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Site description and planned environmental monitoring of the Prinos CCS site within the COREu project

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Abstract

COREu is a pioneering Carbon Capture and Storage (CCS) project funded by the European Community that aims to demonstrate key technologies across the entire value chain at study sites in southern and central Europe. As the largest Research and Innovation project in CCS ever funded by a European programme, COREu aims to move industry closer to implementing integrated, transnational projects that connect emitters with storage sites across Europe. The 4-year project started January 1st, 2024, and brings together over 40 partners from industry, research institutes, and universities across 13 countries. A total of four potential transport routes / storage areas (located in Poland, the Czech Republic, Ukraine and Greece) will be studied within COREu. While work on the first three sites will concentrate more on specific issues of local importance, a full-chain demonstration will be performed at the Kavala-Prinos site in NE Greece. Here, CO_2 will be injected at 2700-3000 m below the sea floor into a sand unit that underlies the presently exploited oil reservoir, meaning that the project is pure storage with no enhanced oil recovery. In addition to all the other work planned for this site, COREu will also conduct environmental monitoring to define baseline biogeochemical and biological conditions within the shallow sediments and overlying water column, both above the storage reservoir and along the route of a planned CO_2 pipeline. Work will be performed during 4 field campaigns, one per season, and will involve the measurement of numerous parameters important for offshore CCS monitoring. This will include, amongst others, atmospheric CO_2 values, the concentration and isotopic content of dissolved CO_2 and other gases, nutrients, and eDNA analyses of sediment and water to assess biodiversity variations. In addition to this discrete sampling, monitoring probes for the continuous measurement of dissolved CO_2 and temperature will be installed to provide a more detailed picture of natural temporal variability of this gas in the water column linked to climatic conditions and the associated biochemical system.

Keywords: COREu; Prinos; CCS; offshore; environmental monitoring; dissolved CO_2, eDNA

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1. Introduction

Europe has been a world-leader in the construction and operation of industrial-scale CCS sites, starting in 1996 with the inauguration of storage at Sleipnir and continuing in 2008 with Snøhvit and soon-to-be started projects like Northern Lights. However, all major sites to date are located in northern Europe, primarily offshore in the North or Barent Seas. If Carbon Capture and Storage (CCS) is to make an effective contribution to reduce European CO_2 emissions, sites will have to be built and operated throughout the Union. The EU-funded COREu project is focused directly on this issue, supporting the development of CCS routes and storage sites in Central and Southern Europe to increase overall capacity and reduce both transport distances and costs.

The main study site in COREu is located in NE Greece, near the city of Kavala (Fig. 1a). In addition to research addressing capture and transport technologies and economics, studies focusing on storage aspects will center on deep permeable layers near the base of the offshore Kavala-Prinos sedimentary basin. This basin is well characterized geologically due to extensive oil and gas exploration, followed by subsequent exploitation of the Prinos oil field and other smaller reservoirs. The Prinos field was first discovered in the 1970's, followed by initial production in 1981 and a peak daily production rate of 27,000 barrels of oil per day in 1985. More recently, a 340 km^2 broadband 3D seismic survey over the area in 2015 greatly improved the quality and resolution of the site's static models and represents a critical asset for future CCS development.

The Prinos field operator, Energean plc, obtained a CO_2 storage exploration permit in September 2022 and aims to receive a storage permit within the second quarter of 2024 and an operation license by the fourth quarter of 2025. The project, whose operation life is estimated to be 25 years, has been designed to avoid any Enhanced Oil Recovery (i.e., no increase in oil production) by storing in a reservoir beneath the hydrocarbon reservoir. Phase 1 of site development will aim for the injection of up to 1 Mt CO_2 per year, which is equivalent to about 10% of Greece's total industrial emissions. Eventual scaling up should allow for the injection of up to 3 Mt CO_2 per year. The Prinos site aims to serve local and remote parties in Greece and the region, capturing CO_2 from hard-to-abate economic activities, via Direct Air Capture technologies, shipping industry, etc. The project is an integral part of the Mediterranean CCS Strategic Plan developed by France, Italy and Greece and aims to create the first industrial- / commercial-scale CO_2 storage hub in the south-eastern Mediterranean.

