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Ecosystem services of saltpans: ornithological biodiversity support and carbon sequestration

Mestrado em Biología Marinha

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Resumo

As zonas húmidas costeiras são consideradas das áreas mais produtivas do planeta. Além disso, são capazes de sequestrar 50 % do carbono orgânico oceânico. Dentro das zonas húmidas costeiras podemos encontrar diferentes tipos de ecossistemas como estuários, mangais, lagoas costeiras ou sapais. Um desses sapais encontra-se na Ria Formosa, localizada na região sul de Portugal, na região do Algarve. Este sapal apresenta uma elevada taxa de produção primária e secundária, o que faz com que crie uma grande quantidade de serviços de ecossistemas, como é o caso da reciclagem de nutrientes, da proteção da área costeira, da regulação do clima, ou ainda atuando como local de reprodução de várias espécies de peixes. Adjacente a tudo isto, a Ria Formosa é também usada como ponto de paragem por algumas espécies de aves migratórias, como é o caso das aves limícolas, onde aqui podem alimentar-se e repousar. A atividade humana é uma enorme ameaça a este tipo de ecossistemas, que já viu mais de 43 % da sua área global reduzida, e que provoca uma diminuição nas populações de certos animais, em particular, das aves limícolas. Por este motivo, as aves limícolas e outros grupos de aves marinhas, necessitam procurar locais alternativos onde possam suprir as suas necessidades de custos energéticos para prosseguir com a sua rota migratória, locais estes que incluem as salinas. As salinas são estruturas criadas pelo homem, localizadas em zonas de lagoas costeiras ou estuários, muito frequentes no sul da Europa. Estas encontram-se divididas em diferentes níveis por onde a água do mar entra e circula, até à sua evaporação total, resultando no tão apreciado sal e flor de sal. O primeiro nível é conhecido como tanque decantador, através do qual a água do mar entra no sistema, seguindo ao segundo nível, para o(s) tanque(s) evaporador(es). Aqui, a água circula por vários tanques com diferentes profundidades, até ao nível final, ao chegar aos tanques cristalizadores, onde se dá a evaporação e se encontra o sal a descoberto, que será mais tarde recolhido e comercializado. Os serviços de ecossistemas fornecidos pelas zonas húmidas costeiras, onde com o tempo se criaram as salinas, são bastante conhecidos, mas pouco se sabe acerca dos serviços de ecossistemas que estas estruturas poderão criar. Com este estudo pretende-se avaliar que papel possuem as salinas em dois importantes serviços de ecossistemas: a biodiversidade de aves e a sequestração de carbono. Para tal, um censo de aves foi levado a cabo durante nove meses. O censo teve lugar nas salinas pertencentes ao grupo NECTON – Companhia Portuguesa de Culturas Marinhas, S. A, na cidade de Olhão, onde os indivíduos foram diferenciados por espécie, comportamento e localização,

tanto dentro da salina bem como da área de sapal adjacente, pertencente à Ria Formosa. O estudo foi realizado durante as três épocas mais importantes para este grupo de aves, 1) a migração invernal, na qual as aves voam para latitudes superiores para passar o inverno, 2) a migração de pre-nidificação, aquando do regresso a latitudes superiores para nidificar e por fim 3) o período de nidificação, no qual se observa nidificação nas salinas por parte de certas aves limícolas. Foi tido também em conta o ciclo de marés, de modo a observar de que forma estas aves utilizam as salinas e o sapal para alimentação, consoante o movimento das marés. Em paralelo, um total de nove cores foram extraídos das salinas, três por cada parte do sistema; um tanque decantador (n = 3) e dois tanques evaporadores com condições diferentes, um de água quente (n = 3) e outro de água fria (n = 3). Para extrair o conteúdo de matéria orgânica, foi necessário secar previamente as amostras numa estufa e posteriormente pulverizar com a ajuda de uma almofariz cerâmico, com o objetivo de realizar a técnica de “Loss On Ingnition” (LOI). Nesta, a mesma amostra é pesada antes e depois de ser queimada num forno, de modo a obter assim a matéria orgânica através da massa perdida. O carbono orgânico foi calculado através de relação direta com a matéria orgânica de cada amostra, utilizando uma equação que relaciona ambos elementos na Ria Formosa. Os resultados mostram que as aves usam a salina do NECTON como paragem durante a sua migração, sobretudo para descansar, e ainda que em menor medida, para alimentação, existindo inclusive, espécies que nidificam nestas salinas. Além disso, através das anilhas que algumas aves apresentavam, foi possível observar que certos indivíduos têm recorrido a esta salina durante vários anos. Os resultados do estudo de carbono mostram que diferentes partes da estrutura das salinas irão resultar em diferentes taxas de carbono, uma vez que cada parte do sistema apresenta profundidades, salinidades e temperaturas diferentes, que influenciam as taxas de sequestração e de sedimentação nos stocks de matéria orgânica e de carbono orgânico. O carbono orgânico apresenta um stock de 6.9 Mg OC ha^{-1}, 63.7 Mg OC ha^{-1}, e 61.7 Mg OC ha^{-1}, para os tanques decantador, evaporador de água fria e evaporador de água quente, respetivamente. Relativamente à matéria orgânica, os resultados foram de 23.3 Mg OM ha^{-1} para o tanque decantador, 292.9 Mg OM ha^{-1} para o primeiro tanque evaporador, e 270.8 Mg OM ha^{-1} para o tanque decantador final. A sequestração de carbono também varia consoante o tanque em questão. No tanque decantador que apresenta água da Ria Formosa, a sequestração de carbono foi de 23 ± 3.9 g OC m^{-2} y^{-1}, e nos tanques evaporadores de água fria e de água quente foi de 20 ± 14.35 g OC m^{-2} y^{-1} e 63 ± 14.77 g OC m^{-2} y^{-1}, respetivamente.

