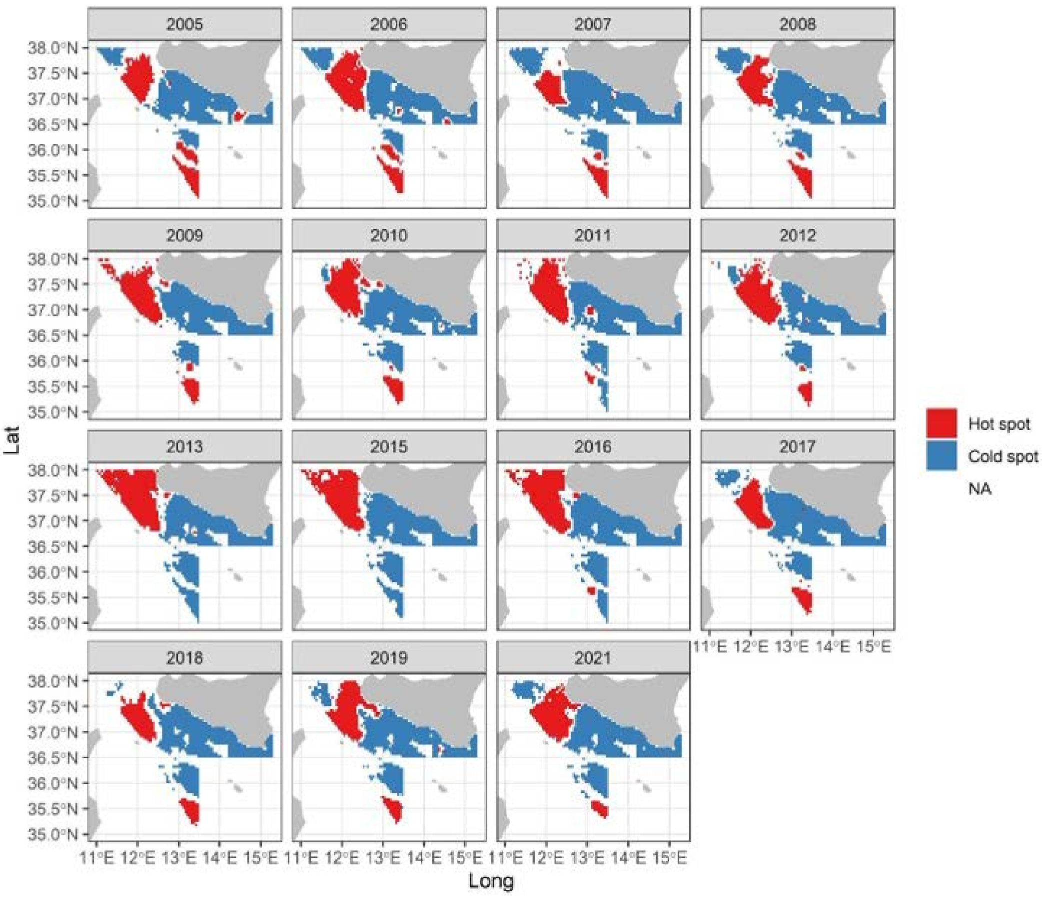


Figure 6 – Annual maps of hotspots and coldspots for the eco-exergy index eco-exergy index in Geographical Sub Area (GSA) 16.

By overlaying the persistent hotspot maps of eco-exergy and Shannon index for each of the three 5-year time intervals, we could identify the areas with the co-occurrence of the highest values of eco-exergy and diversity (Figure 7). These overlap areas were located in the western bottoms of Adventure Bank and the south corner of GSA 16, southeast of Lampedusa Island, with slight variations in their extent across the time three intervals, indicating consistent patterns.

[a] [b] [c]

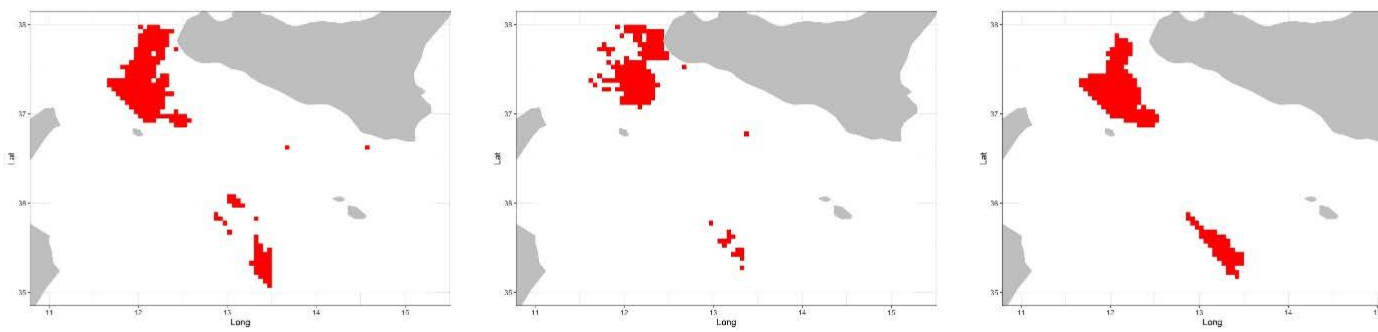


Figure 7 – Areas of co-occurrence of persistent hotspots of eco-exergy and Shannon diversity index in each of the three 5-year time intervals: [a] years 2005–2009, [b] years 2010–2015, [c] years 2016-2021.

4. DISCUSSION

This study applied GFs as ecological indicators to assess NC stock changes of demersal resources in the central Mediterranean. In particular, the eco-exergy indicator measured NC stock through a thermodynamic perspective, quantifying the chemical energy stored in organic matter and the genetic information embodied in living organisms. The joint application of the Shannon biodiversity index as biotic GF allowed us to monitor biodiversity in the investigated marine ecosystem. The choice of the Shannon index was based on its widespread use in previous studies in conjunction with other GFs. For example, Grande et al. (2023) combined biomass-based Shannon index with emergy and eco-exergy to assess ecosystem efficiency in aquatic environments. Similarly, Yuan et al. (2022) applied the eco-exergy method jointly with the Shannon index to monitor changes in NC over 14 years and diversity in fishery resources associated with artificial reefs in Daya Bay (China). Huang et al. (2020) integrated eco-exergy and Shannon index for detecting environmental changes in the Zhoushan archipelago (China). Furthermore, a previous study investigating demersal community biodiversity in the SoS (Garofalo et al., 2007) justified using the Shannon index by demonstrating its strong correlation with other diversity metrics.

Our results highlight a significant decline in NC stocks of the demersal component of the SoS over the 2005–2021 period, which occurred specifically in the slope region. In contrast, no significant decline was observed on the shelf. Overall, bony fish exhibited the highest contribution to eco-exergy, accounting for 62-74% of the total, mainly due to their high biomass density and β value (499, Table 1), reflecting their evolutionary history. However, variations in the contribution to total eco-exergy were observed on the shelf, with bony fish decreasing in percentage and cartilaginous fish increasing. A shift towards k-strategy species such as elasmobranchs (cartilaginous fish) is suggestive of greater efficiency in using energy within ecosystems (Silow & Mokry, 2010), and this was reflected in a slight increase of eco-exergy over the shelf in recent years of the time series. This pattern agrees with the findings by Falsone et al. (2022), who observed improved status for elasmobranch populations on the shelf attributed to reduced fishing activities in this sector of the GSA 16. Indeed, fishing efforts have reduced to 25% from 2004 to 2021. Nevertheless, Falsone et al. (2022) also noted a progressive shift in fishing patterns from shallow-water mixed fisheries to deep-water red shrimp fisheries, which could have contributed to the significant decline of eco-exergy in the slope. Regarding the Shannon index, the analysis did not reveal any significant trends. These findings revealed that eco-exergy can provide earlier warnings on alterations to ecosystem health and functioning compared to the biodiversity index. This finding is supported by a recent study by Alvaro et al. (2023), who assessed the impact of rainfall on phytoplankton and benthic macroinvertebrate communities in 13 reservoirs, demonstrating the ability of thermodynamic and holistic indicators to capture changes in aquatic ecosystems in response to environmental stressors. The authors highlighted the importance of considering thermodynamic indices together with traditional biodiversity measures when evaluating the impact of disturbances on aquatic ecosystems. Indeed, while the Shannon index is less sensitive to species substitutions due to environmental stressors, eco-exergy is responsive to changes in species determined by the shift in the beta value component.

Despite the decreasing trend of fishing efforts in the region, the eco-exergy density has sharply fallen since 2011, describing a decline in the NC stock. By investigating potential environmental stressors (sea temperature, salinity, pH and Primary Production), we found that eco-exergy resulted in a negative correlation to SST and a positive correlation to pH. Both environmental variables exhibited significant trends (positive and negative, respectively) in the SoS related to progressive sea warming and acidification. In particular, examining a time series from 2000 to 2021, a shift in SST anomalies from a negative phase to a positive one was observed between 2010 and 2012, while the reverse occurred for pH anomalies. These findings are consistent with a recent study by Rubino et al. (2024) that examined the impact of rising sea temperatures on fish communities in the continental shelf of the SoS by analyzing the mean temperature of the catch (MTC). The authors found that MTC decreased significantly with increasing depth and had a step-wise rather than linear dynamic concerning increasing water temperature. In particular, after a fast increase between 2005 and 2006, MTC experienced a relatively rapid decrease between 2010 and 2012 within the 10-60 m depth range. The authors argued that the warming of the oceans can lead to the redistribution of marine species and that fish communities may be able to adapt to gradual temperature changes up to a certain point, beyond which abrupt shifts may occur (Rubino et al., 2024).

Primary production did not exhibit a significant trend in the study area across the years. However, it showed a significant positive correlation with eco-exergy, reflecting the ecological efficiency of the investigated marine ecosystem. Reduced primary production may suggest a decline in the ecosystem's ability to capture and convert solar energy into biomass, and the concurrent decrease in eco-exergy could indicate a reduction in the energy flow through the food chain, with cascading effects on the entire ecosystem's health and stability (Silow & Mokry, 2010; Capuzzo et al., 2018). In recent decades, many studies have documented abrupt regime shifts, both in oceanographic parameters and in biological communities of the

Mediterranean Sea. Conversi et al. (2010) documented a regime shift in oceanographic variables and planktonic assemblages in the western Mediterranean basin during the 1980s, while Vasilakopoulos et al. (2014) identified an ecosystem reorganization in fisheries resources as a response to sea warming across the Mediterranean basin over the past 30 years. Damalas et al. (2021) reported a series of environmental step-changes in the Aegean Sea from 1966 to 2017. The Authors highlighted that while the biological system exhibited resilience to environmental changes until 1991, climate-driven regime shifts caused the system to pass through an intermediate state from 1992 to 2002, followed by the most recent state from 2003 to 2016.

Compared with our study, very interesting are the results presented by Sguotti et al. (2022) who studied the fish and macroinvertebrate community of the Northern Adriatic Sea over the last 40 years, using a dataset of commercial fishing landings. The Authors identified three distinct change points in the time series. Two of them, in 1987 and 1997, were synchronous with known large-scale ecological reorganizations observed in other basins (Conversi et al., 2010; Möllmann et al., 2015), while the third one was a new finding of the study not previously observed. It occurred in 2012 and was probably due to the combined effects of increasing water temperature (a gradual increase in water temperature of almost 1°C was observed between 2010 and 2011), changes in primary production and/or changes in fishing pressure. Based on the results of our study, we can expect a regime shift to occur in the SoS in the same period, under cumulative pressures. However, further studies are needed to deepen this aspect and to disentangle the effect of fishing pressure and climate change on the dynamics of the SoS. Some analyses in this direction have been recently performed using a multispecies-multifleet food web model based on Ecosim to explore the potential outcomes of reducing bottom trawling efforts in the SoS combined with changes in primary production induced by climate change (Agnetta et al., 2022). Simulations showed that maintaining fishing efforts at the levels of the year 2019 would worsen resource overexploitation. Conversely, while climate change alone had a limited impact on the recovery of target species, a 30% effort reduction of bottom trawling caused direct rebuilding of target species in the long term and positive indirect effects on the overall food web dynamics, even if preceded by an initial period of biomass decrease and loss of earnings for the fleets. Also, Russo et al. (2019), simulating with the SMART bio-economic model a 15% reduction in trawling effort, highlighted a short transition period with loss of catches and earnings but positive effects on the state of commercial resources in the medium term.

Integrating the eco-exergy and Shannon indexes allowed us to identify two persistent hotspots within the SoS characterized by high values for both indices. Ecosystems with high NC and diversity of the demersal fishery resources are areas of high ecological value and crucial for providing vital human services. These two areas are located in the north-western sector of the SoS, on the western edge of the Adventure Bank, and in the central SoS southeast of the Lampedusa Island. Our results align with Maggio et al. (2022), who recently reported a healthy rhodolite/maerl bed near Lampedusa, a biodiversity hotspot characterized by a diverse benthic assemblage.

A previous study already highlighted a persistent biodiversity hotspot for demersal resources in the area of the Adventure Bank (Garofalo et al., 2007). This hotspot is likely attributable to several offshore banks of volcanic or sedimentary origin. It is mainly located in the euphotic zone (0-100 m), which hosts many species and habitats of conservation interest (Consoli et al., 2021). Their presence naturally constrains bottom trawling activities, thereby reducing seafloor abrasion, which poses the greatest threat to the bottom habitat of the SoS and may impact fragile habitats (Paramana et al., 2024). Nevertheless, hotspots of discarded or lost fishing gear have been discovered near these rocky banks (Garofalo et al., 2020), as they are highly productive areas supporting dense aggregations of commercially valuable species, attracting intensive artisanal and recreational fishing activities. According to Altobelli et al. (2017), these habitats show degraded and pristine areas, still playing a key role in sustaining pelagic and benthic production in the SoS.

Therefore, the results of this study provide an important baseline on the NC stock of the SoS and could be helpful in the definition of future sustainable management strategies for marine ecosystems.

Among the limitations of this study, we acknowledge the focus only on the demersal component of the marine ecosystems, thus requiring further investigations focused on pelagic species and megabenthos. Additional research is needed to understand the ecological consequences of the observed decline in NC stock and potential future trajectories under increasing anthropogenic pressures.