Only a limited number of articles have been published looking into CCS-related issues at this site. Koukouzas et al. [1] present one of the first discussions in the scientific literature regarding the potential for CO_2 storage in the Kavala-Prinos Basin (amongst other Greek sites), examining 3 different storage options and highlighting the good overall potential of the site and the impermeable nature of the local faults. Koukouzas et al. [2] perform very simplistic modelling to assess the potential for leakage and discuss potential monitoring techniques that could be used to ensure site safety. Here the authors stress the need for baseline monitoring to define thresholds that could be used to help recognize leakage anomalies.

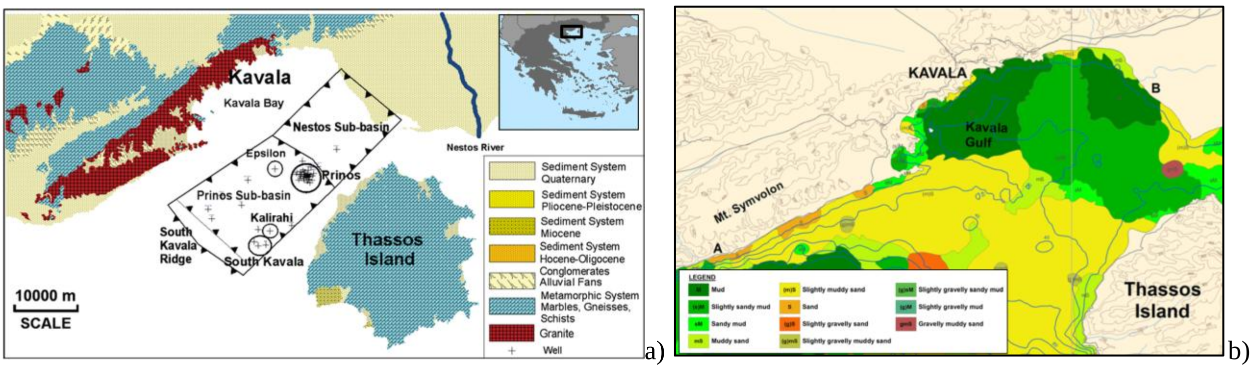

Fig. 1. a) Geological map of the study area showing the faulted boundaries of the Kavala-Prinos Basin, the Nestos and Prinos sub-basins, as well as the locations of the known oil reservoirs and drilled wells [3]. b) Map of surface sediments in the Gulf of Kavala (modified after [4]).

The issue of baseline monitoring of the Gulf of Kavala in general, and the area above the storage complex and planned CO_2 pipeline more specifically, is the focus of the present work. Four field campaigns will be performed within COREu, one per season, to determine the spatial and temporal variability of the present biogeochemical marine system prior to CO_2 injection. Priority will be divided between the monitoring of standard parameters that may change if a leak were to occur (e.g., pCO_2, pH), that may help separate biogenic from leakage anomalies (e.g., dissolved oxygen, nutrients) or that may help locate the origin of an anomaly (e.g., ADCP monitoring), as well as the measurement of parameters to assess overall ecosystem health and possible changes linked to CO_2 leakage (e.g., environmental DNA). An overview of the site characteristics plus a summary of planned monitoring work follows.

2. Site Description

The Gulf of Kavala is located in the North Aegean Sea and covers an area of 461 km^2 [5]. The gulf has an amphitheatric shape with a mean depth of 32 m and maximum depth of 60 m, and is connected to the North Aegean Sea to the east through the Thassos Passage and to the southwest across the Thassos Plateau [6]. The gulf coast can be divided into four major land-use areas, with beaches and tourist infrastructure along the west, the city of Kavala in the NW corner, industrial activity along the north, and nature reserves, fish-farming and agriculture along the east coast. The Nestos River, an important source of fresh water, sediments, and dissolved constituents, discharges further to the east after flowing through the agricultural fields of the Chrysoupolis Plain. Each of these activities / processes impacts the water quality and ecosystem health of the marine system in different ways, and thus can influence baseline values of the various parameters that will be monitored.

The city of Kavala has a population of about 70,000 people, with many employed in tourism, fishing, port activities, oil and gas, and public administration. Aside from surface run-off, port activities, and atmospheric deposition, the main impact of this populated area on the marine environment comes from two wastewater treatment plants (WWTP) that discharge into the gulf at a distance of about 1km from the shore in approximately 20 m deep water [5]. According to these authors, the main plant, just north of Kavala, discharges about 5.1 x 10^6 m^3/yr of treated effluent, while the second, located about 15 km to the south in Palio, discharges about 0.3 x 10^6 m^3/yr.