Tal demonstra que as salinas, tendo como representante esta salina, funciona como sequestradora de carbono, beneficiando na mitigação das alterações climáticas. Facto este, favorece a aceitação das salinas como ecossistemas de carbono azul, uma vez que a área existente de salinas em todo o mundo é bastante elevada, e trabalhando em conjunto como sequestradoras de carbono poderão ser consideradas um ecossistema benéfico.

Palavras-chave: Aves Limícolas, Ecossistemas, Carbono Azul, Salinas, Sapal, Serviços de Ecossistemas.

Abstract

Saltpans are human structures that can be find in coastal lagoons and estuaries in southern Europe, known to be important for ornithological biodiversity. Yet, other ecosystem services that the saltpans deliver are poorly investigated. Here, we assessed the role of saltpan in the support of ornithology biodiversity and, for the first time in the capacity of the saltpans to sequester and store organic carbon in their sediment. I made a survey of waterbirds in several tanks belonging to saltpans from Necton – Companhia Portuguesa de Culturas Marinhas, S.A. and at an adjacent saltmarsh area, in the Ria Formosa, lasting nine months. I covered three important epochs of bird's life (winter migration, pre-breeding, and breeding) to investigate if this saltpan works as a stop-point of birds and if they use it to rest, feed, or nest. Also, several cores were extracted from the decanter tank (n = 3), where the water of Ria Formosa enters to the system, the cold-water (n = 3) and hot-water (n = 3) evaporator tanks, where the water of decanter tank passes by several evaporator tanks that differ in depths to then, passes to crystallizer tank (last step in the saltpan system). Results showed that the Necton saltpan is an important stop-point to waterbirds, especially waders, that use saltpan mostly for to rest of their long trips but also to feed and nest. The estimated carbon stocks differed with the type of tank: 6.9 Mg OC ha $^{-1}$ for the decanter tank, 63.7 Mg OC ha $^{-1}$ for the first evaporator tank, and 61.7 Mg OC ha $^{-1}$ for the final evaporator tank. The carbon sequestration rates were 23 ± 3.91 g OC m^{-2} y^{-1} for the decanter tank, 20 ± 14.35 g OC m^{-2} yr^{-1} for the first evaporator tank, and 63 ± 14.77 g OC m^{-2} yr^{-1} for the final evaporator tank, demonstrating that saltpans are carbon sinks and should be included as blue carbon ecosystems in coastal wetlands.

Keywords: Waterbirds, Waders, Saltpans, Biodiversity, Blue carbon, Carbon sequestration, Ecosystems. Ecosystem services, Saltmarshes.

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List of abbreviations

1) DBD – Dry bulk density
2) DW – Dry weight
3) LOI – Loss on ignition
4) OM – Organic matter
5) OC – Organic carbon
6) CHN – Carbon, Hydrogen, and Nitrogen
7) CSR – Carbon sequestration rate
8) SAR – Sediment accumulation rate.

1. Introduction

Coastal wetlands are among the most productive habitats worldwide (Rocha et al.,2017), and bury 50 % of the organic carbon of the ocean (O'Connor et al.,2020). Many coastal wetlands are in the form of coastal tidal lagoons, rias, or estuaries in temperate regions, harbouring extensive vegetated habitats such as saltmarshes and seagrass meadows (Mcquaid et al., 2008). The Ria Formosa, is a coastal mesotidal lagoon in South Portugal with a high primary and secondary production, whereby it delivers a huge number of ecosystem services (Barbier et al., 2011; Herbert et al., 2018; Rendón et al., 2019; Chefaoui, 2021). The saltmarshes and seagrass meadows of the Ria Formosa are two important ecosystems due to the wide variery of services they provide. Some of these services are coastal protection from storms or wave damage, water purification, biodiversity support, fish nurseries leading to the maintenance of commercial fisheries, carbon sequestration and storage important for climate change mitigation, and cultural services such as tourism support (Barbier et al., 2011). All these services are under threatened by human activity that is causing water pollution; increasing of CO2 concentration that derived in ocean warming; habitat loss by the destruction of the coastal wetlands; or degradation of breeding sites among others (Sripanomyom et al., 2011; Yang et al., 2018). Saltpans are another common type of ecosystem found in coastal wetlands, yet little is known about their ecosystem services.

Coastal saltpans are supratidal human structures compound by several interconnected ponds with different sizes and depths separated by dikes (Rocha, 2013; Sripanomyom et al., 2011). They are formed with low permeable terrain in which seawater circulates following three phases: 1) the first one is called decanter tanks – are those tanks that receive the water from the sea, 2) the second one is evaporation tanks (normally formed with hot water ponds), where the water follows a route decreasing in depth that results in an increase on chloride concentration by evaporation and, 3) the last one, crystallization tanks, where the salt and the *fleur de sel* are collected (Susano et al., 2020). Published literature shows two important services of the saltpans. The first well-acknowledge service is the social-economic-cultural value for the collection of salt and *fleur de sel* (Susano et al., 2020); Secondly, saltpans are used by waterbirds, especially waders, as complementary places to feed and rest, but they need to be managed to have success as feeding and roosting places (Sripanomyom et al., 2011; Soares et al., 2018; Susano et al., 2020). Other ecosystem services less known are oxygen supply and pests regulation improving water quality (Soares et al., 2018; Chefaoui, 2021). However, the role of saltpans in carbon sequestration and storage is virtually unknown even though saltpans accumulate organic-matter rich sediments in their tanks, therefore potentially acting as carbon sinks. Investigating the sequestration rates and stocks in these ecosystems will improve our understanding on how coastal wetlands contribute to climate change mitigation.