5. CONCLUSIONS

This study proposes a multi-methodological approach to assess Natural Capital stock changes in the Mediterranean Sea, focusing on the Strait of Sicily (SoS). Eco-exergy as a thermodynamic Goal Function has proved to be a more sensitive indicator to detect changes in ecosystem functioning and complexity in response to environmental variables. Conversely, while the Shannon index is important in measuring ecosystem diversity, it does not fully capture an ecosystem's dynamics and functional aspects. Integrating the eco-exergy and Shannon indices proved to be a promising approach to exploring marine ecosystems, adopting a holistic and ecosystem perspective. By combining both approaches, this study has identified key ecological areas located west of the Adventure Bank and near southeast of Lampedusa Island, suggesting the importance of their protection and conservation in marine ecosystem management strategies. This result can provide helpful scientific information to policymakers in support of strategic conservation efforts and effective, sustainable fishery management measures in the broader framework of marine spatial planning.

Authors contributions

U. Grande: Investigation, Data curation, Software, Data interpretation, Writing-original draft. E. Buonocore: Conceptualization, Methodology, Writing-review & editing. F. Fiorentino: Conceptualization, Methodology, Data interpretation, Writing-review & editing, Supervision. P.P. Franzese: Conceptualization, Methodology, Writing-review & editing, Supervision. V. Lauria: Writing-review & editing. A. Piernik: Conceptualization, Writing-review &editing E. Sabatella: Witing-review & editing. D. Scannella: Methodology, Sampling, Writing-review & editing. S. Vitale: Data curation, Supervision. G. Bono: Data curation, Supervision. G. Garofalo: Conceptualization, Investigation, Data curation, Data interpretation, Software, Writing-original draft, Supervision.

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3.3 Manuscript 3

Grande U., Husein K., Nardella L., Kamiński D., Buonocore E., Franzese P.P., Piernik A. Assessing forest ecosystem assets and services based on an international statistical standard. Ecological Indicators (under review)

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Assessing forest ecosystem assets and services based on an international statistical standard

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Corresponding Author:	Umberto Grande, M.D. University of Naples Parthenope Naples, ITALY
First Author:	Umberto Grande, M.D.
Order of Authors:	Umberto Grande, M.D.
	Kevin Husein
	Lorenza Nardella
	Dariusz Kaminski
	Elvira Buonocore
	Pier Paolo Franzese
	Agnieszka Piernik
Abstract:	The contemporary era is facing several global environmental challenges that have raised growing concerns about the sustainability of human societies. Ecosystems support human society by providing various Ecosystem Services (ES). Conserving and monitoring natural ecosystems is urgently needed to ensure the long-term provision of ES and human well-being. Several approaches and methodologies have been developed to assess and value ES, leading to the establishment of the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA) as a standardised statistical framework adopted by the United Nations. In this study, we implemented the SEEA-EA framework to assess the ecosystem assets and then ES provided by the Tuchola Forest UNESCO-MAB Biosphere Reserve (Poland). According to the SEEA-EA framework, we included selected ecosystem extent and condition indicators to focus on the estimation of regulating ES regarding air pollution regulation. In addition, we assessed the variation in ES supply caused by a strong hurricane in 2017 that destroyed 15,236 ha of the Biosphere Reserve forests. Results showed that a hurricane led to changes in forest composition, affecting the ES supply. The provisioning of air filtration service estimated in this study was 8,062.5 Mg before the hurricane, with a corresponding economic value of 791.5 M€. The ecosystem service lost due to the hurricane impact amounted to -296.8 Mg, resulting in an economic loss of -7.2 M€. To our knowledge, this is the first study implementing the SEEA-EA framework to assess ecosystem assets and services of the UNESCO-MAB Biosphere Reserve.

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Authors: Umberto Grande, Kevin Husein, Lorenza Nardella, Dariusz Kaminski, Elvira Buonocore, Pier Paolo Franzese, Agnieszka Piernik

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Supplementary material

Dear Editors,
The contemporary era is facing several global environmental challenges that have raised growing concerns about the sustainability of human societies. Ecosystems support human society by providing various Ecosystem Services (ES). In this study, we implemented the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA), a standardised statistical framework adopted by the United Nations, to assess the ecosystem assets and then ES provided by the Tuchola Forest UNESCO-MAB Biosphere Reserve (Poland).
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The application of the SEEA-EA framework facilitated the integration of ecological and socio-economic aspects. The air filtration service is directly linked to human health and well-being, as it reduces exposure to harmful pollutants, mitigating respiratory problems and other health issues. Therefore, we believe that our research contributes to the knowledge of new aspects of forest ecosystem assets and services.

Sincerely,

Umberto Grande, Kevin Husein, Lorenza Nardella, Dariusz Kaminski, Elvira Buonocore, Pier Paolo Franzese, Agnieszka Piernik

We hereby affirm that the content of this manuscript has not been previously published in any journal, is not being submitted for publication elsewhere, and has been approved by all the authors (i.e., no conflicts of interest).

Corresponding author: Umberto Grande; e-mail: umberto.grande@collaboratore@uniparthenope.it; umbertogrande@gmail.com

- coniferous forests Functional Group was the main extent within the Biosphere Reserve
- the air filtration forest service was 8,062 Mg with a corresponding value of 791.5 M€
- the hurricane destroyed 15,236 ha of the Tuchola Forest Biosphere Reserve forests
- the hurricane caused a forest ecosystem service loss of -296.8 Mg, resulting in a loss of -7.2 M€

Assessing forest ecosystem assets and services based on an international statistical standard

Umberto Grande [a,b], Kevin Husein[a], Lorenza Nardella[b], Dariusz Kaminski[a], Elvira Buonocore[b], Pier Paolo Franzese[b], Agnieszka Piernik[a]*

[a]Department of Geobotany and Landscape Planning, Nicolaus Copernicus University in Torun, ul. Lwowska 1, 87-100, Toruń, Poland.

[b]International PhD Programme / UNESCO Chair "Environment, Resources and Sustainable Development", Department of Science and Technology, Parthenope University of Naples, Centro Direzionale Isola C4 (80143), Naples, Italy.

[*]Corresponding author: umberto.grande@collaboratore.uniparthenope.it

Abstract

The contemporary era is facing several global environmental challenges that have raised growing concerns about the sustainability of human societies. Ecosystems support human society by providing various Ecosystem Services (ES). Conserving and monitoring natural ecosystems is urgently needed to ensure the long-term provision of ES and human well-being. Several approaches and methodologies have been developed to assess and value ES, leading to the establishment of the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA) as a standardised statistical framework adopted by the United Nations. In this study, we implemented the SEEA-EA framework to assess the ecosystem assets and then ES provided by the Tuchola Forest UNESCO-MAB Biosphere Reserve (Poland). According to the SEEA-EA framework, we included selected ecosystem extent and condition indicators to focus on the estimation of regulating ES regarding air pollution regulation. In addition, we assessed the variation in ES supply caused by a strong hurricane in 2017 that destroyed 15,236 ha of the Biosphere Reserve forests. Results showed that a hurricane led to changes in forest composition, affecting the ES supply. The provisioning of air filtration service estimated in this study was 8,062.5 Mg before the hurricane, with a corresponding economic value of 791.5 M€. The ecosystem service lost due to the hurricane impact amounted to -296.8 Mg, resulting in an economic loss of -7.2 M€. To our knowledge, this is the first study implementing the SEEA-EA framework to assess ecosystem assets and services of the UNESCO-MAB Biosphere Reserve.

Keywords: ecosystem services, SEEA-EA, air quality regulation, UNESCO-MAB, biosphere reserve, ecosystem extend, ecosystem condition

1. Introduction

The contemporary era is marked by several global environmental challenges that have raised growing concerns about human well-being and the sustainability of our planet (Wu, 2013; Inbit et al., 2024). These challenges are largely attributed to human activities, which have led to non-linear changes in natural ecosystems, causing local and global environmental issues, including biodiversity loss, soil degradation, air pollution, and climate change (Ochoa-Hueso et al., 2017; Liu et al., 2022; Buonocore et al., 2024).

Concurrently, in the last decades, the awareness of the strong link between the degradation of natural ecosystems and human well-being has grown (Balmford and Bond, 2005; Wu, 2013). Indeed, it is widely recognized that ecosystems and human well-being are intricately interconnected and mutually dependent (Russell et al., 2013). Ecosystems play a vital role in supporting human societies by providing a wide range of Ecosystem Services (ES) encompassing the benefits that people derive from ecosystems (Gomez-Baggethun and Barton, 2013; Kadykalo et al., 2019; Sokolova et al, 2024). However, when ecosystems are degraded, their ability to provide these services decreases, thus posing a threat to human well-being (Haines-Young and Potschin, 2010).

Forests are important ecosystems able to host a large terrestrial and aquatic biodiversity. Globally, forest ecosystems cover 31% of the land area (FAO and UNEP, 2020), and their ecological and socio-economic role is widely recognized in ensuring human well-being (Brockerhoff et al., 2017; Mori, 2017). Indeed, forests are considered the most ecosystem service providers worldwide (Aznar-Sánchez et al., 2018). Estimates suggest that forests offer a wide array of services, potentially reaching up to 100 types, ranging from the production of food, timber, and fuel to the conservation and regulation of water, retention of nutrients, sequestration of carbon, protection of biodiversity, regulation of climate, promotion of ecotourism, or spiritual experiences (MA, 2005; Martin-Lopez, 2016). Despite the well-known role of forest ecosystems in supporting mankind, several anthropogenic threats are affecting such environment, leading to forest loss, fragmentation and degradation, contributing to the decline of ecosystem services supply (FAO 2015; Brockerhoff et al., 2017; Song et al., 2018).

Recognizing the role of natural ecosystems in providing benefits to humans and understanding our dependence on nature, the urgent need to protect and preserve our planet emerges (Braat & De Groot, 2012; Diaz et al, 2018). The conservation and sustainable management of natural ecosystems have become imperative in ensuring long-term human well-being (Bunch et al., 2011). In addition, ES assessment facilitates their incorporation into decision-making and trade-off analysis processes (Inostroza et al., 2017).

In this context, Ecosystem Accounting seeks to assign biophysical and economic values to nature's benefits to humans (Edens & Hein, 2013). In the last decades, several approaches and methodologies have been developed to assess the value of ES adopting different perspectives (El Alam et al., 2024). Standardized Ecosystem Accounting models allow comparative analysis at a global scale (Bagstad et al., 2013). Among them, the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA) was developed by the United Nations as a standardized statistical framework. The SEEA-EA provides an integrated spatially explicit approach to organizing biophysical data, measuring ecosystem services, and tracking changes in ecosystem extent and condition (De Fioravante et al., 2023). In particular, the SEEA-EA framework emphasizes the strong relationship between humans and the environment, connecting ecosystem stocks and flows to economic assets, through the principles of the System of National Accounts (SNA) (King et al., 2024). The SEEA-EA framework has gained wide acceptance as a conceptual and methodological framework for monitoring and analysing the human use of ecosystems, and it has been adopted as an international statistical standard for ecosystem accounting by the United Nations (Vallecillo et al., 2022). Numerous countries are currently producing ecosystem accounts implementing the SEEA-EA framework at different scales, from local to national. In particular, Bruzon et al. (2023) used the SEEA-EA framework to monitor forest condition accounts at the national level (Spain). Maes et al. (2023) implemented SEEA-EA framework accounting for European forest conditions. De Fioravante et al. (2023) implemented the SEEA-EA framework mapping ecosystems extent in Italy and assessing crop provisioning and carbon stock at a national level. Farrell et al. (2021) implemented the SEEA-EA framework at the catchment scale to develop ecosystem extent and condition accounts in Ireland. Schenau et al. (2022) assessed ecosystem services and ecosystem assets in the Netherlands using the SEEA-EA framework, only focusing on the estimation of the economic value of human benefits produced by ecosystems, excluding non-economic values and 'non-human' benefits.

This study aimed to implement the SEEA-EA framework for the assessment of forest ecosystem assets and services within the Tuchola Forest Biosphere Reserve (TFBR), a UNESCO Man and Biosphere (MAB) Reserve located in Northern Poland. Specifically, our study focused on two main aspects: 1) assessing the ability of the TFBR to improve air quality and 2) tracking changes in ES supply after natural disasters. Our analyses primarily focused on forest ecosystem types, the predominant ecosystems within this Biosphere Reserve. Following the purpose of our goals, we expect a decreased ability of the TFBR to improve air quality and a decreased ES supply after a hurricane in 2017.

Furthermore, aligned with the goals MAB programme, an intergovernmental scientific program that aims to establish a scientific basis for enhancing the relationship between people and their environments (Klaver et al., 2024), we foresee that the SEEA-EA framework serves as a valuable tool for assessing and monitoring ES, highlighting and enhancing the intricate relationship between human well-being and ecosystems. To the best of our knowledge, this is the first study that aims to implement the SEEA-EA framework within the MAB Biosphere Reserve, assessing variation in ES supply caused by natural disasters.

2. Materials and methods

2.1 Study area

The Tuchola Forest Biosphere Reserve (TFBR) is one of the biggest forest complexes in Poland, included in the UNESCO-MAB programme (Fig. 1). Located in the North-West part of the country, the TFBR covers an area of 319,524.6 ha. The Reserve is divided into three distinct areas according to the regulations of the UNESCO-MAB programme, which integrates ecological and socio-economic aspects (Nienartowicz et al., 2010; Nienartowicz and Kunz, 2020). The TFBR encompasses 22 municipalities across four counties in two administrative regions: Kuyavian-Pomeranian and Pomeranian. Key human activities within the TFBR include forestry, tourism, recreation, wood processing, fishing, and agriculture (Nienartowicz and Kunz, 2020).

The TFBR represents an area of high ecological value with ecological systems typical for the lowlands of Middle Europe (Jarzebski et al., 2010). The TFBR encompasses a variety of natural ecosystems designated as priority conservation areas within the Natura 2000 network. These include heathlands, mid-forest lobelia lakes, dystrophic lakes with charophyte grasslands, Atlantic-type peat bogs, and deciduous forests (Nienartowicz et al., 2010; Nienartowicz and Kunz, 2020). These habitats support a rich biodiversity, including numerous rare, relict, and protected species of plants (vascular and non-vascular), fungi, and animals, encompassing both vertebrates and invertebrates, with endangered species present (Nienartowicz et al., 2010; Nienartowicz and Kunz, 2020). Over 86% of the Reserve is covered by forests, primarily a vast pine forest (Krawiec et al., 2022). This forest, largely composed of pine monocultures has evolved from ancient forests. Indeed, human activities and climate change have significantly altered these primary forest ecosystems, leading to the current dominance of middle-aged stands (Krawiec et al., 2022). The Biosphere Reserve has also a high socio-economic value and a strong tradition of forest and water exploitation takes place (Krawiec et al., 2022).