The main industrial activities to the east of Kavala include hydrocarbon processing and fertilizer production. The former, linked directly via a seafloor pipeline to the offshore oil and gas platforms that exploit the Prinos and South Kavala reservoirs, consists of facilities for sulfur and liquid natural gas (LNG) separation and crude oil treatment [7]. The latter involves facilities for the production of nitrogenous fertilizers with the production, storage and/or use of nitrogen, phosphorous, potassium, sulfuric acid, phosphoric acid, ammonia, nitric acid, etc. [8]. In addition, the production of phosphoric acid generates 4.5 times as much calcium sulfate by-product, also known as phosphogypsum, which is stored in open-air storage stacks near the coast [6]. Other industrial activities in this area include marble quarries and trade in inert materials.

A total of 9 lagoons are located along the east coast of the Gulf, isolated from the open water by sand bars and spits deposited by coastal currents bringing sediments from the Nestos River delta. These wetlands cover an area of 17 km^2 and act as a buffer for agricultural nutrients flowing seaward from the cultivated fields of the Chrisoupolis plain [9]. These lagoons are used for aquaculture and fish farming, with one lagoon (Vassova) producing over 30 t of fish per year [6]. In total, more than 30 aquaculture farms, producing fish and shellfish, are located in or on the edge of the Gulf. The wetlands, deltas and associated coastal areas of this region are protected under the Natura Conservation Act [10], as they are important for sea grass meadows and marine flora / fauna and provide nesting / foraging areas for migratory sea birds. Moreover, the Nestos Delta and Adjoining Lagoons are protected under the convention on Wetlands of International Importance, also known as “Ramsar Convention”. This area is also a part of the National Park of East Macedonia and Thrace.

In addition to aquaculture activities described above, the Gulf of Kavala is an important area for both commercial and recreational fisheries, especially for species such as European anchovy and sardine. Around 40 species, including crustacean, shellfish, squid and octopuses, sharks, rays and bony fish, are captured and the yearly total landings in 2016 were estimated to be approximately 8,000 to 10,000 tons [10]. The most common fishing vessels (c. 250) are smaller boats (<15m) that operate relatively close to the shore.

The Nestos River is the only fresh water source in the area, and one of the main rivers in the northern Aegean. In addition to transporting sediments, nutrients and other dissolved constituents from the agricultural plain upstream, this freshwater influx also has an impact on local salinity stratification. Over the period of 1966-1990 the river had an average annual flow rate of 45 m^3/s, however after the construction of two dams upstream for power production and irrigation purposes in 1997 this was reduced to about 28 m^3/s in the period 2000-2005 [11]. Maximum flow is during the period of December to June. Due to prevailing currents, the Nestos River plume tends to flow through the Thassos Passage into the Gulf of Kavala, where it contributes to sedimentation, mixing, and transport processes.

Based on this overview it is clear that the Gulf of Kavala is significantly impacted by various existing human activities, including fisheries, municipal and industrial pollution, and habitat destruction due to coastal development. As such, the baseline monitoring work planned within COREu will measure the present-day status of the biogeochemistry and biodiversity of the Gulf of Kavala ecosystem.

3. Geology

3.1. Stratigraphy and Structures

The fault-bounded (i.e., taphrogenic) Prinos-Kavala basin is about 38 x 20 km in size (about 800 km^2), with the majority situated offshore between the island of Thassos and the mainland plus a minor part located onshore to the northeast in the Delta Nestos Plain (Fig. 1a). The basin depocenter contains 5,800 m of sediments that range in age from the Lower Miocene to the Pleistocene [3,12]. These sediments can be divided into three main units that overlie, from bottom to top, the metamorphic basement rocks:

i) Lower-Middle Miocene turbiditic clastics that locally contain hydrocarbon accumulations [13]. These units formed while subsidence migrated from the NE to the SW;
ii) An 800 m thick sequence of Miocene evaporates and clastics. The emergence of the South Kavala Ridge during the Upper Miocene isolated the basin from the open sea and transformed it into a lagoon during the Messinian, resulting in the formation of 7 major evaporitic cycles [13,14];
iii) Pliocene-Pleistocene clastics of marine origin that prograde upwards higher in the sequence [15].