Waders are migratory waterbirds that are very sensitive to the changes in coastal wetlands, zones they use for resting, feeding, and nesting during their migration (Almeida et al., 2020). They carry out one of the longest migration known in the animal kingdom (Lindstrom, et al., 2013). Many species may travel between 5,000 to 10,000 km of non-stop so the habitat losses are causing that 48 % of wader populations are declining worldwide and just 16% are increasing (Rocha, 2013). Most of the declining populations are from long-distance migrants or resident species with small populations (Zockler et al., 2003; Meltofte et al., 2006). Saltpans are a complementary place in which waders can supply their energy costs by migrations, although the macroinvertebrate species present on saltpans are not the same that whose present on the saltmarsh, but the abundances and the availability of the saltpan macroinvertebrate is higher (Amaral et al., 1999). At high-tide periods, waders go up to the saltpans to rest and feed, being important sites, especially for small waders because they need to feed more frequently to supply their higher energy intake (Sripanomyom et al., 2011). During low-tide periods they return to natural coastal areas, such as saltmarshes, to feed on bivalves, gastropods or others macroinvertebrates (Rocha, 2013).

Blue carbon is the organic carbon captured and stored in coastal and marine ecosystems, mostly seagrass meadows, saltmarshes, and mangrove forests (Mcquaid et al., 2008; Nellemann et al., 2009). These carbon stocks are the results of the balance between the carbon burial rate and the carbon remineralization rate, which vary with abiotic and biotic factors. For instance, location with lower hydrodynamics promote the deposition of fine-grain sediment particles that have higher organic carbon content, thus having higher carbon stocks and sequestration rates (Martins et al., 2021). Places with high primary production present more carbon burial rates than other places with lower production (Brown et al., 2021). A global average for organic carbon accumulation in saltmarsh around 245 ± 26 g OC m^{-2} y^{-1} meanwhile for hypersaline tidal flats are 21 ± 6 g OC m^{-2} y^{-1} (Brown et al., 2021). This sequestration and storage of organic carbon in the sediment helps in the mitigation of climate change. As previously said, the capacity of saltpans to sequester and store organic carbon is unknown up to date, yet there are reasons to expect high stocks even if there are unvegetated systems. Their high primary and secondary production (phytoplanckton and zooplanckton), along with the still nature of the water in the tanks, are two factors that can promote a high accumulation of organic matter in the sediment of the saltpan tanks.

In this study, I investigated two ecosystem services of saltpans, ornithological biodiversity support and carbon sequestration and storage. The study was conducted in an active saltpan of the Necton company, in the Ria Formosa, South Portugal. My specific objectives were: 1) investigate the role of the saltpan, in comparison to the saltmarsh, in supporting waterbirds, specifically waders, during their migration, by providing a feeding, resting, and breeding habitat, 2) investigate the sedimentary carbon stocks and sequestration rates in the tanks of the saltpan to evaluate if saltpan could be included as blue carbon ecosystems in coastal wetlands.

2. Material and methods

2.1. Study area

The Ria Formosa is a mesotidal coastal lagoon located in the South of Portugal in the Algarve region (Figure 2.1.1). The place encompasses 60 km of coast and includes five barrier islands presenting not only coastal lagoon area but other large areas of saltmarsh, mudflats, sandbanks and dunes. The climate for this region is a Mediterranean climate with hot and dry summers that present a mean of 25º C and with warms and wet winters reaching as mean 12º C. Between 50 to 75 % of the water present in the lagoon is exchange daily by tides. All of this makes the place a special region to nature including it in the Ramsar Convention and Natura 2000 for present ecological roles of breeding and

Figure 2.1.1. Aerial view of Ria Formosa lagoon, showing the location of study area.

nursery ground of different species and the stop places to migratory birds' species (Bebianno, 1995; Newton & Mudge, 2003, 2005).

The two study areas were the saltpans of the Necton company (Companhia Portuguesa de Culturas Marinhas, S.A.), in Olhão (37°01'31.21" N; 7°52'07.34" W), and the adjacent saltmarsh area belonging to Ria Formosa (Figure 2.1.2A).

The study area in the saltpan has 42,481 m^2, distributed in eighteen tanks with their respective walls (Figure 2.1.2B). The water system in the saltpan begins in the decanter tank, where the water from Ria Formosa enters to the system through a manual gate located between the decanter tank and a water channel. Then, the water passes to the cold evaporator tanks (called first evaporator tanks henceforth), which differ in depths and salinity concentrations, then it passes to the hot evaporator tanks (called final evaporator tanks henceforth), where the temperature increases, warming the water by a solar radiation, to finalize in the crystallizer, where the salt is collecting for commercialization (Figure 2.1.2C).