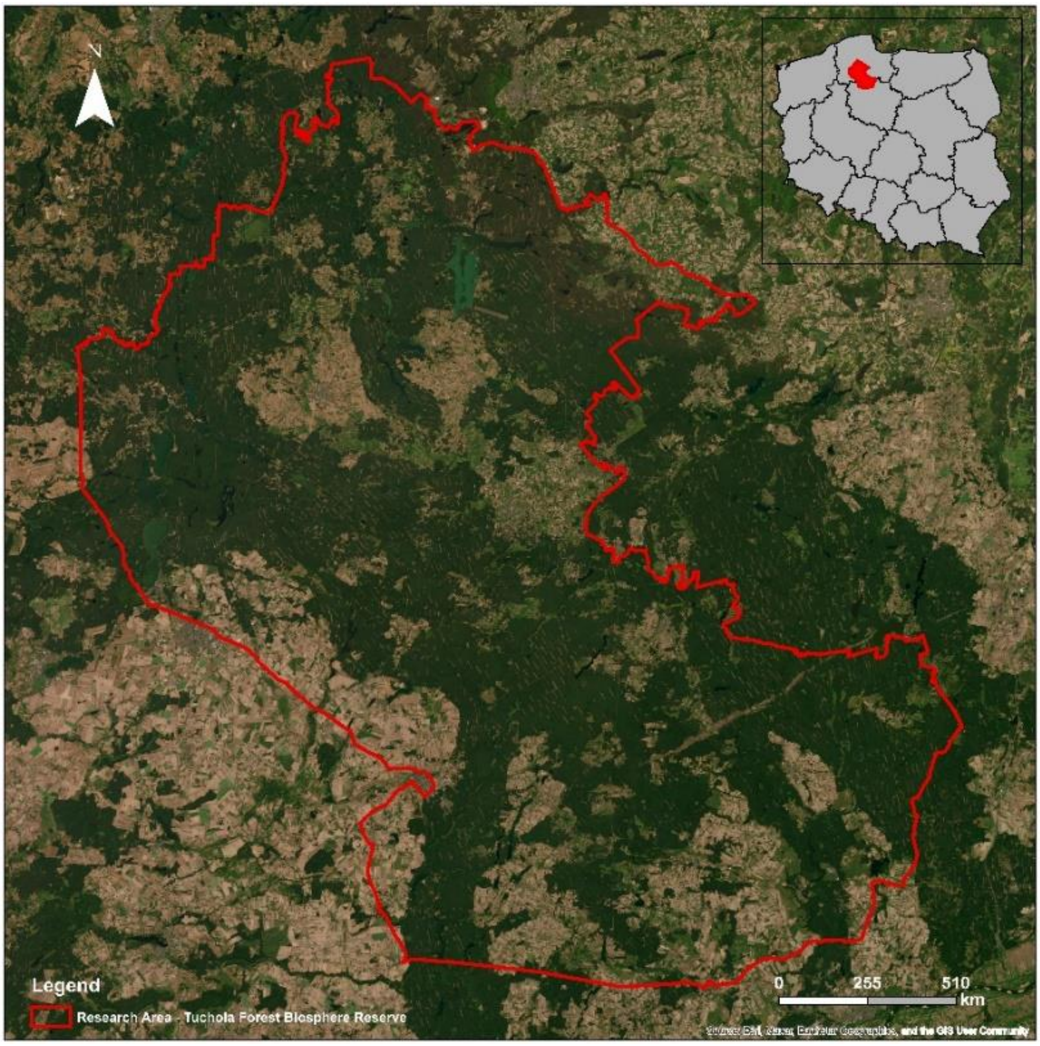

Figure 1. Boundary of the Tuchola Forest Biosphere Reserve (TFBR), (Poland).

2.2 The SEEA-EA accounting framework

In this study, the SEEA-EA framework was applied to assess the extent, condition and a set of regulating ecosystem services related to improving air quality provided by the TFBR before and after a natural disaster. The framework is divided into five main steps. The first step covers the *Ecosystem extent account*, which gives information on the extent of different ecosystem types (e.g., forests, wetlands, agricultural areas, artificial areas), tracking changes over time in our case, with a special focus on forest vegetation. The second step is related to the *Ecosystem condition account*, especially related to our research on air quality. The third and fourth step deals with the *Ecosystem services' physical and monetary flow account*, which measures the ES flows, highlighting the relationship between humans and the environment. The fifth step covers *the Monetary ecosystem asset account,* which records changes in the supply in monetary terms (United Nations et al., 2021).

Ecosystem extent evaluation was performed using Quantum Geographic Information System (QGIS) software (version 3.26.3). Corine Land Cover (CLC) products provided by the Copernicus Land Monitoring Service (CLMS) were chosen and analysed as the source for the land cover classification. By exploring the effect of the hurricane that occurred in the Biosphere Reserve in August 2017, CLC 2012 and 2018 years were selected. 2012 has proven to be the closest available data before the extreme event. A total of 44 classes divided in hierarchical three-level nomenclature were in the CLC classification. By aligning the classification following the IUCN Global Ecosystem Typology as reported in the SEEA-EA guidelines (Vallecillo et al., 2022), the ecosystem types were aggregated into 16 classes and listed in Table A1 of supplementary material. We focused mostly on forests, which were ecosystem types (ET) the most affected by the hurricane, and semi-natural areas (transitional woodland-shrub). Therefore, we provided LULC Classification. The first step of the analysis aimed to identify the main functional groups (FGs) occurring within the TFBR. CLC was the source for the land cover classification in TFBR. CLC 2012 and 2018, produced by the Copernicus Land Monitoring Service, were already correlated with land cover or land use status. Of 44 founded classes, broadleaf and coniferous forests were selected as key FGs, while the rest of the categories were defined as other areas according to the aim of the study. The spatial resolution was set at 10 meters to preserve the accuracy necessary for the correct visualization of the typology of the territory and its geometric characteristics.

The purpose of Ecosystem Condition is to assess the condition of an ecosystem over time, providing information about its biotic, abiotic and landscape characteristics according to its composition, structure, and function. Assessing the condition of an ecosystem means having a broad view of its integrity and, consequently, its ability to provide ecosystem services (United Nations, 2021). At this stage, a set of quantitative indicators must be selected to describe different aspects of an ecosystem. The selection of indicators was driven by the investigated ecosystem type and data limitation. We focused on abiotic state indicators, i.e. air pollutant indicators - concentrations of particulate matter 10 (PM_{10}), particulate matter 2.5 ($PM_{2.5}$), nitrogen dioxide (NO_2) and ozone (O_3). To quantify the mean seasonal concentrations of PM_{10}, $PM_{2.5}$, NO_2, and O_3, data from the Copernicus Atmosphere Monitoring Service (CAMS) were used. CAMS, hosted by the European Centre for Medium-Range Weather Forecasts (ECMWF), produces European annual air quality (interim) reanalyses at a 0.1-degree (approximately 10 km) spatial resolution, which is higher than global reanalyses. This model utilizes nine European air quality data assimilation systems. A median ensemble is calculated from the outputs of these systems, as ensemble products generally perform better than individual model products. The spread across the nine models allows for the estimation of analysis uncertainty. The ensemble comprises eight models: CHIMERE, EMEP, EURAD, LOTOS-EUROS, MATCH, MOCAGE, SILAM, and the Ensemble Median. These models provide uniform spatial and temporal coverage, offering a physically based approach to air quality prediction. However, post-processing their predictions is essential to reconcile them with observations and provide a more accurate air quality diagnosis. CAMS models provide "background" values representative of relatively large-scale phenomena, which may not capture local gradients associated with high variability.

For this research, 2018 data with the Ensemble Median method were selected. This represents the closest available year with conditions comparable to those of the study period (before and after the hurricane in 2017). Data obtained in NetCDF format were processed in QGIS software to extract the relevant air pollution data based on seasons. The second step consisted of retrieving the vegetation state indicator - the LAI of the FGs, which is essential to estimating the ability to remove PM pollutants by trees (Nardella et al., 2024). By definition, LAI is half of the total canopy green area per unit of horizontal ground area and it serves as a measure of the extent of vegetation cover (CGLS, 2023). The seasonal means of the Leaf Area Index for the accounting year was retrieved from Copernicus Global Land Services (CGLS). This product has been based on Sentinel-3/OLCI with PROBA V with 300 or 1000 meter resolution. 300 m resolution was selected in this study. The LAI is calculated globally on a 10-day basis and made available for download. Values were averaged on a seasonal basis using the GRASS GIS software. (v. 7.8.3). LAI of the FGs groups were assessed according to the meteorological season classification (NOAA, 2023). In detail, the winter season of a non-leap year accounted for 90 days, 92 for spring and summer, while autumn seasons accounted for 91 days. Due to the fact that deciduous trees lose their leaves during the winter season, the LAI for this FG was arbitrarily set to 0 (Sebastiani et al., 2021). Because of the data availability, the Leaf Area Index of 2016 was applied - the year before the hurricane.

The key concepts in accounting for Ecosystem Services (ES) refer to assessing the biophysical value of ecosystem assets, with a particular emphasis on recording their economic contribution to the National Accounting System. In particular, the SEEA-EA framework uses ecosystem services assessment to link ecosystems and society to understand how ecosystems contribute to human well-being (Edens et al., 2022). According to the CICES ES classification, this study assessed a set of regulating ES provided by forest FG. In particular, the ability to remove PM_{10}, $PM_{2.5}$, NO_2 and O_3 was evaluated for the state of forests before and after the hurricane to record changes in the provisioning of services after a hurricane destroyed thousands of hectares of trees in 2017. The analysis was first conducted by assessing the ES provided by the forest in 2012 for the main FGs occurring in the TFBR assuming the stable air pollution as was recorded in the most recent data set in 2018. Subsequently, the lost forest area by the hurricane was then quantified, and the ES loss was assessed. For PM assessments, the Leaf Area Index provided by Copernicus Global Land Services (CGLS) data of 2016, the year before the hurricane, was applied. The flowchart shown in Figure 2 summarizes the workflow applied in this study and related sources of dataset.

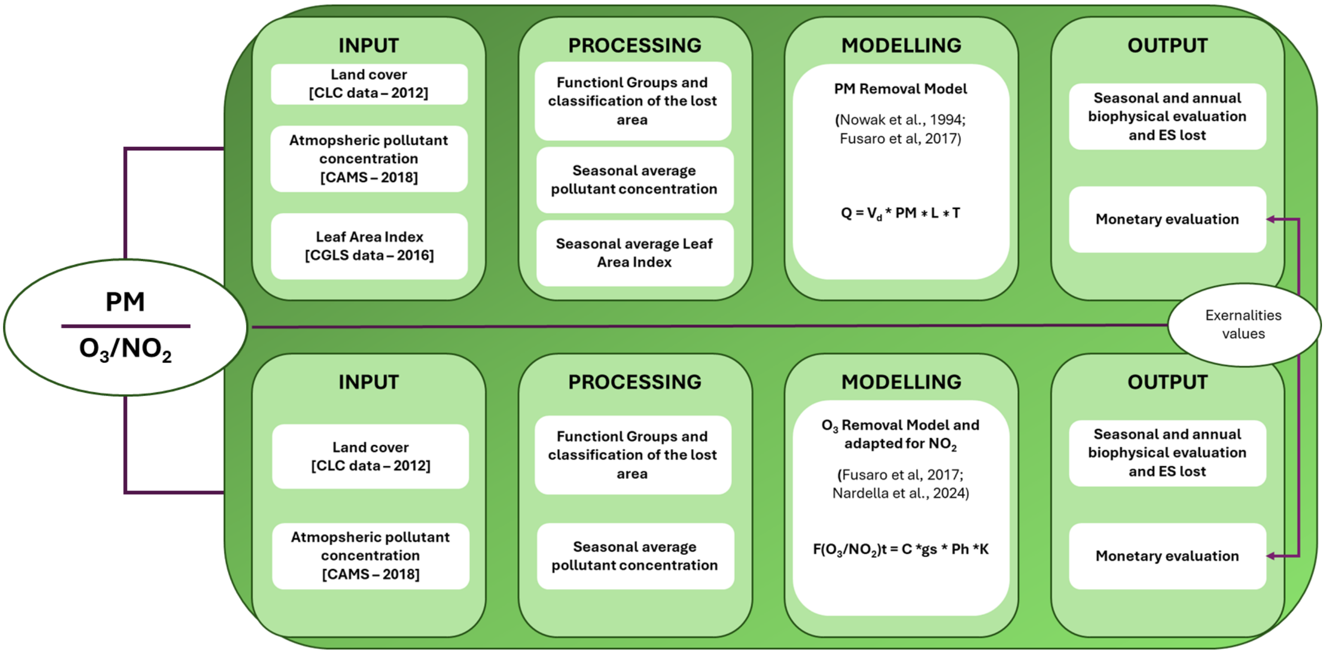

Figure 2 – Workflow for the assessment of air filtration services.

2.3 *Particular matter deposition model*

The deposition of the PM_{10}, $PM_{2.5}$ on the vegetation was estimated following the equation proposed by Nowak et al. (1994) and Fusaro et al., (2017), applied in different studies (Nowak et al., 2013; Silli et al., 2015; Nardella et al., 2023) and reported below:

$$Q = F * L * T \qquad (1)$$

Where Q is the amount of pollutant which is adsorbed; F is the flux of pollutant, defined as the deposition velocity of the pollutant multiplied by the pollutant concentration; L is the LAI for the considered period; T is the vegetative period of the considered FG of vegetation. According to Sebastiani et al. (2021), conifers are considered to provide ESs all year long. Instead, deciduous trees provide it for 275 days per year, according to their different phenology.

In the context of PM_{10}, the deposition velocity (V_d) in this study has a median value of 0.0064 m/s, which is based on a mean annual LAI value of six and then adjusted according to the actual LAI (Escobedo and Nowak, 2009). Previous studies suggested that V_d may change according to air temperature, humidity, and tree species (e.g., needle-like leaves of broadleaf). However, as stated by Mariraj Mohan (2016), further studies are needed to properly simulate the dry deposition of PM onto the leaf's surface, even if this bias was widely accepted in previous studies.

In the case of $PM_{2.5}$, a median value of 0.0019 m/s was adopted according to the local wind speed and adjusted according to the actual LAI (Hirabayashi et al, 2012).

Lastly, the results of the equation were multiplied by the FGs mask (area of coniferous and broadleaf forests) in order to obtain the total biophysical value of the service.