Marginal, long, and large-scale gravity faults of various angles encircle the basin in a northeast-southwest and northwest-southeast direction, extending from the Nestos Delta in the north to the South Kavala Ridge in the south (Fig. 1a). In addition, major internal faults, primarily trending northwest-southeast, traverse the basin and locally contribute to hydrocarbon trapping. An example of this is found in NW-SE striking faults that formed in correspondence with a topographic basement high that separates the northeastern Nestos and southwestern Prinos sub-basins [16] (Fig. 1a). These faults dip southward toward the basin center, influenced by prograding sedimentation that followed the topographic relief. Additional sliding movements, supported by salt deposition, further complicate this area. A sliding fault underlies the Prinos oil field along the basal salt, displacing the overlying formation to the south and creating the expansive North Prinos 1 anticline. In this densely faulted region, most of the Prinos traps are constrained by rollover anticlines located in front of syngenetic faults. Pinch-out traps at the basin flanks are quite common.

The basin hosts four off-shore hydrocarbon reservoirs: the Prinos and Prinos-North oil fields; the South Kavala gas field; and the Epsilon field (Fig. 1a). The Prinos oilfield and the South-Kavala gas field are, up to now, the sole areas in Greece for oil and gas production; both fields are traps in anticlines. The Prinos oil field occurs within a low-relief anticline that is bounded and cut by various NW-SE striking impermeable faults. The oil-bearing units occur in a depth interval from 2490 to 2770 m within a Middle-Upper Miocene clastic sequence formed by dominant massive sand units with interbedded claystones and siltstones. The various sand intervals range from fine- to coarse-grained and matrix content can reach 20%. The caprock consists of a 10 m thick overpressured claystone above the reservoir, itself overlain by the evaporite sequence described above. The impermeable nature of salt deposits, combined with their potential for self-sealing if faulted, means that the Prinos reservoir is very effectively sealed. Finally, the caprock is overlain by up to 2000 m of Plio-Pleistocene sands and clays. Oil is extracted through at least twelve producing wells combined with some seawater injection wells. The reservoir produces under-saturated sour crude oil with an API gravity of between 27 and 30 degrees and a dissolved gas content of 674 scf/bbl ($120m^3/m^3$). Prinos contains up to 60% hydrogen sulfide gas which is separated at the on-shore 'Sigma' plant. The field has produced more than 120 million bbls since 1981.

Favorable conditions for CCS beneath the hydrocarbon reservoirs in the Kavala-Prinos Basin include depths greater than 2700 m, an average permeability on the order of 50 mD, porosity on the order of 15-20%, and low seismicity [1], although the moderate to high geothermal gradient in the area (40 – 80 °C/km; [17] will decrease CO_2 density and thus have a negative impact on the total storage volume potential [1].

3.2. Shallow sediments

The surface sediments of Kavala Gulf are mostly fine-grained (Fig. 1b), consisting of sand and sandy silts, especially in the southeastern part and along the northeastern and eastern coastlines, while the central part consists of clayey silts supplied by the Nestos River [18]. Stamatis et al. [19] measured grain size and organic matter content at 3 points along a transect similar to the one planned in this project (see Section 5), finding 31-66% mud, 34-64% sand, 4.5 to 25% gravel, and 6-9.2% organic matter. These same authors report that the most abundant mineral phases in the coarse-grained fraction are quartz (10-20%) and feldspars (40-50%), while in the fine-grained fraction they are amphibole and pyroxene (5-10%), garnet (2-4%) and epidote (<4%). A preliminary interpretation of Chirp and Sparker seismic profiles in the area did not show evidence of shallow gas-charged sediments [10].