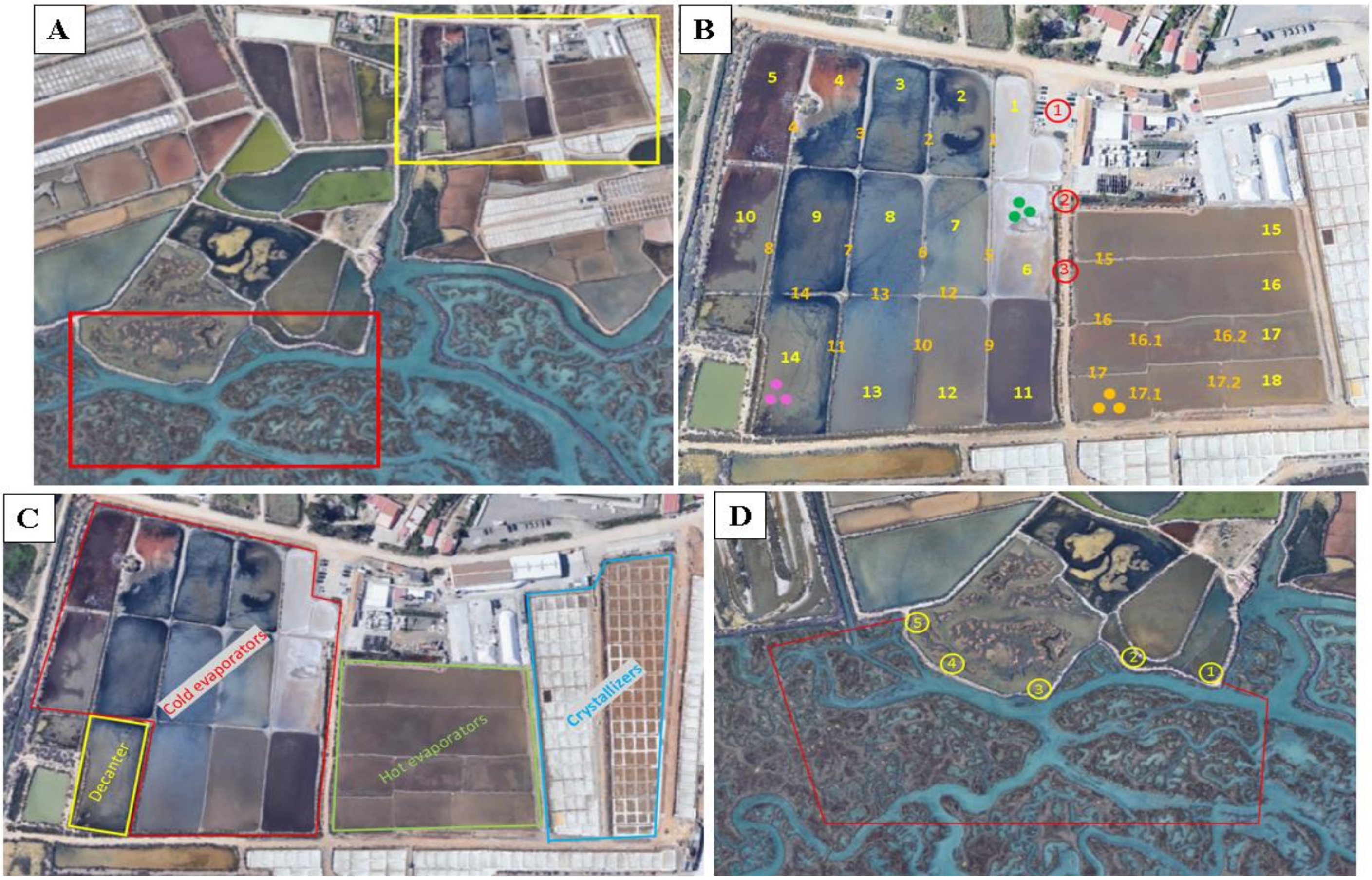

Figure 2.1.2. Aerial view of the two study areas. A) yellow square shows the saltpan area and red square shows the saltmarsh area, B) saltpan area with the tanks numbers in yellow, walls numbers in orange, coloured full circles showing the position of the sediment cores samplings and the three stop-points of bird observations in the saltpan in red; C) division of the saltpan tanks by type; D) saltmarsh study area with the five stop-points for birdwatching

2.2. Birdwatching survey

The evaluation of the ornithological biodiversity support was conducted in: A) the saltpans, including three types of tanks (the decanter, first- and final-evaporators), where higher concentration of waders is observed (J. Narvalho, personal communication), and B) the adjacent saltmarsh of the Ria Formosa. For the saltpans, three stop-points were set to cover the whole areas of three type of tanks (Figure 2.1.2B, 2.1.2C). The saltmarsh observational site has an area of 44,236 m^2, and five stop-points were set for the birdwatching (Figure 2.1.2D).

Bird observation and counting was conducted using: a binocular (10x42 Opticron) to observe and identify nearby birds or recognise groups in the distance; a terrestrial telescope (33.5X RSPB AG80), with a tripod to improve the observations in the distance and to recognise birds' legbands when possible; and a photograph camera (Panasonic Lumix DC-FZ82 20-1200) to take photos and videos of the birds to check the field counting and identification, when necessary. All type of birds were counted.

The counting was made twice a week, once during high tide and another during low tide, from 12th of November of 2020 to 14th of July of 2021, encompassing nine months and covering three important epochs for birds: overwinter migration (winter henceforth, covering from November to January), pre-breeding migration (pre-breeder henceforth, covering from February to May), and breeding (covering June and July). Tide information was retrieved from tidal charts and observations started 1.5 h before the selected tide and finished 1.5 h after it. The birdwatching was always done in the same order, first the saltpans then the saltmarsh. The birds in the saltpans were observed from three stops: one in front of tank 1 and two in front of tank 6 so that were possible observed all the tanks and walls without scaring the animals (Figure 2.1.2B). Only walls enumerated were included in the study, which are those more frequented by birds (Figure 2.1.2B) (personal observation). The observation started in the saltpans from tank number 1 to tank number 18 (numbers giving the direction of the observations, Figure 2.1.2B). Observations in the saltmarsh were done from each stop-point, from point 1 to 5 (Figure 2.1.2D), with care not to scare away the birds, and using distant geographical delimitations at both sides of each stop point to avoid double counting of birds. If the birds scared away, the sampling was started again not to count the same birds twice. In the breeding period, were counted the chicks of the species that nest on the saltpan.