2.4 Nitrogen dioxide and ozone uptake model

O_3 uptake was estimated using a spatially explicit model (Fusaro et al., 2017; Nardella et al., 2024). The equation of this model is presented below:

$$FO_3t = C * gs * Ph * K \qquad (2)$$

FO_3t is the total cumulated O_3 flux (ppb), C is the O_3 concentration (ppb), gs represents the stomatal conductance to water vapour (mol/m^{2}s) and Ph indicates the length of the photoperiod (s). The mean photoperiod was estimated according to the season and the local daylight amount (NOAA, 2023). K is a constant given by the following equation:

$$K = (48 * 0.613 * 0.5) / (0.3 * 10^9) \qquad (3)$$

48 refers to the molecular weight of O_3 (g/mol), *0.613* represents the diffusibility ratio between O_3 and water vapour, *0.5* is a conversion factor from μg/m^3 to ppb (assuming an average temperature of 25 °C and pressure of 1 atm), and 10^9 is a dimensional correction factor (from mol to nmol). The stomatal conductance (gs) values were collected from the literature according to Emberson et al. (2000) and Nardella et al. (2024). Based on previous studies on coniferous and broadleaf forests, 0.3 represents 30% of the total potential O_3 removal of both stomatal and non-stomatal processes. The same equation was used to assess the NO_2 uptake, being the NOx precursor of O_3, varying the molecular weight (46) and the diffusibility ratio (0.62), according to the nitrogen dioxide molecule.

Lastly, the results of the equation were multiplied by the FGs mask (area of coniferous and broadleaf forests) in order to obtain total biophysical value of the service.

2.5 Monetary evaluation

The economic value of the air filtration service was determined by applying the externality cost of pollutants, as outlined in Sebastiani et al. (2021). These externality costs represent the societal impacts of air pollution on human health and environmental effects, which are typically not recorded in market transactions. In this study, the monetary evaluation was performed based on the values reported in the (EEA, 2024). For Poland, the externalities value for PM_{10} was 76,089 €/Mg, $PM_{2.5}$ was 136,198 €/Mg, while 15,994 €/Mg for NO_2 and O_3.

3. Results

3.1 Ecosystem types

According to the third level of CLC classification for 2012 and 2018, forests were the main ET in TFBR. Coniferous forests FG resulted to be the main extent within the Biosphere Reserve, accounting for 56.16% (180,218.94 ha) and 51.41% (164,982.92 ha) in 2012 and 2018, respectively. Broadleaf forests were much smaller extent FG with an area of 2,478.7 and 2461.6 ha in 2012 and 2018, respectively. Figure 3 presents changes in coniferous and broadleaf forests FGs distribution before (2012) and after (2018) the hurricane in 2017. In terms of changes in extent between the investigated years, the most significant net change occurred in coniferous forests and transitional woodland shrubs. In particular, coniferous forests decreased by 15,236.02 ha (- 4.75%), while transitional woodland shrubs increased by 16,333.70 ha (5.09%). By analysing the FG's contribution before and after the hurricane cross, notable is the huge loss of forest in the North-Wester sector of the TFBR.

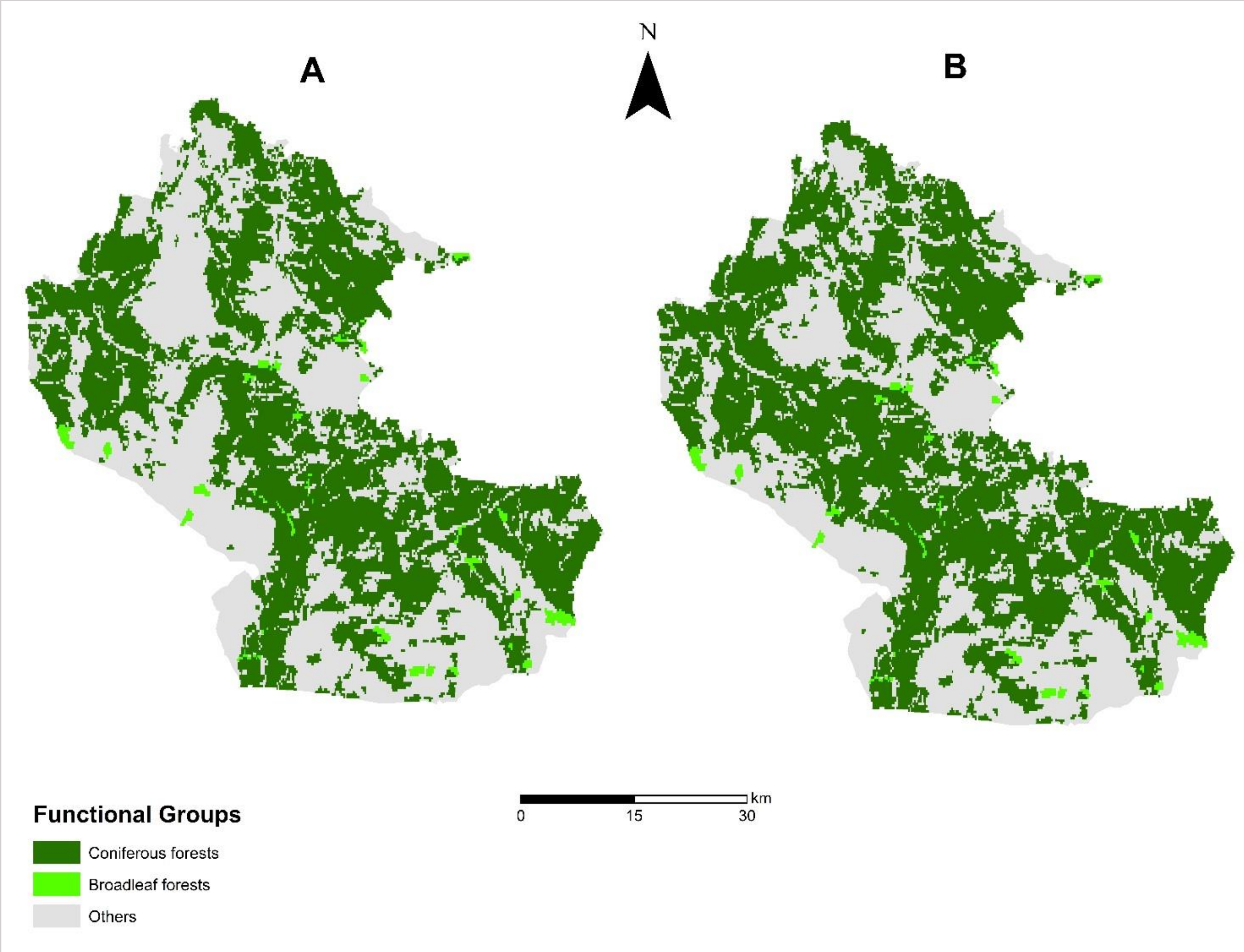

Figure 3 - Changes in coniferous and broadleaf forest distribution before and after the hurricane in 2017 (A, 2012: B, 2018).

3.2 Condition of the TFBR

According to the World Health Organization (WHO), results showed that PM_{10} and $PM_{2.5}$ concentrations exceeded the thresholds for all the seasons, in summer for O_3, with no exceedance for NO_2 (WHO, 2021). Furthermore, results highlighted the highest concentration values in autumn and winter for PM_{10}, $PM_{2.5}$, and NO_2. In the case of O_3, the highest values occurred in spring and summer, according to the pollutants pattern (Table 1).

In the context of biotic indicators necessary for future assessments of ESs related to PM removal, our findings revealed that the LAI followed the same pattern for both the FGs (coniferous and broadleaf forests), with the highest values in spring and summer when the leaves are fully developed. In particular, the average peak LAI for deciduous trees was in summer (3.2) and in spring season (3.1), while decreasing in autumn (1) and reaching zero in winter according to their phenology. In the case of coniferous trees, the mean LAI showed the highest value in summer (2.8) and spring season (2.1), followed by autumn (1.1) and winter (1.1).

Table 1 - Indicator values of the abiotic and biotic state descriptors. Data according to their availability.

Ecosystem Condition Typology Class	**Indicators**	**Unit measure**	**Mean observed values**			
			Winter	**Spring**	**Summer**	**Autumn**
	PM_{10}	$\mu m/m^3$	22.7	18.8	12.4	25.4

Abiotic characteristics (2018)	Chemical state	$PM_{2.5}$		17.9	14.4	9	20.2
		NO_2		8.7	5	3.8	8.4
		O_3		41.4	59	70.6	42
Biotic characteristics (2016)	Functional state	Coniferous LAI	-	1.1	2.2	2.8	1.1
		Broadleaf LAI	-	0.0	3.1	3.2	1.0

3.3 Air filtration service

3.3.1 PM_{10} removal Ecosystem Service potential

The spatial distribution of removal efficiency potential (kg/ha) for PM_{10} is shown in Figure 4. Broadleaf FG displayed the highest removal efficiency for the spring (16.3 kg/ha) and summer (11.7 kg/ha). However, the removal efficiency of broadleaf forests drastically decreased in autumn (2.48 kg/ha) and winter (0 kg/ha). Instead, the PM_{10} removal efficiency of conifers showed peak values in summer (9.1 kg/ha) and spring (8.6 kg/ha), decreasing in autumn (3.09 kg/ha) and winter (2.48 kg/ha). Overall, yearly total PM_{10} removal efficiency was higher for broadleaf (30.48 kg/ha) than coniferous forests (23.27 kg/ha). Contrarily, the total annual PM_{10} removed by the FGs showed the highest value for conifers (3606.22 Mg) then broadleaf (82.3 Mg) due to their huge area extent. In addition, by analysing the ecosystem service lost due to the hurricane, findings showed a decreased annual PM_{10} removal of 24.62 Mg for conifers and 0.26 Mg for broadleaf. The efficiency removal potential for FG, season and on an annual basis are summarized in Table A2 in the supplementary material.

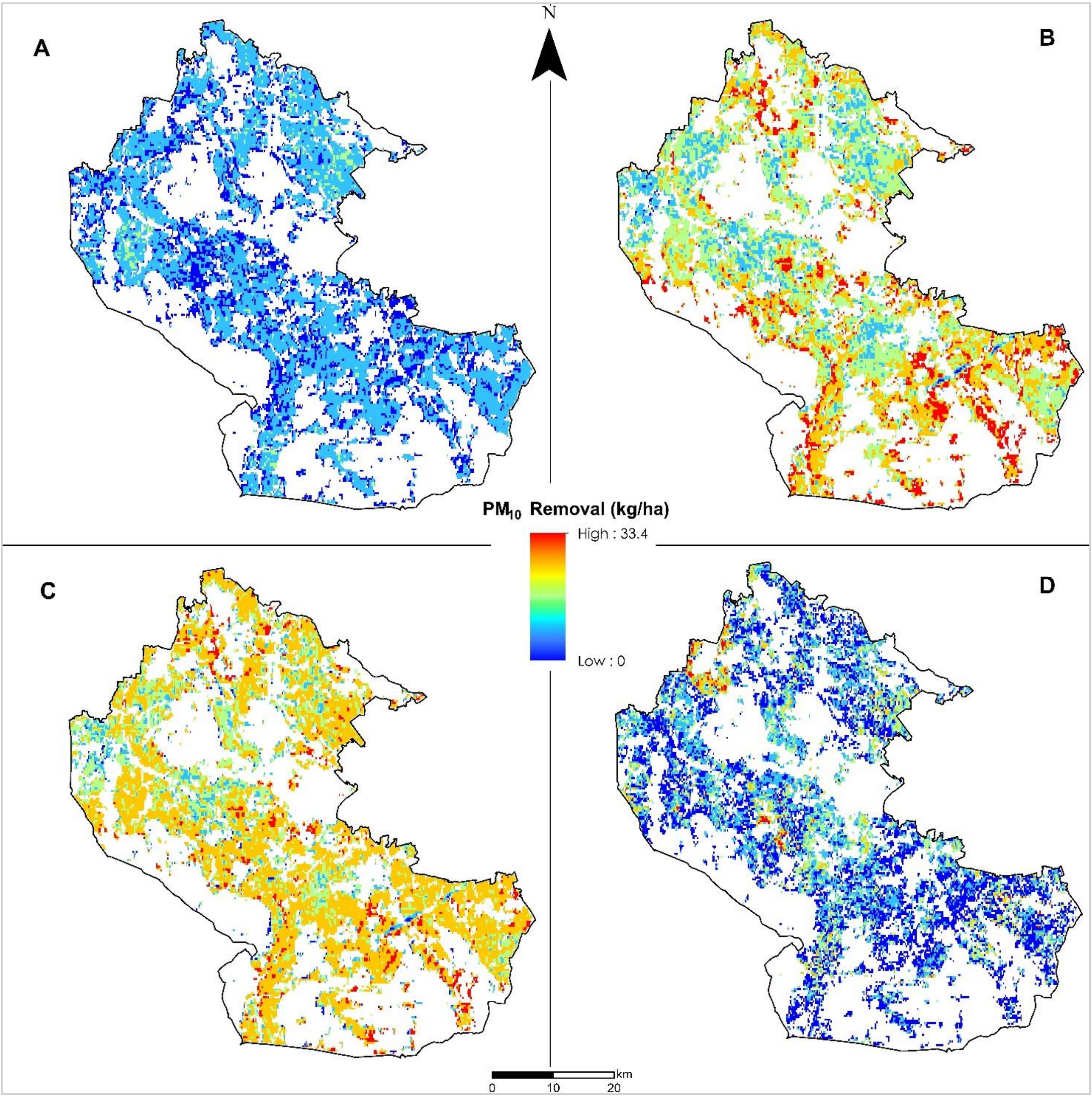

Figure 4. Spatial distribution of removal efficiency potential (kg/ha) for PM_{10} divided by seasons (A = Winter; B =Spring; C = Summer; D = Autumn).