4. Environmental conditions

4.1. Climate

The climate in the area is characterized as intermediate between Mediterranean and continental type, with moderate precipitation, cold winters, and arid summer periods. A brief summary is given of the meteorological conditions at the site [10], because they will influence the production of biogenic CO_2, mixing and migration processes in the water column, the choice of monitoring targets and goals, and the feasibility of conducting sampling. The dominant wind direction during the entire year is from the NE, with secondary winds from the SW and E during the winter and from the SW and N during the summer. In terms of wind strength, during the winter (February) 57% are < 5 m/s, 31% are 5 to 10 m/s, 11% are 10 to 15 m/s and 1% are 15 to 20 m/s while during the summer (June) 79% of winds are < 5 m/s, 20% are 5 to 10 m/s and 1% are 10 to 15 m/s. Total average annual precipitation is 430 mm / year, with highest rates in December (76 mm) and lowest in August (14 mm). Average annual temperature is 15 °C, with average monthly values ranging from 5.6 °C in January to 26 °C in July. Modelled wave heights range from low levels in the summer (June: 82% <0.5m, 17% 0.5 to 1m, and 0.6% 1 to 2 m) to higher levels in the winter (February: 60% < 0.5m, 30% 0.5 to 1m, 7% 1 to 1.5m, 2.5% 1.5 to 2.5m, and 0.6% 2.5 to 4m).

4.2. Physical Oceanography

The waters of the North Aegean can be described based on three different origins: i) the colder, low salinity (<30 psu) outflow of Black Sea Waters (BSW) from the Dardenelles; ii) warmer, intermediate salinity waters (38.5-39 psu) from the Cretan Sea, known as the Levintine Intermediate Waters (LIW); and iii) the high salinity North Aegean Deep Water (NADW) isolated in deep sub-basins [20]. The first two interact and mix in the Thracian Sea in the shallower waters on the Samothraki and Thassos Platforms, including the Gulf of Kavala. The movement and mixing of these waters are controlled by major currents, regional or local eddies, and wind shear effects, all of which are influenced by seasonal changes and major meteorological events (e.g., storms). The major North Aegean currents are cyclonic [21], meaning a counterclockwise movement in the northern hemisphere which tends to transport a portion of the less dense BSW along the Turkish-Greek coast and throughout the Thracian Sea (especially during the winter [22]), bringing with it a higher nutrient load which makes this part of the Aegean more productive and less oligotrophic compared to the southern part [23].

Particularly important for water movement in the study area are the currents through the Thassos Passage, given that they transport the freshwater plume from the Nestos River (with associated nutrients and sediments) and because this restriction can increase flow rates and vertical mixing as well as affect flow directions as they enter the Gulf of Kavala [24]. In particular it has been shown that bottom currents tend to be deflected clockwise and follow the coast once exiting the Passage while the stronger surface currents flow westward across the Gulf and counterclockwise around Thassos Island [24]. Fresh water lenses (10-15 psu) on the surface linked to this flow have been observed in the Gulf throughout the year [6]. In general it has been postulated that Nestos River contributions dominate during the winter and spring whereas the influence of the low salinity water masses from the Dardanelles prevails during the summer and fall [20].

Currents can be formed in the Gulf via wind-shear, however this is primarily related to southerly winds given the lack of effective fetch in the other directions [20]. Instead, alternating northerly and southerly winds disrupt stable flow regimes and contribute to vertical mixing [21]. Large scale weather systems have also been shown to have an important influence on current direction and strength, in particular low pressure systems over the general Aegean Sea that force water and the the BSW-LIW boundary northward, bringing with it higher salinity waters [20,21]. In terms of current strength, an average value of 7 cm/s with maximum levels up to 45 cm/s have been measured, although it is not clear if these are representative of the entire year. Based on measured current speeds the water renewal period of the Gulf has been estimated to be between 1 to 4 days [20]. The water column is stratified from mid spring to mid fall, with a maximum surface to bottom water temperature difference of about 15°C in mid-summer, although the thermocline can be temporarily eroded given strong southerly winds [24]. Bottom water salinities appear to be relatively constant at about 37.6 psu, while shallower waters are influenced by higher discharge rates from the Nestos River during the winter/spring [24]. Finally, the study area is micro-tidal, with the tidal range varying between 0.12 m during neap tides and 0.30 m during spring tides.

In summary, current strengths and directions, vertical mixing processes, and the presence or absence of temperature- or salinity-defined stratification, all of which are seasonally variable, are important for the present study for two reasons. First, these will strongly influence the natural biological system and thus the production, accumulation, movement and loss of baseline biogenic dissolved CO_2 in the water column. Second, if a CO_2 leak were to occur from eventual CCS operations, be it the storage site or pipeline, these physical processes will control dilution (i.e., maximum exposure concentrations), dispersion (i.e., exposure times), and direction (i.e., affected area), all of which are important to understand ecosystem impacts and design effective monitoring programs.