During the survey, the following information was recorded: date, tide information, sampling site (tank and wall for the saltpan or stop-point for the saltmarsh), species observed (number of individuals of each species, distinguishing between chicks, juveniles and adults), behaviour of each observed individual (feeding, resting or nesting) and any other relevant information.

The information of the legbands found during the research were send to the European Union for Bird Ringing (EURING) Data Bank to try to know the story life of the individuals.

2.3. Abiotic measurements

Depths were taken with a metre stick in the tanks of the saltpan on 14th of July of 2021, and the average of the three measurements per tank was registered. But the variation in the ground of each tank is higher by the presence of several hills inside them.

2.4. Blue carbon assessment

2.4.1. Sediment sampling

Replicated sediment cores (n = 3) were taken in three different tanks: decanter, first evaporator, and final evaporator (Figure 2.1.2B). Sediment cores were extracted by manually hammering 50-cm PVC tubes (internal diameter = 4.6 cm, bottom edge serrated) into the ground, until the total length was reached or until penetration was not further possible. They were manually extracted in a vertical position keeping the original structure of the sediment layers, by making the vacuum with a stopper in the upper part of the tube and closing it at the bottom with a lid.

The sediment elevation inside and outside the core was measured with a rule to calculate the sediment compaction generated during the coring process (Glew et al., 2001) which ranged from 0.6 to 0.9 (Table 2.4.1). Depth and volume of the sediment samples along the core were corrected using the compaction factor, and all results presented hereafter refer to corrected decompresses measures.

The tubes with the sediment were transported vertically to the laboratories of CCMAR where they were immediately frozen at -20º C.

Table 2.4.1 Information of the sediment cores taken in the saltpan tanks, showing the maximum depth reached into the ground (corrected depth) and, the compaction factor.

Core name	Sampling tank	Maximum depth (cm)	Compaction factor
S01	First evaporator	36.7	0.8
S02	Final evaporator	44.4	0.8
S03	Final evaporator	32.9	0.9

S04	First evaporator	39.5	0.8
S05	Final evaporator	34.4	0.8
S06	First evaporator	40.8	0.7
S07	Decanter	45.8	0.6
S08	Decanter	37.4	0.7
S09	Decanter	37.6	0.6

2.4.2. Sediment analyses

The sediment cores were halved longitudinally with a circular saw and the sediment core from one half was divided into 1-cm slices and placed into pre-weighted zip-lock plastic bags. The volume of the samples (cm^3) was estimated by geometrical approximation, as the thickness of each sample multiplied by the core diameter and divided by two. The other core half was sampled for eDNA analysis at regular intervals, yet these methods are not included in the present thesis because the results have not been received from the external laboratory where they were sent for analysis.

The sediment samples were dried in an air oven (60º C, 48 h), to obtain the dry weight (g dw) and calculate the dry bulk density (DBD, g cm^{-3}) as the sample dry weight divided by its volume (eq. 2.4.2). Dried samples were pulverized with a ceramic mortar and a pestle, cleaning the ceramic material between samples with distilled water and ethanol to avoid cross-contamination.

The loss-on-ignition method (LOI) was used to obtain the sediment organic matter percentage content (OM, % dw) in all the sediment samples along core. For that purpose, small aluminium containers were weighted empty (*Container*) and weighted again after transferring to it from 2 to 4 g dw of the sample (pre-ignition sample weight, *PreIW*). Then, they were placed into the furnace (450º C, 4 h) to obtain post-ignition samples, which were weighted again (post-ignition sample weight, *PostIW*). The OM content was obtained from the difference in weight during the LOI (eq. 2.4.3).

A selection of pre-ignition and post-ignition sediment samples were sent for elemental analysis (CHN) in order to calculate directly the content of organic carbon in the sediment. However, the results are not ready at the time of the thesis writing.

$$\textbf{(eq. 2.4.2)} \quad DBD = \frac{DW\ (g)}{Total\ volume\ (cm^3)}$$

$$\textbf{(eq. 2.4.3)} \quad OM = \frac{(PreIW - PostIW)}{(PreIW - Container)} * 100$$

2.4.3. Sedimentary carbon stocks and sequestration rate

The OM content is a proxy of the organic carbon (OC) content in the sediment, being both variables positive and linearly correlated. Thus, the percentage in OC in the samples was estimated based on the equation of a linear regression between OC and OM previously described for the sediments of the Ria Formosa (Martins et al., 2021), assuming that the sediment characteristics of saltpan is similar to that of the vegetated sediment in the Ria Formosa (eq. 2.4.4).

$$\textbf{(eq. 2.4.4)} \quad OC = -0.066 + 0.3102 * OM(\%)$$

The OM stock (g OM cm^{-2}) was obtained by the sum of OM content (g OM) in each 1-cm sample along the sediment core, divided by the corer area (cm^{-2}). Since the cores presented different depth penetrations (Table 2.4.1), the stocks were standardised to 30 cm depth to be comparable among them. For each type of tank, the average OM stock was obtained from the three cores collected in each of them. Then, the OM stock in the complete tank (Mg OM), was calculated as the product of the average 30-cm stock (in units of Mg OM ha^{-1}) by the area cover by that specific type of tank (ha). The area of each tank was measured with the polygon tool in Google Earth^{TM}. Similar to the OM calculations, OC stocks per unit of area and in the total area of the saltpan tanks were calculated using the estimated OC content in each sample and core.