3.3.4 *$PM_{2.5}$ removal Ecosystem Service potential*

Figure 5 shows the spatial distribution of removal efficiency potential (kg/ha) for $PM_{2.5}$. Broadleaf FG displayed the highest removal efficiency for the spring season (4.18 kg/ha) and summer (2.72 kg/ha). In comparison, it decreased in autumn (0.56 kg/ha) and winter (0 kg/ha), according to the vegetational period. The $PM_{2.5}$ removal efficiency of conifers showed the highest similar value in summer (1.94 kg/ha) and then in spring (1.92 kg/ha), decreasing in autumn (0.72 kg/ha), and winter (0.56 kg/ha). Although the better efficiency in removing $PM_{2.5}$ referred to broadleaf (7.46 kg/ha) compared to conifers (5.14 kg/ha), the total $PM_{2.5}$ potentially removed by the FGs showed the highest value for conifers (821.87 Mg) rather than broadleaf (17.65 Mg). This finding reflects the greater spatial extent of conifers. The efficiency removal potential for FG, season and on an annual basis are summarized in Table A2 in the supplementary material. In addition, by analysing the ecosystem service lost due to the hurricane, findings showed a decreased annual $PM_{2.5}$ removal of 9.12 Mg for coniferous while 0.06 Mg for broadleaf forests.

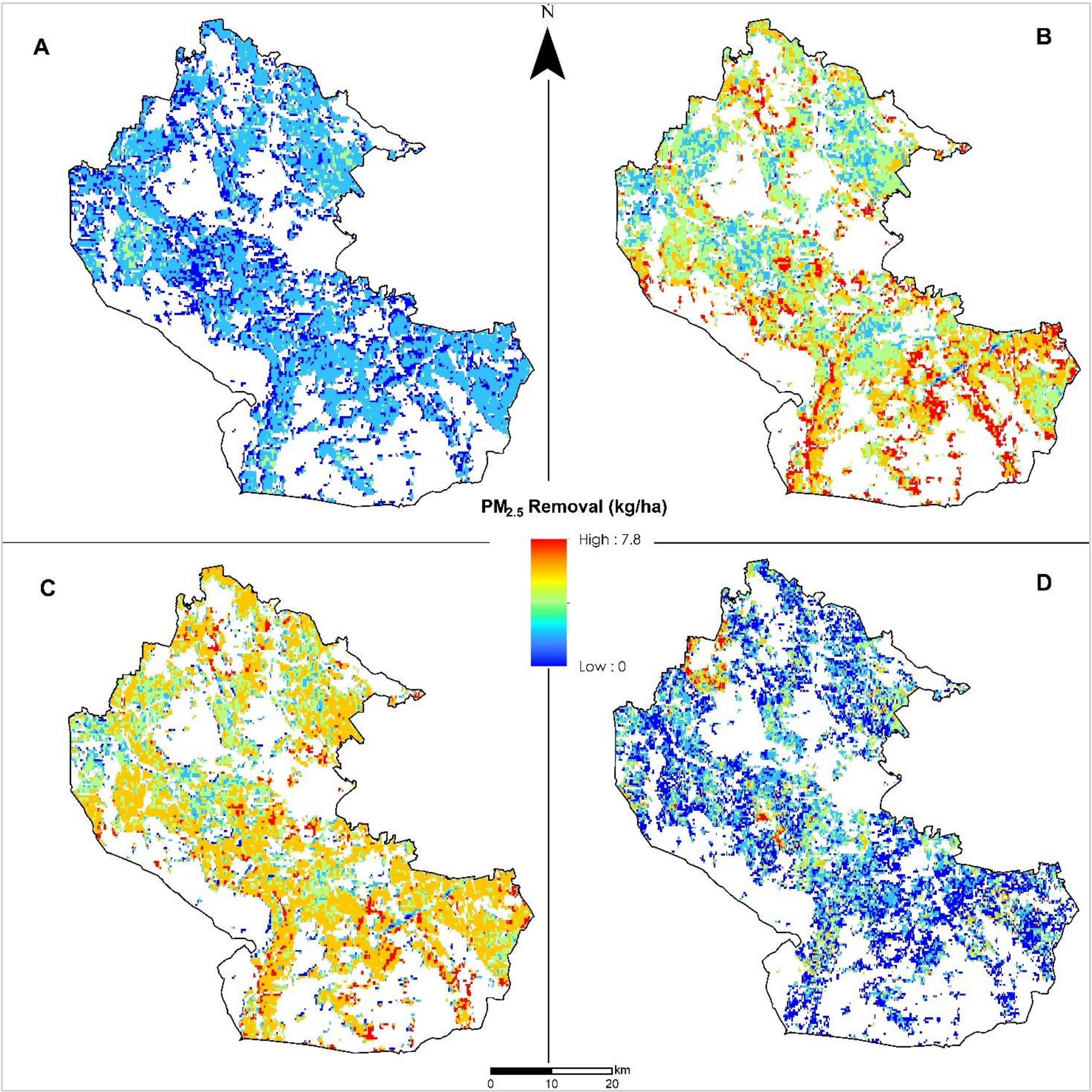

Figure 5. Spatial distribution of removal efficiency potential (kg/ha) for $PM_{2.5}$ divided by seasons (A = Winter; B =Spring; C = Summer; D = Autumn).

3.3.5 NO_2 removal Ecosystem Service potential

The spatial distribution of removal efficiency (kg/ha) for NO_2 is shown in Figure 6. Broadleaf FG displayed the highest removal efficiency for autumn (3.15 kg/ha), decreasing for spring (2.44 kg/ha) and summer (2.21 kg/ha). The NO_2 removal efficiency of conifers followed a similar pattern in all seasons, with the highest value in autumn (0.47 kg/ha) followed by winter (0.38 kg/ha), spring (0.36 kg/ha) and summer (0.32 kg/ha). Although the better efficiency potential in removing NO_2 was higher in broadleaf (7.8 kg/ha) compared to conifers (1.53 kg/ha), the total NO_2 annually removed by the

FGs showed the highest value for coniferous (273.61 Mg) rather than broadleaf forest (49.15 Mg) because of the higher spatial extent. The efficiency removal potential for FG, season and on an annual basis are summarized in Table A2 in the supplementary material. In addition, by estimating the ecosystem service lost due to the hurricane, findings showed a decreased annual NO_2 removal of 22.13 Mg for coniferous and 0.25 Mg for broadleaf forests.

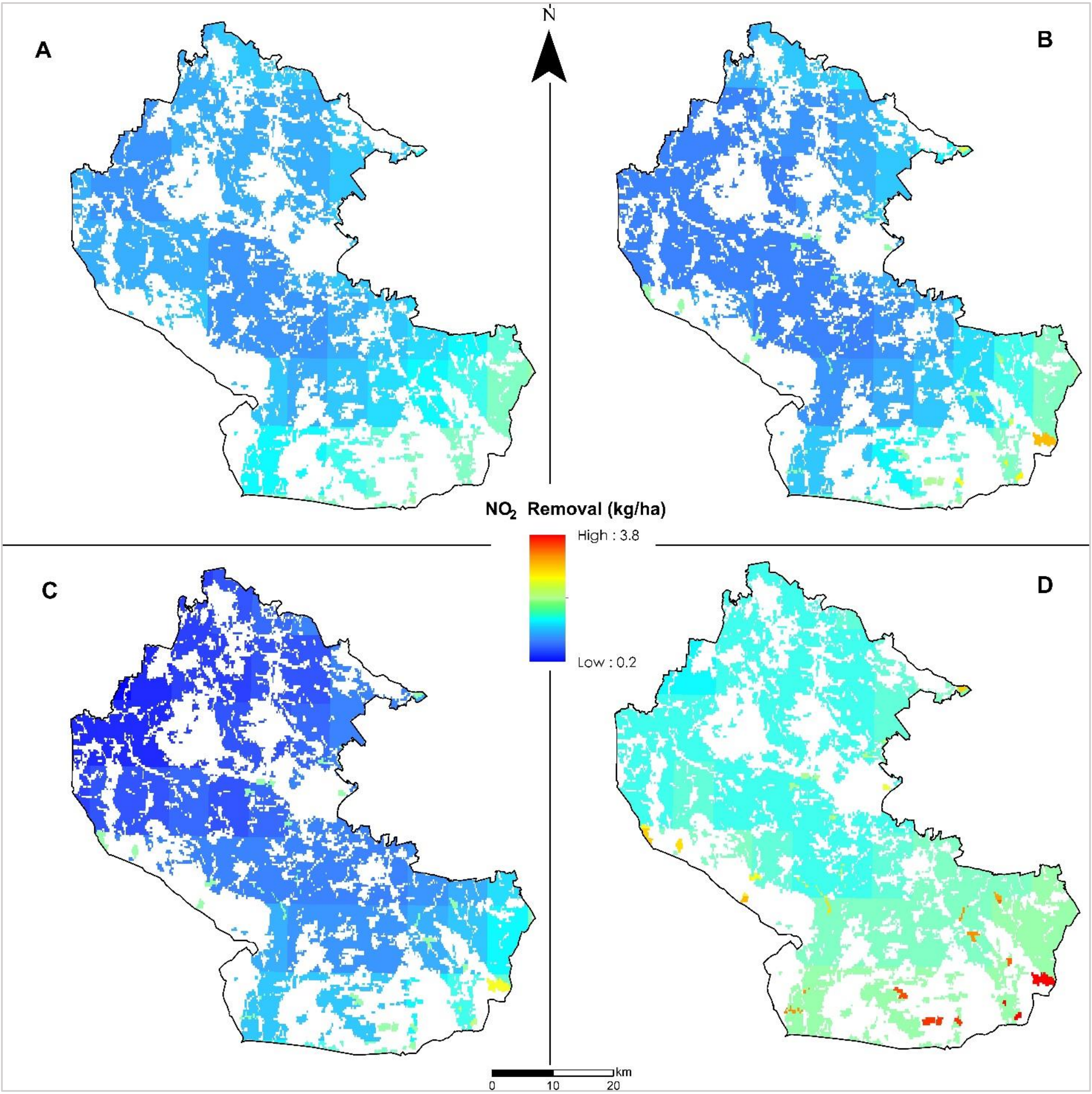

Figure 6. Spatial distribution of removal efficiency potential (kg/ha) for NO_2 divided by seasons (A = Winter; B =Spring; C = Summer; D = Autumn).

3.3.6 O_3 removal Ecosystem Service potential

The spatial distribution of removal efficiency potential (kg/ha) for O_3 is shown in Figure 7. Broadleaf FG displayed the highest removal efficiency for the summer season (37.59 kg/ha) and spring (28.53 kg/ha), reaching 14.02 kg/ha in autumn. Instead, the O_3 removal efficiency of conifers showed peak values in summer (6.28 kg/ha) and spring (4.54 kg/ha), decreasing in autumn (2.5 kg/ha) and winter (1.9 kg/ha). Although the annual efficiency in removing O_3 was higher in broadleaf (80.14 kg/ha) compared to conifers (15.22 kg/ha), the total O_3 annually removed by the FGs was higher for coniferous (2707.94 Mg) rather than broadleaf forest (503.77 Mg). This was according to the dominant area of coniferous forest in TFBR. The efficiency removal potential for FG, season and on an annual basis are summarized in Table A2 in the supplementary material. In addition, by estimating the ecosystem service lost due to the hurricane, findings showed a decreased annual O_3 removal of 237.78 Mg for conifers and 2.58 Mg for broadleaf.

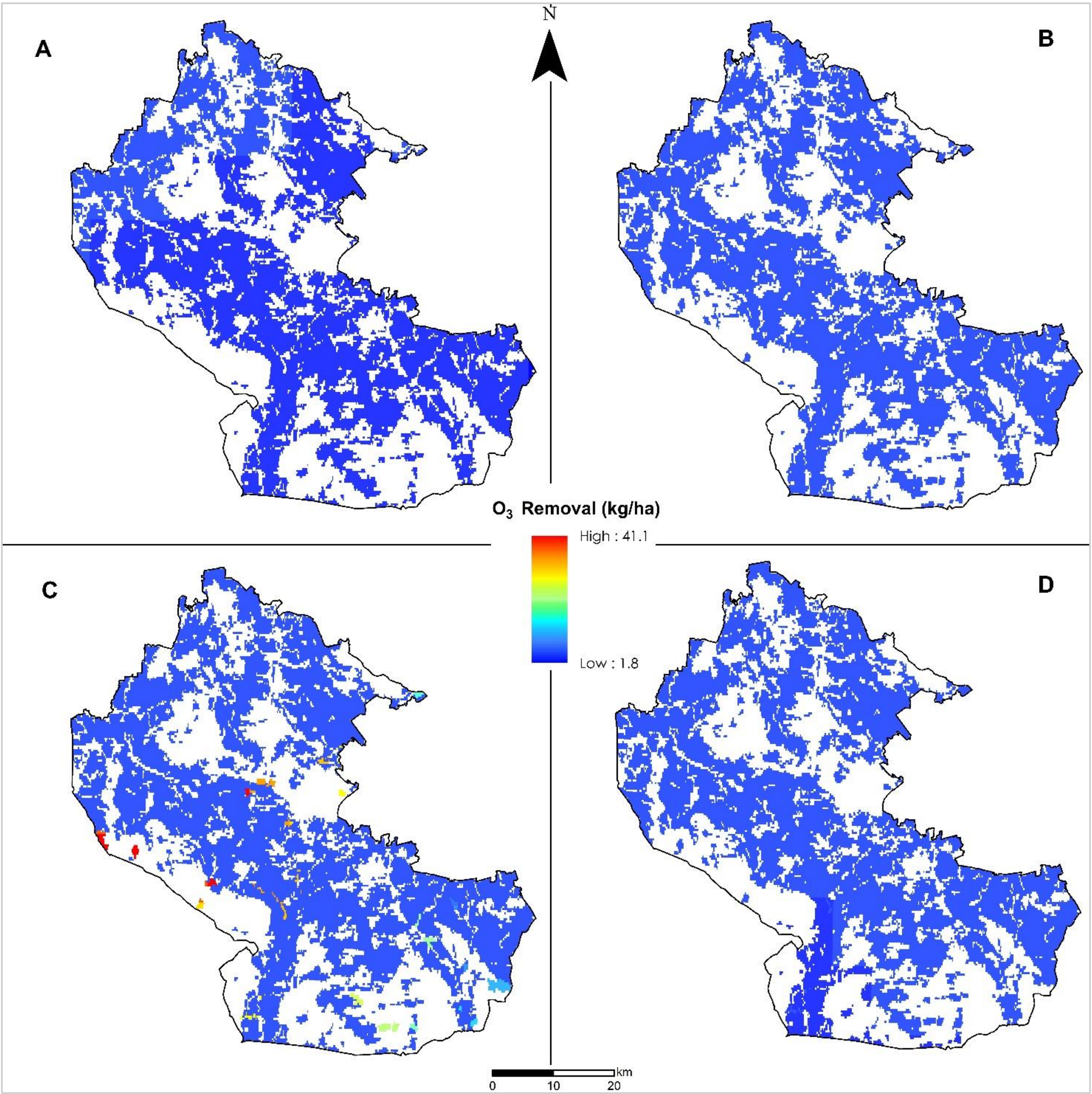

Figure 7. Spatial distribution of removal efficiency potential (kg/ha) for O_3 divided by seasons (A = Winter; B =Spring; C = Summer; D = Autumn).