4.3. Biogeochemistry and the carbonate system

The central Aegean Sea has high N:P numbers, higher than the Redfield ratio of 16, however in the surface layer of waters above the North Aegean shelf values decrease below 16, indicating nitrogen limitation due likely to a higher phosphorous load in both inorganic and organic form from the BSW and fluvial inputs [23]. While measurements in the Gulf of Kavala by [6] also show a nitrogen limitation, laboratory experiments using offshore waters from the gulf collected in February 2022 indicate that phosphorous was the limiting nutrient at that time [25]. As stated above, the North Aegean is less oligotrophic than the central and southern sectors, resulting in higher relative production of phytoplankton and zooplankton biomass in this area.

Total alkalinity and total dissolved inorganic carbon values in the North Aegean are very high, with values up to 2827 umol kg^{-1} and 2428 umol kg^{-1}, respectively, for a site east of Thassos Island in 20 m deep water [26]. These high values show a strong negative correlation with salinity, indicating a link with BSW and fluvial inputs. Such high values increase the potential for CO_2 uptake from the atmosphere, also illustrated by measurements showing surface water being under-saturated with respect to CO_2 during winter conditions [27]. This enhanced CO_2 uptake, combined with ventilation events, results in the transfer of CO_2 into deeper waters and high levels of excess alkalinity throughout the water column beyond the shallow water platforms [26].

4.4. Marine biodiversity

The Gulf of Kavala is highly productive due to the input of trans-frontal river waters, upwellings and the input of nutrient-rich water from the Black Sea, and it is characterized by a wide range of marine life, from microscopic plankton to larger species like fish, molluscs, crustaceans, and marine mammals. The diversity of marine life in the gulf is typical for similar depths throughout the Thracian Sea. More than 20 native fish species are assumed to be abundant in the area, although the number of fish species observed is higher [10]. None of these fish species appear to be endangered, although information about occurrence of endangered or vulnerable marine species in the Gulf of Kavala is sparse. Three of seven species of sea turtles are occasionally present in the gulf, but the area is not believed to be an important nesting location. Seagrass meadows, recognized as important habitats for many species, are widespread in the gulf. Both meadows with the native seagrass *Cymodocea nodosa* and the endemic *Posidonia oceania* are found in the area [28]. The meadows are affected to a varying degree by human activities, with some in good condition while others are significantly impacted.

The Gulf of Kavala is an important area for sea birds [29]. It is of particular importance for the Mediterranean Shag, as approximately 10% of the Greek population nest in the Gulf while about 17% of the national population overwinter in the area. Moreover, the area is an important feeding area for the Yelkouan Shearwater, the Cory's shearwater and the yellow legged gull. The main threat for the Mediterranean Shag and the Yelkouan Shearwater is disturbance at colony sites and in surrounding marine areas, mainly due to tourists and fishermen but also introduced rats feeding on eggs in the nesting colonies.

The gulf is also home to a range of marine mammal species, including the cetaceans (whales) bottlenose dolphins, common dolphins, striped dolphins, the "Endangered" harbour porpoises, Risso's dolphins, Fin whales and Sperm whales, as well as the Mediterranean monk seal [30]. The monk seal is the only seal living in the Mediterranean Sea; with a global population of fewer than 1000 individuals, it is considered "Vulnerable" following the latest assessment by the International Union for the Conservation of Nature (IUCN) [31]. The occurrence of these marine mammals in the Gulf has led to that the area being proposed as a potential cetacean conservation area by ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and Contiguous Atlantic Area).

More than 1,000 marine non-indigenous species (NIS) have been recorded to date in the Mediterranean Sea [32]. Although the highest number of fish NIS in the Aegean Sea occur in its southernmost part [33], 13 out of a total of 37 fish NIS observed in the Aegean Sea have recently been found in the Trachian sea, including the Gulf of Kavala [34]. One of the reasons for the increased occurrence of fish NIS in the area may be recent and intense marine heatwaves that may open "invasion windows" for fish NIS from warmer waters [35]. Little is known about the situation for other invasive species in the gulf, but it is not unreasonable to expect that climate changes in the future will involve significant ecosystem changes in the area.