Carbon sequestration rate (CSR, g OC $y^{-1}cm^{-2}$) was obtained as the product of the sediment accumulation rate (SAR, cm y^{-1}) estimated from each core and its OC density (OCD, g OC cm^{-3}). To estimate the SAR, the length (cm) of the OM-rich layer from each core was divided by the age of the tank where it was collected. The length of the OM-rich layer was obtained by visual inspection in the cores and from the profiles of the geochemical measurements (OM, DBD) performed along with the cores.

The age of each tank was estimated based on historical aerial images of the study area from the Army Geospatial Information Centre of Portugal (in 1947, 1968, 1969, and 1972) and from Google Earth™ (in 2006) and based on the knowledge of the owner about the saltpan history.

2.5. Statistical analysis

2.5.1. Ornithological biodiversity support assessment

For the saltpan the species abundances were measured as the number of individuals of each species per sampling effort (number of days that I went to the field each month) to obtain the number of individuals per visit in each month (ind. $visit^{-1}$) To make comparison between saltmarsh and saltpans, frequencies per species (%) were calculated, because the counting at the saltmarsh was difficult due to the tall vegetation, and the absolute number of individuals may be underestimated. Tables and statistical analyse of Chi-square (alpha level of 0.05) were done using Excel® version for Microsoft 365 16.0 and maps were made with QGIS® version 3.18.

2.5.2. Blue carbon assessment

All variables are presented in results as mean ± standard deviation. The normality test and homoscedasticity were done for all the variables used in the research. Data meeting parametric assumptions were analysed by the statistical test of ANOVA 1-way (SAR, CSR, OM stock, OC stock) to test differences among type of tank (fixed factor with three levels: decanter, first-evaporator, and final-evaporator). Those variables that did not meet the parametric assumptions were analysed by the Kruskal-Wallis test (DBD) to test differences among type of tank. The alpha (α) level used was 0.05 for all the hypotheses tests and all were conducted in R program software (R version 3.6.1).

3. Results

3.1. Ornithological biodiversity support assessment

3.1.1. Necton saltpan

A total of 34 species were observed on the saltpan (Table 3.1.1). The top six most abundant species were waders. The two first species were small waders that appeared in a huge number in comparison with the rest of birds. Another type of birds came to the saltpan to feed or rest as is the case of the flamingos that came in a rate of 9 individuals per visit. The least abundant species were passerines, which were also observed using the saltpan to feed and rest on the walls, followed by egrets and herons, such as the Grey heron (*Ardea cinerea*) or the Eurasian spoonbill (*Platalea leucorodia*) which prefers saltmarsh to feed (Table 3.1.1).

Table 3.1.1. Table shows the species found on the saltpan, in number of individuals (N) and in average of number of individuals per visit. (ind. vist^{-1}).

SALTPAN					
Species	**Number (N)**	**Abundance (ind. visit^{-1})**	**Species**	**Number (N)**	**Abundance (ind. visit^{-1})**
Calidris alpina	12,954	259	*Egretta garzetta*	23	<1
Charadrius hiaticula	3,832	77	*Motacilla alba*	16	<1
Limosa limosa	2,211	44	*Larus fuscus*	16	<1
Recurvirostra avosetta	2,135	43	*Tringa nebularia*	15	<1
Charadrius alexandrinus	1,226	25	*Arenaria interpres*	7	<1
Himantopus himantopus	570	11	*Calidris ferruginea*	7	<1
Phoenicopterus roseus	471	9	*Gallinago gallinago*	7	<1
Calidris alba	386	8	*Passer domesticus*	5	<1
Pluvialis squatarola	370	7	*Ardea cinerea*	5	<1
Sternula albifrons	248	5	*Motacilla flava*	4	<1
Tadorna tadorna	171	3	*Spatula clypeata*	2	<1
Calidris minuta	110	2	*Alcedo atthis*	2	<1
Chroicocephalus genei	80	2	*Platalea leucorodia*	1	<1
Tringa totanus	79	2	*Larus audouinii*	1	<1
Chroicocephalus ridibundus	51	1	*Alauda arvensis*	1	<1
Larus michahellis	35	1	*Pluvialis dominica*	1	<1
Actitis hypoleucos	27	1	*Larus delawarensis*	1	<1

Dunlins (*Calidris alpina*) were mostly counted in the winter epoch (334 ind. visit^{-1}) and it was the most abundant species in the other two periods (295 ind. visit^{-1} in pre-breeding and 36 ind. visit^{-1}in breeding). A total of 3,832 individuals of common ringed plover (*Charadrius hiaticula*) was observed (Table 3.1.1), presenting a higher abundance in the winter period (115 ind. visit^{-1}), and been the second most abundant in the pre-breeding season (77 ind. visit^{-1}). Its abundance decreased in the breeding season (20 ind. visit^{-1}) being only the third most abundance bird in this season (Table 3.1.2). The species black-tailed godwit (*Limosa limosa*) presented the highest abundance in winter (97 ind. visit^{-1}) (Table 3.1.2) over a total of individuals counted of 2,211 (Table 3.1.1). Other species were observed in the saltpans just in one or two of the periods as is the case of the grey plover (*Pluvialis squatarola*) which was only seen in winter (25 ind. visit^{-1}), or the little tern (*Sternula albifrons*) which was only seen during the breeding period (15 ind. visit^{-1}) (Table 3.1.2).