Overall, the value of the air filtration service before the hurricane in 2017 for coniferous was estimated as 7,409.64 Mg/year and 653 Mg/year for broadleaf forest, while the total air filtration service potential was 8,062.51 Mg/year for the entire TFBR. Furthermore, the service lost for coniferous forests was estimated as 293.65 Mg and 3.15 Mg for deciduous forests, while the total air filtration service lost was estimated as 296.8 Mg for the whole TFBR (Tab. 2).

Table 2 – Estimates of biophysical values of air filtration service potential in the TBFR before the hurricane in 2017 and after.

Type of service	Pollutant indicators	Coniferous forests (Mg)		Broadleaf forests (Mg)		Total supply (Mg)	
		Before the hurricane	2018 (ES Lost)	Before the hurricane	2018 (ES Lost)	Before the hurricane	2018 (ES Lost)
Air filtration	PM_{10}	3,606.22	-24.62	82.3	-0.26	3,688.52	-24.88
	$PM_{2.5}$	821.87	-9.12	17.65	-0.06	839.52	-9.18
	NO_2	273.61	-22.13	49.15	-0.25	322.76	-22.38
	O_3	2,707.94	-237.78	503.77	-2.58	3,211.71	-240.36
Total service		7,409.64	-293.65	652.87	-3.15	**8,062.51**	**-296.8**

3.3.7 Monetary evaluation of air filtration service potential

The yearly monetary evaluation of the pollutants potentially removed by forests in TFBR is reported in Table 3. The highest value was shown for O_3 (391 M€/y) while the lowest for NO_2 (5.2 M€/y), both accounted for the period before the hurricane in 2017. The total monetary evaluation in the TFBR before the hurricane in 2017 resulted in about 791 M€/y. The money lost due to the hurricane disaster affecting forest ecosystems accounted for 7.23 M€/y.

Table 3 – Estimates of the monetary values of the air filtration service potential in the TBFR before the hurricane in 2017 and after.

Type of service	Pollutant	Coniferous forests (M€/yr)		Broadleaf forests (M€/yr)		Total Economic Value (M€/yr)	
		Before the hurricane	2018 (ES Lost)	Before the hurricane	2018 (ES Lost)	Before the hurricane	2018 (ES Lost)
Air filtration	PM_{10}	274.4	-1.9	6.3	-0.02	280.7	-1.88
	$PM_{2.5}$	111.9	-1.2	2.4	-0.01	114.3	-1.19
	NO_2	4.4	-0.4	0.8	0	5.2	-0.4
	O_3	383.2	-3.8	8.1	-0.04	391.3	-3.76
Total service		773.9	-7.3	17.6	-0.07	**791.5**	**-7.23**

4. Discussion

The presented study provides a comprehensive overview of the application of the SEEA-EA framework for the assessments of forest ecosystem extent, condition, and a set of regulating ecosystem services related to forest role in atmospheric pollutants removal. We also focused on the ES lost due to a hurricane crossing the TFBR in 2017.

The analysis of forest ecosystem extent indicators revealed that forests were the dominant ecosystem type before and after a hurricane in 2017. The dominant functional group was coniferous forests. Notably, the most significant changes in extent between the investigated periods occurred in coniferous forests and transitional woodland shrubs. Coniferous forests decreased (- 4.75%), while transitional woodland shrubs increased (5.09%), highlighting the impact of the hurricane. Post-natural disaster successional dynamics often exhibit an increase in transitional woodland-shrub communities. In our case, this ecological response reflects the natural regeneration processes initiated within the forest ecosystem following storm-induced disturbances (Hesslerova et al., 2018; Zoncova et al., 2020).

In the context of the ecosystem condition, within the abiotic indicators, the atmospheric pollutants concentration was assessed. Findings revealed that only $PM_{2.5}$ and PM_{10} exceeded the limit average concentration imposed by the WHO (Tab. 1). Overall, pollutant concentrations were consistent with the expected pollutant patterns with PM_{10}, $PM_{2.5}$, and NO_2 higher in the autumn and winter seasons, while O_3 peaked during the spring and summer (Rogula-Kozłowska et al., 2013; Li et al., 2017; Voiculescu et al., 2020; Yildizhan et al., 2024). However, concentrations of $PM_{2.5}$ and PM_{10} were found to be higher in autumn (20.2 and 25.4, respectively) than in winter (17.9 and 22.7, respectively), contrary to the common pattern of higher winter concentrations. Such results could be obtained due to particular meteorological conditions that affect e.g. the heating intensity.

In the case of biotic indicators, the leaf area index (LAI) is one of the core parameters reflecting the growth status of vegetation (Gao et al., 2024). Leaf area index (LAI) is an important parameter related to carbon, water, and energy exchange between canopy and atmosphere and is widely applied in process models that simulate production and hydrological cycles in forest ecosystems (Zhu et al., 2016). Our results demonstrated that LAI reflects the forest phenology pattern, which is consistent with the findings of other authors (Liu et al., 2015; Zhu et al., 2016; Gao et al., 2024). LAI showed the highest values in spring and summer for both the FGs. However, conifers showed a consistent LAI for all the seasons, while broadleaf drastically decreased the LAI values in autumn, reaching zero in winter. In this way, LAI can affect in different seasons the PM removal ability of the forest ecosystems (Nowak et al., 1994, Fusaro et al., 2017).

The assessment of ES focused on regulating services provided by forests, particularly the air filtration service. The ability of the forest to remove PM_{10}, $PM_{2.5}$, NO_2, and O_3 was assessed. Coniferous and deciduous forests were the FGs selected for the analyses, being the main forest types in the TFBR (56.06 % conifers; 0.77% broadleaf). As mentioned above, conifers cover the main area of the TFBR, facing the greater change due to the hurricane impact (- 15,236.02 ha), while broadleaf cover slightly decreased according to their substantial distribution (-17.12 ha). The removal efficiency by FGs was analysed for each season and on an annual basis. The spatial distribution of removal efficiency for pollutants highlighted variations depending on the LAI, vegetation period and pollutant concentration. Overall, deciduous trees proved to be the most efficient FG in removing pollutants in the vegetative period, while conifers' efficiency has been shown for the whole year. Such results are consistent with other studies that assessed the ability of conifers and broadleaf trees to remove pollutants (Manes et al., 2016; Marando et al., 2016; Sabastiani et al., 2021). Although the total removal efficiency was higher in deciduous broadleaf, the total annual air filtration service resulted in higher conifers FG for each pollutant due to the great area covered (see Tab. A2 in supplementary material).

The annual efficiency for PM_{10} and $PM_{2.5}$ resulted in higher deciduous FG than conifers for each pollutant. Although it is well-known that conifers are more efficient than broadleaf in adsorbing particulate matter due to the shape of their canopy and leaves (Chen et al., 2017), our findings are, in contrast, reporting the efficiency higher in deciduous forests. These differences likely result from the interplay of spatial concentration patterns and the distribution of tree species within the study area. Furthermore, an unexpected result was obtained in the seasonality of the efficiency removal. Although the highest pick of PM_{10} and $PM_{2.5}$ values was in the autumn and winter seasons, the efficiency resulted in higher in spring and summer. The reason could be attributed to the contribution of vegetation in releasing pollutant precursors. Indeed, Stafoggia et al. (2019) demonstrated the impact of vegetation on pollutant precursor concentrations within their modelling framework. Vegetation emits substantial quantities of PM precursors, such as biogenic volatile organic compounds (BVOCs). Furthermore, pollen, a component of coarse PM, may also contribute to elevated pollutant concentrations, particularly during warmer months when plant reproduction is active (Mucke et al., 2014). Furthermore, the highest efficiency in removing PM occurred in autumn rather than in winter, due to the highest pollutant concentration in the autumn months.

In the case of NO_2, results showed the highest values in autumn and winter, following the common ability of the FGs to remove the pollutants (Golay et al., 2022). However, autumn revealed the highest values according to the pollutant distribution in the TFBR. Lastly, O_3 outcomes reflected the higher ability of broadleaf FG to remove this atmospheric pollutant compared to conifers. In particular, the O_3 was higher in spring and summer when the photoperiod was at the maximum level. Furthermore, deciduous forests consistently demonstrated higher average values than coniferous forests across all seasons, except during winter when leaf senescence occurs in deciduous species. This disparity can primarily be attributed to the significantly higher stomatal conductance observed in broadleaf trees compared to conifers (0.24 and 0.04, respectively). However, the contribution of O_3 in winter and autumn is not significant due to the low daylight which is the driver of the O_3 formation.

The forest ES's ability to air pollutants removal is directly linked to the human well-being. Khaniabadi et al. (2017) found the excess mortality risk for cardiovascular diseases related to PM10, NO_2, and O_3. Most recent estimates indicated that in 2013 in EU-28, 16,000 premature deaths were attributable to ozone exposure (Nuvulone et al., 2018). Exposure to ozone is especially dangerous for children. Consistent evidence exists of small decreases in children’s lung function, even associated with very low levels of short-term ozone exposure. Long-term ozone exposure decreases both lung function and lung function growth in children (Holm and Balmes 2022). Maji et al. (2019) revealed that ozone exposure can lead to adverse respiratory effects in individuals, causing inflammation of the airways and difficulties in breathing, including pain and breathlessness during deep inhalation. Long-term exposure to ozone is considered a contributing factor to the development of asthma (Dewan and Lakhani 2024). Oxides of nitrogen (NOx) released into the atmosphere can react in the presence of solar irradiation, leading to additional ozone formation in the troposphere (Zhang et al. 2019). Vehicle-derived pollutants, as well as industrial emissions, simultaneously release deleterious fine-grained PM into the atmosphere. Fine PM, especially $PM_{2.5}$ and PM_{10}, are particularly deleterious to human health. Air pollution PM is an important environmental health risk factor for several respiratory and cardiovascular morbidity and mortality. Further, PM is inextricably linked with genotoxicity and mutations (Rai, 2015). Pathophysiological and epidemiological studies have demonstrated an association between $PM_{2.5}$ and respiratory diseases, cardiovascular diseases, and neurological disorders. The underlying mechanisms through which $PM_{2.5}$ adversely affects human health include the induction of oxidative stress, cytokine release, deoxyribonucleic acid (DNA) damage, altered gene expression, immune toxicity, inflammatory responses, and apoptosis (Sangkham et al., 2024).

The human well-being risk because of air pollution is in some way included in the monetary evaluation of ES (EEA, 2024). The assessment of ES highlighted the huge contribution of the TFBR in monetary terms. The economic value of the air filtration service was higher in conifers FG (773.9 M€) compared to the broadleaf FG (17.6 M€), reflecting the great area extent of conifers. According to our results, the total economic value of the air filtration service resulted in 791 M€/year. In addition, changes in ES supply due to natural disasters were proved, highlighting how climate changes and related extreme events can compromise the provisioning of benefits to mankind. The ES lost due to the hurricane impact was assessed at 7.4 M€.

Overall, these findings have provided valuable insights into the SEEA-EA framework and its application for the implementation of the UNESCO-MAB goals.

5. Conclusions

The application of the SEEA-EA framework facilitated the integration of ecological and socio-economic aspects, aligning with the goals of the UNESCO-MAB programme. By integrating ecological and economic assessment, the complex interplay between ecosystems and human well-being was highlighted. The SEEA-EA framework emphasized the ability of trees to remove air pollutants and the risks related to their loss. The air filtration service is directly linked to human health and well-being, as it reduces exposure to harmful pollutants, mitigating respiratory problems and other health issues. Natural disasters such as hurricanes caused by climate changes negatively affect the condition and resilience of trees and their ability to provide ES, as occurred in the TFBR, posing serious risks to human health. Significant impacts are also evident in the monetary cost associated with their loss.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data to this article can be found online at https://doi. org/10.1016/.

Data availability

Data will be made available on request.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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4. DISCUSSION

4.1 Formation, complexity and efficiency of Natural Capital

In this doctoral thesis, GFs were used to investigate value, complexity and development of ecosystems. In the first part of the project, the thermodynamical GF, emergy and eco-exergy, were jointly applied to assess the value of NC stocks in three forest lakes characterized by different trophic states and developmental stages. Specifically, oligotrophic, mesotrophic, and eutrophic lakes were investigated, with the eutrophic lake affected by anthropogenic pressures. Emergy GF was applied to quantify the ecosystem's investment of matter and energy flows in supporting the generation of autotrophic and heterotrophic NC stocks. At the same time, eco-exergy GF was used to evaluate the organization and complexity underlying the NC stocks.

The eutrophic lake exhibited the highest emergy investment, attributable to nutrient inputs from human activities that significantly influenced NC formation. Particularly, the substantial influx of nitrogen and phosphorus from a nearby salmon farm drove the functional dynamics of the eutrophic ecosystem. In contrast, the NC formation in the oligotrophic and mesotrophic lakes, devoid of direct human inputs, was primarily driven by the chemical potential energy within precipitation. This result was aligned with typical forest lake dynamics, where ecological processes are influenced by external factors such as nutrient inputs from the surrounding forest (Staehr et al., 2010, 2012).

The eutrophic lake displayed the highest eco-exergy values by accounting for ecosystem and NC development and complexity. In particular, the results identified macrophytes and aquatic birds as the dominant taxa, in terms of biomass contribution within the eutrophic system. Furthermore, these taxa exhibited the highest beta values, indicating a greater genetic information content in terms of evolutionary history and key adaptation strategies. In the case of oligotrophic and mesotrophic lakes, macrophytes and zooplankton were the primary contributors to ecosystem structure.