4.5. Possible anthropogenic impact

Low to moderate heavy metal concentrations are reported by various authors in the sediments of deep-water sites [10,19,36,37]. Of samples collected close to the shore, the highest values were consistently observed in front of the Phosphorous Fertilizer Plant and within Kavala Harbour [19,37,38]. Of the trace elements measured by the various authors, those linked to anthropogenic input were determined to be Cu and Cd [10], Cu, Zn and Pb [37], Zn and Pb [39], and As, Cd, Cu, Pb, U and Th [38]. In terms of nutrients that can impact the trophic level of the Gulf, the two main sources are the Phosphorous Fertilizer Plant and the wastewater treatment plants. During the period of 2008-2012 the estimated annual discharge of nitrogen and phosphorous from the former was 390 and 53 tons, while from the latter values were about an order of magnitude lower [5]. Based on various sediment pollution indices, the Gulf of Kavala ranges from unpolluted to moderately polluted [37–39].

In terms of organic contaminants, Fytanos et al. [40] measured bi-monthly for two years at a site about 2 km from the oil well platform and found average values of Polycyclic Aromatic Hydrocarbons (PAHs) equal to 80 ng/L and tetrachloroethene and trichloroethene values near 3 ug/L; these authors defined these sites as unpolluted or slightly polluted. Instead, measurements performed by LDK Consultants [10] in the vicinity of this infrastructure yielded non-detect analyses for PAHs. Other research conducted close to shore in front of the industrial area [7,8,41] found moderate to high PAH values. These authors used PAHs and petroleum biomarker analyses to separate contaminants having a petrogenic origin (i.e., introduced into the environment by the discharge of petroleum and its products) or pyrogenic origin (incomplete combustion of organic matter including fossil fuels); the majority of these anomalies were found to have a petrogenic origin.

5. Planned work

All anthropogenic activities, including nature-based solutions aimed at protection or conservation of nature, will to some extent affect biodiversity and ecosystems. In some cases, the impacts might be large and lead to the loss of local ecosystem types, while in other cases the impacts might be virtually undetectable or be considered insignificant. In this regard it is imperative to collect detailed baseline data that can be used to assess the status of potentially impacted areas on an ecosystem level. Similarly, an understanding of the natural range of values for dissolved CO_2 and associated tracers is needed for monitoring purposes to separate anomalies caused by background, near-surface processes from those caused by a CO_2 leak. Such baseline data should optimally be collected over several seasons and years to account for natural variations in physical conditions (e.g., currents, mixing, stratification, etc.), their impact on biogeochemical processes (e.g., carbonate system cycling), and ultimately also biodiversity. Hence, baseline data, both chemical and biological, should indicate the status of the ecosystem with the current level of human impacts, which is not the same as the status of an unaffected ecosystem.