Table 3.1.2. Number of individuals per species and per visit (ind. visit^{-1}) in each epoch studied on saltpan (0 = no appearance of the species in the saltpan).

SALTPAN (ind. visit $^{-1}$)			
Species	**Winter**	**Pre-breeder**	**Breeding**
Calidris alpina	334	295	36
Charadrius hiaticula	115	77	20
Limosa limosa	97	33	8
Recurvirostra avosetta	46	44	29
Charadrius alexandrinus	39	20	15
Himantopus himantopus	11	12	9
Phoenicopterus roseus	9	10	8
Calidris alba	13	8	0
Pluvialis squatarola	25	2	0
Sternula albifrons	0	3	15
Tadorna tadorna	1	3	7
Calidris minuta	1	3	1
Chroicocephalus genei	0	<1	7
Tringa totanus	3	1	0
Chroicocephalus ridibundus	3	1	0
Larus michahellis	0	1	<1
Actitis hypoleucos	1	<1	<1
Egretta garzetta	1	<1	<1
Motacilla alba	1	<1	0
Larus fuscus	<1	1	0
Tringa nebularia	1	<1	0
Arenaria interpres	<1	<1	<1
Calidris ferruginea	0	<1	0
Gallinago gallinago	1	<1	0
Passer domesticus	<1	0	0
Ardea cinerea	<1	<1	0
Motacilla flava	0	<1	<1
Spatula clypeata	<1	0	0

Alcedo atthis	<1	0	0
Platalea leucorodia	0	<1	0
Larus audouinii	0	<1	0
Alauda arvensis	0	<1	0
Pluvialis dominica	<1	0	0
Total	701	516	155

The first peak of bird abundance appeared in December with a total of 802 ind. visit $^{-1}$, and the second one in February and March with 710 and 688 ind. visit $^{-1}$, respectively (Table 3.1.2) (Figure 3.1.3).

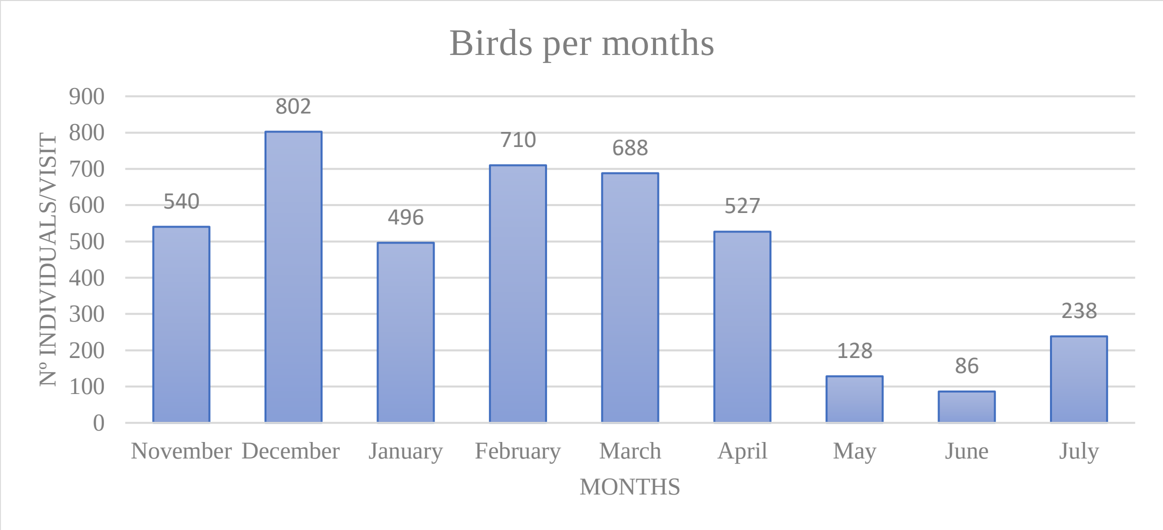

Figure 3.1.3. Total individuals per visit of all species in each living epoch on the saltpan.

The Necton saltpan acted as a resting place during the whole observation period yet with a high variability, with abundances from 54 ind. visit $^{-1}$in June to 681 ind. visit $^{-1}$in December (Figure 3.1.4). The feeding behaviour was also present the whole duration of the study, with rates ranging from 16 ind. visit $^{-1}$ in November to 123 ind. visit $^{-1}$in December (Figure 3.1.4). The nesting behaviour ranging from 2 ind. visit $^{-1}$ in April and July to 13 ind. visit $^{-1}$ in May (Figure 3.1.4). In addition, Necton saltpan was a nesting place with abundances ranging from 2 ind. visit $^{-1}$ in April and July to 13 ind. visit $^{-1}$ in May (Figure 3.1.4).