Furthermore, the application of the eco-exergy/emergy ratio allowed us to investigate the efficiency with which these ecosystems organized matter and energy flows. Although the eutrophic system demonstrating the highest energy and eco-exergy values, only the lakes sustained by natural input flows (oligotrophic and mesotrophic) were more efficient in maintaining and developing ecosystem structures and organization (Bastianoni, 2002). Overall, in healthy ecosystems, energy flows through the trophic chain with a progressive dispersion, according to the second law of thermodynamics (Jorgensen & Svirezhev, 2004). In eutrophic lakes, the excess of nutrients led to biomass production that exceeded the system's capacity to utilize it effectively. The large amount of biomass produced (primarily by macrophytes and algae) is not efficiently transferred to secondary and tertiary consumers (fish, and aquatic birds) (Carpenter, 2005; O’Hare et al., 2018). This created a 'bottleneck' in the energy flow (Klemmer et al., 2020). Instead of being incorporated into animal tissues through predation, the energy is diverted towards bacterial decomposition (Feng et al., 2019; Ji et al., 2021). Aoki (1998) proposed an "entropy law for eutrophication," which suggests that entropy production in lake ecosystems increases as eutrophication progresses. This increase in entropy reflects the disorder and degradation of the ecosystem (Luo et al., 2017). Indeed, the increase in entropy is linked to a decrease in the ecosystem's ability to maintain its organization and function. This can lead to reduced biodiversity, decreased water clarity, and other negative ecological impacts (Palffy and Voros, 2019). In our case, the excessive nutrient load from the nearby aquaculture farm surpassed the carrying capacity of the eutrophic lake, compromising ecosystem balance and, consequently, its future organization and integrity.

Such results are aligned with several studies on eutrophic ecosystems. Yang et al. (2008) highlighted the effects of eutrophication due to human activities (e.g., aquaculture) that lead to imbalances in trophic chain and ecosystem degradation. Radbourn et al. (2019) described the effect of eutrophication in lakes, showing how external nutrient loads impact the ecosystem balance. Still, Sinclair et al. (2023) discussed the challenges of managing eutrophication in aquatic ecosystems caused by human-driven nutrient load, emphasizing risks to human well-being regarding ecological imbalance and decline in ES supply.

The jointly application of the thermodynamical GF implemented in the study was compared to biotic GF, in particular the biomass-based Shannon diversity index (Nielsen and Jorgensen, 2013). Findings showed that the values of the eco-exergy/emergy ratio were in line with the calculated biomass-based Shannon diversity index. Indeed, the highest diversity resulted in the mesotrophic lake, showing a positive correlation between the lake ecosystems’ efficiency and their capability to build biodiversity.

In general, emergy and eco-exergy GF have been widely used to investigate ecosystems. Emergy was applied to assess performance and carrying capacity of lakes in China (Zhong et al., 2018) or to evaluate the sustainability in lacustrine ecosystems, as well as the ES supply (Pan and He, 2011; Li et al., 2018; Zhong et al., 2019). Still, eco-exergy was used to assess ecosystem condition of lakes (Xu et al., 2012), also in combination with others ecological indicators (Zhang et al., 2016). Previous studies also suggest the joint application of emergy and eco-exergy for investigating the health status, organization level and efficiency of aquatic ecosystems (Bastianoni and Marchettini, 1997; Bastianoni, 2002; Marchi et al., 2012). In addition, the combination of emergy and eco-exergy methodologies was also used to assess NC in marine protected areas (Buonocore et al., 2020).

4.2 Ecosystem dynamic and identification of areas for conservation concerns

Dealing with the hypothesis, which assumed that ecosystem Natural Capital complexity can be affected by human activity and environmental parameters, and can change over time, the next part of the research addressed the application of GFs to assess temporal changes in NC stocks, to identify main drivers of changes and to identify areas of conservation interest in the central Mediterranean. Specifically, demersal NC stocks were quantified in both shelf and slope regions, and the analyses were conducted over the last fifteen years to illustrate the ecosystem dynamics. The eco-exergy GF was employed to quantify NC stocks from a thermodynamic perspective, measuring the chemical energy stored in organic matter and the genetic information embodied in living organisms. Our findings revealed a significant decline in demersal NC stocks over the 2005–2021 period. Carrying out the analyses by region, variations were primarily observed in the slope region with a significant trend, while no decline or significant trend was detected on the shelf. Among the examined taxa, bony fish principally contributed to the eco-exergy values, accounting for 62-74% of the total, largely due to their high biomass density and β value, which reflects their evolutionary history.

By employing a holistic accounting of the area (shelf and slope), variations occurred in the total eco-exergy on the shelf, with a decrease in the percentage of bony fish and an increase in cartilaginous fish. This shift towards k-strategy species, such as elasmobranchs (cartilaginous fish), suggested enhanced energy efficiency within ecosystems (Silow and Mokry, 2010), which was reflected in a slight increase in eco-exergy on the shelf in the last years. This trend aligned with observations by Falsone et al. (2022), who reported improved status for elasmobranch populations on the shelf, attributed to reduced fishing activities in the study area. Indeed, fishing efforts have decreased by 25% from 2004 to 2021. Nevertheless, Falsone et al. (2022) also documented a progressive shift in fishing patterns from shallow-water mixed fisheries to deep-water red shrimp fisheries, potentially contributing to the significant decline in eco-exergy on the slope.

Despite the overall reduction in regional fishing efforts, eco-exergy values have sharply decreased since 2011, indicating a decline in NC stocks. To elucidate the causes of this decline, potential ecological stressors (sea temperature, salinity, pH, and primary production) were investigated. A negative correlation between eco-exergy and sea temperature and a positive correlation with pH and primary production, were found. Sea temperature and pH variables also exhibited significant trends (positive and negative, respectively) in the SoS, consistent with progressive sea warming and acidification. Specifically, a shift in sea temperature anomalies from a negative to a positive phase was observed between 2010 and 2012, while the reverse occurred for pH anomalies, over a 2000-

2021 time series. These findings are consistent with Rubino et al. (2024), who examined the impact of rising sea temperatures on fish communities on the continental shelf, analysing the mean temperature of the catch (MTC). They reported that MTC decreased significantly with increasing depth and exhibited a step-wise dynamic in response to increasing water temperature. Notably, a rapid increase in MTC between 2005 and 2006 was followed by a sharp decrease between 2010 and 2012 within the 10-60 m depth range. The authors posited that ocean warming can lead to species redistribution and that fish communities may adapt to gradual temperature changes up to a threshold, beyond which abrupt shifts occur (Rubino et al., 2024). Primary production showed no significant trend in the SoS, but the significant positive correlation with eco-exergy reflected the ecological efficiency of the marine ecosystem. Reduced primary production may indicate a decline in the ecosystem's capacity to capture and convert solar energy into biomass, with a concurrent decrease in eco-exergy suggesting a reduction in energy flow through the food chain, impacting ecosystem health and stability (Silow and Mokry, 2010; Capuzzo et al., 2017). Recent decades have seen numerous studies documenting abrupt regime shifts in both oceanographic parameters and biological communities in the Mediterranean Sea. Conversi et al. (2010) reported a regime shift in oceanographic variables and planktonic assemblages in the western Mediterranean during the 1980s, while Vasilakopoulos et al. (2014) identified an ecosystem reorganization in fisheries resources due to sea warming across the Mediterranean over the past 30 years. Damalas et al. (2021) documented environmental step-changes in the Aegean Sea from 1966 to 2017, noting that while the biological system showed resilience until 1991, climate-driven regime shifts led to an intermediate state from 1992 to 2002, followed by a new state from 2003 to 2016. Particularly relevant are the findings of Sguotti et al. (2022), who studied the fish and macroinvertebrate community of the Northern Adriatic Sea over 40 years, using commercial fishing landings data. They identified three distinct shift points, two of which (1987 and 1997) aligned with known large-scale ecological reorganizations (Conversi et al., 2010; Möllmann et al., 2015), and a novel change point in 2012, likely due to combined effects of increased water temperature, changes in primary production, and/or fishing pressure. Furthermore, the Shannon index biotic GF was assessed, revealing no significant trend overtime. However, this analysis was crucial for identifying areas of high NC and diversity, designated as conservation concern areas within the study region. A previous study (Garofalo et al., 2007) already highlighted a persistent biodiversity hotspot for demersal resources, likely attributable to offshore banks of volcanic or sedimentary origin, located primarily in the euphotic zone (0-100 m), which supports diverse species and habitats of conservation interest (Consoli et al., 2021). These banks naturally constrain bottom trawling, reducing seafloor abrasion, a major threat to bottom habitats (Paramana et al., 2024). However, hotspots of discarded or lost fishing gear have been found near these rocky banks (Garofalo et al., 2020), as they are productive areas attracting intensive fishing. According to Altobelli et al. (2017), these habitats, despite showing both degraded and pristine areas, remain critical for sustaining pelagic and benthic production.

Overall, this study provided valuable insights into demersal NC stocks and their temporal dynamics. The thermodynamic eco-exergy GF proved to be a sensitive indicator of ecosystem functioning and complexity in response to environmental variables. At the same time, the Shannon index, though important for diversity assessment, does not fully capture ecosystem dynamics. However, their combined application was essential for identifying highly ecologicalcally valuable areas, crucial for policymakers in supporting strategic conservation and sustainable fishery management within marine spatial planning. In general, it is imperative to monitor and quantify NC stocks over time due to their provision of essential goods and services for human life. Our study area, significantly impacted by human activities yet ecologically and socio-economically vital, exemplifies this need. Indeed, a decline of NC can be understood as a thermodynamic response to environmental stressors, particularly those driven by human activities such as climate change and resource exploitation (Nielsen et al., 2020; Swedan, 2022). From a thermodynamic point of view, ecosystems work as open systems that exchange energy and matter with their surroundings, operating at an optimum point far from the thermodynamical equilibrium. External drivers as consequences of climate change can modify these patterns and, if ecosystems are not able to resist at these perturbations (finding another operating point), the systems collapse being not capable of maintaining their structures and functions and the provisioning of benefits (Nielsen et al., 2020; Swedan, 2022).

4.3 Ability of ecosystems in ensuring human well-being and associated risks due to their loss

The next part of the project was dedicated to testing the hypothesis that variation in ES supply can be caused not only by human activity but also by intense natural disasters. The research assessed the capacity of ecosystems to provide essential benefits for human well-being and the associated risk of their loss due to natural disasters in a Biosphere Reserve (BR). Specifically, implementing the internationally standardized System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA-EA) framework (Unite Nation et al., 2021), the study was carried out initially accounting for the extent and condition of forests within the BR, and subsequently assessing a set of regulating ES. In particular, the role of forests in removing atmospheric pollutants was investigated in both biophysical and monetary terms, focusing on the ES loss resulting from a hurricane.

The extent analyses revealed the forest structure, primarily composed of conifers and broadleaf functional groups (FGs). Assessing the impacts of the hurricane on forest composition, it was demonstrated that conifers experienced the greatest damage, with a loss of 4.75%. Concurrently, transitional woodland shrubs exhibited an increased cover (+5.09%), reflecting the natural forest response to storm-induced disturbance through successional dynamics.

Subsequently, the forest ecosystem condition revealed that quantified abiotic indicators, i.e. the atmospheric concentrations of PM_{10}, $PM_{2.5}$, NO_2, and O_3 aligned with expected patterns, with PM_{10}, $PM_{2.5}$, and NO_2 peaking in autumn and winter, while O_3 peaked during spring and summer. However, PM_{10} and $PM_{2.5}$ exceeded the World Health Organization thresholds (WHO, 2021), raising concerns for human well-being.

Regarding biotic indicators, the Leaf Area Index (LAI) was selected as a key parameter for assessing tree status, given its involvement in all ecological processes and functions that determine the ecological integrity of forest systems (Gao et al., 2024). In particular, the LAI of the main FGs was quantified. Our results demonstrated that LAI reflected the forest phenology pattern, consistent with findings from other studies (Liu et al., 2015; Zhu et al., 2016; Gao et al., 2024). LAI exhibited the highest values in spring and summer for both FGs. However, conifers maintained a consistent LAI across all seasons, while broadleaf species showed a substantial decrease in LAI during autumn, reaching zero in winter. Thus, LAI influences the PM removal capacity of forest ecosystems differently across seasons (Nowak et al., 1994; Fusaro et al., 2017).

Accounting for forest extent and condition was a crucial step for assessing ES supply. The ES evaluation focused on regulating forest services, offering insights into ecological functions and benefits for humans. Specifically, the forest's ability to remove air pollutants (PM_{10}, $PM_{2.5}$, NO_2, and O_3) was evaluated, highlighting its role in enhancing ecological and socio-economic systems. Furthermore, ES losses following the hurricane impact were quantified. Conifers and broadleaf FGs were selected for analysis, representing the primary forest types (56.06% conifers; 0.77% broadleaf).

The spatial distribution of pollutant removal efficiency revealed variations depending on LAI, the vegetation period, physiological parameters, and the pollutant concentration. Overall, broadleaf species demonstrated the highest efficiency in removing pollutants during the vegetative period, while conifers exhibited efficiency throughout the year. These results align with other studies assessing the pollutant removal capacity of conifers and broadleaf trees (Manes et al., 2016; Marando et al., 2016; Sabastiani et al., 2021). However, differing patterns emerged based on the pollutant and FG physiology, with some contrasting results. Although conifers are generally considered more efficient in adsorbing particulate matter due to their canopy and leaf morphology (Chen et al., 2017), the annual efficiency for PM_{10} and $PM_{2.5}$ was higher in broadleaf species. These differences likely stem from the interplay of spatial concentration patterns and tree species distribution within the study area. Furthermore, an unexpected result was observed in the seasonality of removal efficiency. Despite the peak PM_{10} and $PM_{2.5}$ values occurring in autumn and winter, efficiency was higher in spring and summer. This discrepancy may be attributed to the phenological parameters that affect the model, including LAI and vegetative period which are higher in spring and summer seasons.

In the case of NO_2, results showed the highest values in autumn and winter, consistent with the FGs' general ability to remove pollutants (Golay et al., 2022). However, autumn exhibited the highest values, reflecting the pollutant distribution within the BR. O_3 results indicated a higher removal capacity in broadleaf species compared to conifers. Specifically, O_3 concentrations were higher in spring and summer, coinciding with maximum photoperiod. Deciduous forests consistently demonstrated higher average values than coniferous forests across all seasons, except winter due to leaf senescence. This disparity primarily results from the significantly higher stomatal conductance in broadleaf trees than conifers (0.24 and 0.04, respectively). However, the contribution of O_3 removal in winter and autumn is insignificant due to low daylight, which drives O_3 formation.

The assessment of regulating ES and applying the SEEA-EA framework underscored the significant contribution of natural systems to human well-being and the risks associated with their loss due to natural disasters. By monitoring and quantifying extent and condition, the SEEA-EA allows for the determination of ecosystem ecological integrity, and the state and development of NC stocks. Ecosystems in good status and health are capable of continuously providing ES, supporting society and ensuring human well-being.