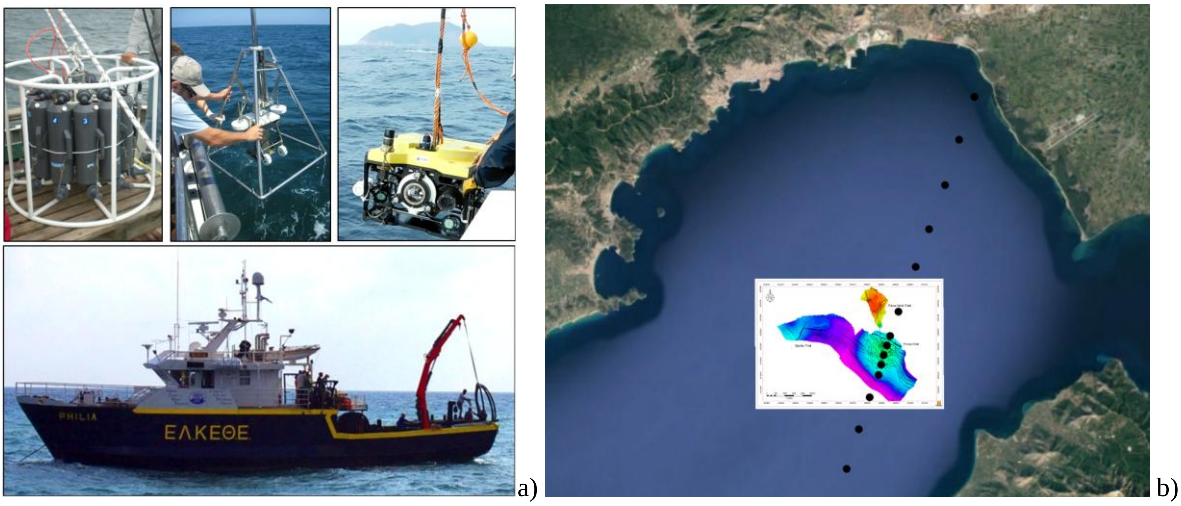

Fig. 2. a) Some of the sampling methods and the ship (HCMR RV Philia) that will be used during the sampling campaigns. b) Map of the study area showing the proposed sample points superimposed on a contour / structure map of the Prinos reservoir (https://www.energean.com/operations/greece/prinos-concession/).

In COREu, sampling of the water column and sediments, ROV studies, and atmospheric monitoring will be conducted from the RV Philia of the Hellenic Centre for Marine Research (Fig. 2a). We will sample the same NNE-SSW transect of 15 points across the Gulf of Kavala during the four seasons, assessing both the spatial and temporal variability of the natural system. The transect (Fig. 2b) starts to the south of the Prinos platform, crossing the area of oil and gas infrastructure and the NW-SE trending faults that bound the reservoir in greater detail (c. 500 m spacing) before following the general trend of the gas pipeline towards the shore at lower detail (c. 2500 m spacing). Whereas the initial section addresses an area where leakage could potentially occur from the storage complex, the latter considers pipeline safety and assesses changing ecosystem conditions moving shoreward (e.g., coastal inputs, different current conditions, changing temperatures, greater light penetration linked to shallower waters, etc.).

The collection of biological baseline data for offshore CCS that represent the overall status of a given ecosystem is challenging [42], especially if traditional sampling practices are applied. In such cases, numerous samples from all ecosystem components must be collected in a representative manner and subsequently analysed by taxonomical experts. This is time consuming and costly and is limited by the fact that the required scientific expertise has unfortunately become a rare commodity. However, the development over the last decade of novel molecular methodologies, commonly referred to as environmental DNA analyses (eDNA), has opened new ways to obtained baseline data that represent the biological status of ecosystems on an overall level. All living organisms shed cells or particles that contain their DNA and advanced molecular methods allow us to use DNA even from single cells to determine the presence of a species in soil, sediment, air and water samples [43]. This information can in turn be used to analyse the species composition in certain areas or periods, and thus also to assess potential impacts on biodiversity and ecosystem status due to anthropogenic activities. Previous research has shown that potential environmental impacts might be first detected in benthic organisms with short generation time close to the potential impact zone [44]. As such we will focus primarily on analysing biodiversity variations in micro- and meiofauna in the shallow sediments of the 15 planned stations to demonstrate how such data can provide detailed baseline information. It should be noted, however, that since eDNA sample preparation involves the extraction of all DNA, and that this DNA can be stored almost indefinitely, follow-up analyses focusing on different, specific taxonomic groups can be conducted at a later stage in case leakage actually does occur in the future.

Chemical analyses to be performed will concentrate on carbonate system components, dissolved oxygen and nutrients, both in the shallow sediments as well as at 4 depths in the water column. Analysis of pCO_2 and associated $\delta^{13}C\text{-}CO_2$, pH, and alkalinity, together with dissolved oxygen, will be used to determine the spatial and temporal variability of these parameters as a function of temperature and salinity stratification, current direction, insolation, and nutrients given their control over (or involvement in) the biological processes that produce (respiration) and consume (photosynthesis) CO_2 in the water and influence the physical transport of CO_2 to and from the atmosphere. In addition to discrete sampling, fixed point continuous monitoring of dissolved CO_2 and temperature will also be performed to look into short term variability of these parameters.

6. Conclusion

The COREu project represents a key step in advancing Carbon Capture and Storage (CCS) technologies in Southern Europe, with the Kavala-Prinos site in Greece serving as a critical full-chain demonstration. Through detailed geological, environmental, and biogeochemical assessments, coupled with innovative monitoring techniques such as environmental DNA (eDNA), this project aims to establish a comprehensive baseline for offshore CO_2 storage. The outcomes will not only enhance the safety and efficacy of CCS operations at Prinos site but will also provide valuable insights for future storage initiatives across the Mediterranean and Europe.

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