The removal of atmospheric pollutants can be regarded as a pivotal GF, especially when examining its human and ecological implications. Noteworthy are the negative effects of pollutants to mankind and environments. Due to their minute size, PM penetrates deep into the respiratory system, inducing irritation and inflammation, and exacerbating pre-existing respiratory conditions such as asthma and bronchitis. Prolonged exposure to these particles is also associated with increased risks of cardiovascular diseases, stroke, and lung cancer (Xing et al., 2016; Manisalidis et al., 2020). Similarly, NO_2 irritates the respiratory tract, leading to coughing, breathing difficulties, and heightened susceptibility to respiratory infections. Chronic exposure to NO_2 has been linked to the development of asthma in children and the worsening of respiratory ailments in adults, in addition to cardiovascular damage (Gillespie-Bennett et al., 2011; Krzyzanowski, 2022). Ground-level O_3, a potent respiratory irritant, causes coughing, chest pain, breathing difficulties, and reduced lung function. This pollutant also aggravates asthma and other chronic respiratory diseases (EPA, 2024; Krismanuel and Hairunisa, 2024).

Beyond human health, these pollutants exert detrimental effects on ecosystems. PM settles on foliage, reducing the ability to capture light for photosynthesis and increased temperature of the leaf (Mohapatra and Biswal, 2014). It also contributes to soil and water acidification, harming vegetation and aquatic ecosystems (Grantz et al., 2003; Singh et al., 2016). NO_2 contributes to the acidification of soil and water, thereby damaging ecosystems and fostering ground-level ozone formation, which adversely affects vegetation (Graf-Jaccottet and Jaunin1 1998; Ok et al., 2008; Wang et al., 2022). Ozone damages plant leaves, diminishing the vegetation growth, and renders plants more vulnerable to diseases and pests (Grulke and Heath, 2020).

In this context, quantifying the role of vegetation in air pollutant reduction is crucial for informing decision-makers responsible for implementing of strategies aiming to expand green spaces and, consequently, improve human well-being. The ES assessment highlighted the substantial contribution of the BR in monetary terms. The economic value of the air filtration service was higher for coniferous FGs (773.9 million euros) compared to broadleaf FGs (17.6 million euros), reflecting the larger area extent of conifers. The total economic value of the air filtration service was estimated at 791 million euros per year.

Furthermore, changes in ES supply due to natural disasters were demonstrated, highlighting how climate change and related extreme events can compromise the provision of benefits to humanity. The ES loss due to the hurricane impact was assessed at 7.4 million euros.

5. CONCLUSION

The presented research proved the application of thermodynamic goal functions to be a valuable tool for evaluating ecosystems' complexity, dynamics, and efficiency. These indicators can effectively capture the intrinsic value of natural systems, offering insights beyond traditional economic assessments. In addition, thermodynamic goal functions were revealed to be sensitive indicators in capturing ecosystem changes due to environmental and human stressors.

The research demonstrated that the employing of broad methodological approaches to account for the spectrum of ecosystem benefits, costs, and impacts as the System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA-EA) framework enables the ecological and economic assessment of ecosystem services while also facilitating the quantification of the socio-economic risks caused by ecosystem services loss due to natural disasters.

The integration of biophysical and economic perspectives to achieve a comprehensive understanding of ecosystem value resulted to be crucial for highlighting the contribution of ecosystems to human well-being. In addition, these integrated approaches are helpful for the incorporation of the value of nature into decision-making processes.

In conclusion, this study provided a more comprehensive framework for monitoring and assessing natural capital and ecosystem services.

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APPLYING GOAL FUNCTIONS FOR NATURAL CAPITAL STOCK CHANGE ASSESSMENTS IN MARINE ECOSYSTEMS

Supplementary material

U. Grande, E. Buonocore, F. Fiorentino , P.P. Franzese, V. Lauria, A. Piernik, E. Sabatella, D. Scannella, S. Vitale, G. Garofalo

Table S1. Biomass density (kg/m^2) for the different taxonomic groups and time intervals (2005-2009; 2010-2015; 2016-2021) in shelf and slope in Geographical Sub-area 16 of the Mediterranean Sea.

		Shelf	
Taxonomic Groups	2005-2009	2010-2015	2016-2021
Bony fish	1276.03	995.76	864.18
Cartilaginous fish	364.38	396.02	427.62
Crustaceans	39.02	77.65	42.27
Cephalopods	151.71	171.72	114.08
		Slope	
Bony fish	733.95	546.99	418.08
Cartilaginous fish	271.87	211.39	164.40
Crustaceans	112.63	98.11	61.49
Cephalopods	48.48	57.11	48.23

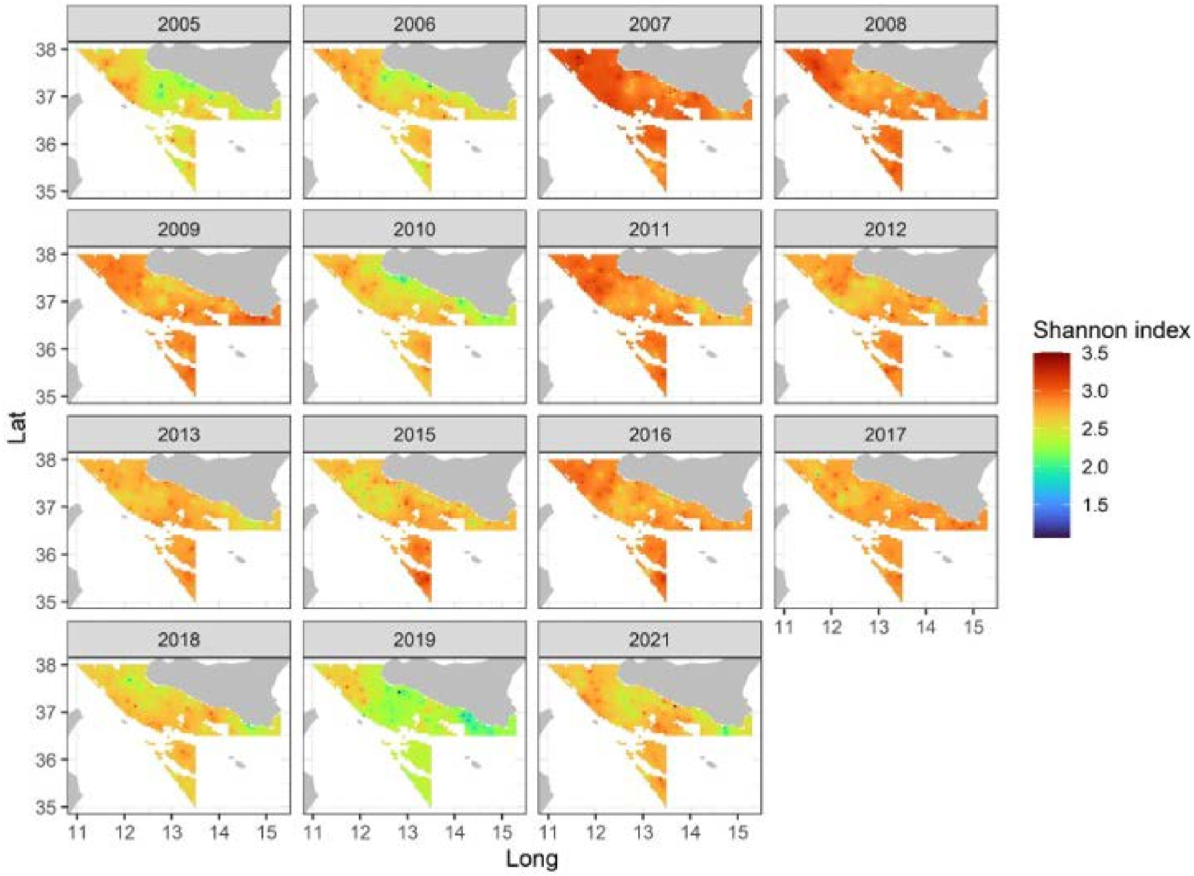

Figure S1 – Annual distribution maps of the Shannon diversity index in Geographical Sub Area (GSA) 16.

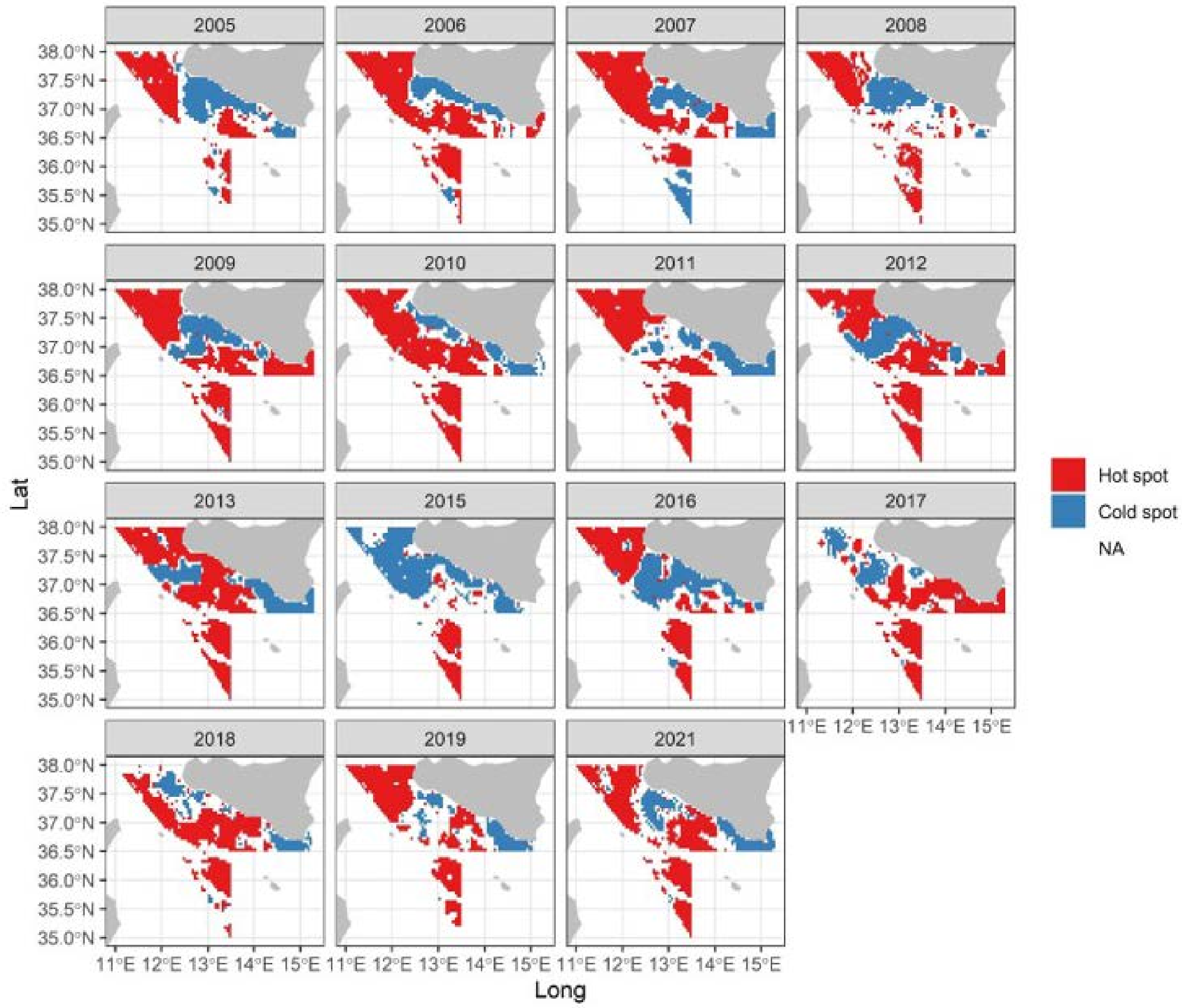

Figure S2 – Annual maps of hotspots and coldspots for the Shannon diversity index in Geographical Sub Area (GSA) 16.

Assessing forest ecosystem assets and services based on an international statistical standard

Umberto Grande, Kevin Husein, Lorenza Nardella, Dariusz Kaminski, Elvira Buonocore, Pier Paolo Franzese, Agnieszka Piernik

Supplementary material

Table A1 - CORINE Land Cover (CLC) nomenclature and classification based on the IUCN Global Ecosystem Typology referred to the study area.

Realm	**Terrestrial**					
Biome	**Temperate-boreal forests and woodlands (T2)**					
	Level 1	**Code 1**	**Level 2**	**Code 2**	**Level 3**	**Code 3**
Ecosystem type (T2.2)	Artificial surfaces	1	Urban Fabric	11	Discontinuous urban fabric	112
			Industrial, commercial and transport units	12	Industrial or commercial units	121
					Road and rail networks and associated land	122
					Airports	124
			Mine, dump and construction sites	13	Mineral extraction sited	131
			Artificial, non-agriculture vegetated areas	14	Sport and leisure facilities	142
	Agriculture areas	2	Arable land	21	Non-irrigated arable land	211
			Pastures	23	Pastures	231
			Heterogeneous agriculture areas	24	Complex cultivation patterns	242
					Land principally occupied by agriculture, with significant areas of natural vegetation	243
	Forest and semi-natural areas	3	Forest	31	Deciduous forest	311
					Coniferous forest	312
					Mixed forest	313
			Shrub and/or herbaceous vegetation associations	32	Transitional woodland-shrub	324
	Wetlands	4	Inland wetlands	41	Inland marshes	411
	Water bodies	5	Inland waters	51	Water bodies	512

Table A2 – Efficiency removal potential (kg/ha) of air pollutants before hurricane divided by year and season.

	Winter	**Spring**	**Summer**	**Autumn**	**Annual average**
		PM_{10}			
Coniferous	2.48	8.6	9.1	3.09	**23.27**
Broadleaf	0	18.3	11.7	2.48	**30.48**
Annual average	2.48	24.9	20.8	5.57	**53.75**
		$PM_{2.5}$			
Coniferous	0.56	1.92	1.94	0.72	**5.14**
Broadleaf	0	4.18	2.72	0.56	**7.46**
Annual average	0.56	6.1	4.66	1.28	**12.6**
		NO_2			
Coniferous	0.38	0.36	0.32	0.47	**1.53**
Broadleaf	0	2.44	2.21	3.15	**7.8**
Annual average	0.38	2.8	2.53	3.62	**9.33**
		O_3			
Coniferous	1.9	4.54	6.28	2.5	**15.22**
Broadleaf	0	28.53	37.59	14.02	**80.14**
Annual average	1.9	33.07	43.87	16.52	**159.65**