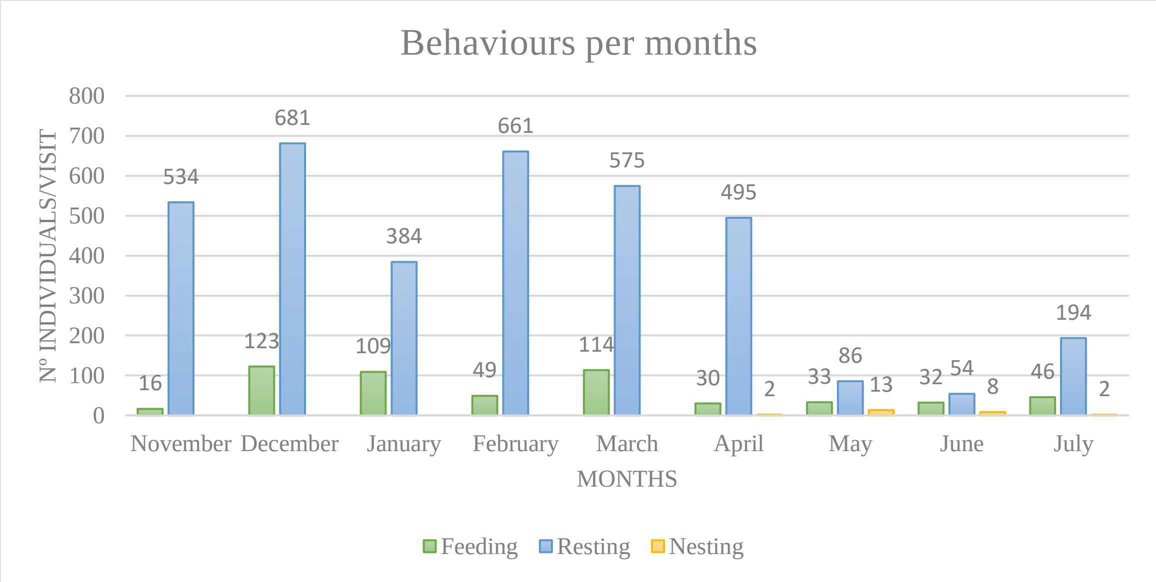

Figure 3.1.4. Number of individuals per visit during each epoch and presenting different behaviours, observed on the saltpan.

The abundances per month during the high tide were highest in winter period (November – 516 ind. visit $^{-1}$, December – 703 ind. visit $^{-1}$, and January – 424 ind. visit $^{-1}$) and in the two first months of pre-breeding season (February – 594 ind. visit $^{-1}$, and March – 628 ind. visit $^{-1}$) than those months belonging to the breeding period (May – 49 ind. visit $^{-1}$, June – 56 ind. visit $^{-1}$). Although the last months of breeding period present a high abundance again (July – 217 individuals/visit). During low tide the highest rate happened in the April (292 ind. visit $^{-1}$it) and May (69 ind. visit $^{-1}$) months, meanwhile for the rest of months the amounts never reached more than 116 individuals per visit (Figure 3.1.5).

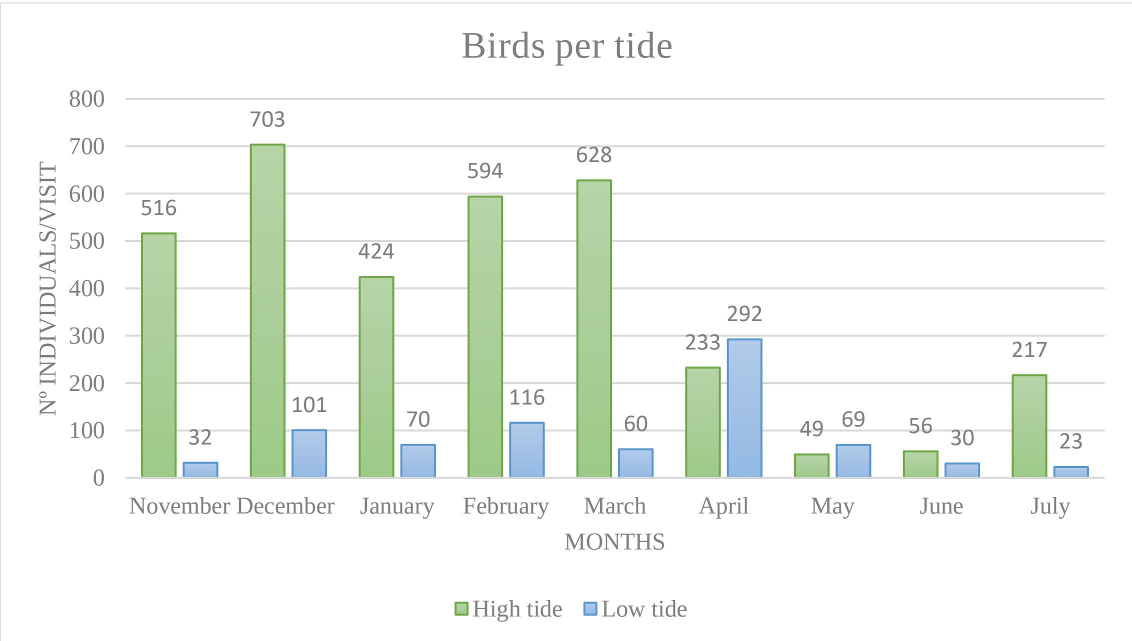

Figure 3.1.5. Number of individuals per visit during different tides on the saltpan.

In winter period during high tide the abundances of birds resting (6,739 ind. visit $^{-1}$) were higher than the feeding (724 ind. visit $^{-1}$) abundances meanwhile during the low tide the abundances of both behaviours were similar (feeding – 496 ind. visit $^{-1}$, resting – 487 ind. visit $^{-1}$) (Figure 3.1.6A). In pre-breeding season, the abundances of birds resting were higher during high tide (5,576 – individuals/visit) than during feeding behaviour (720 – individuals/visit). Also, in low tide the resting behaviour (854 ind. visit $^{-}$1) were higher than feeding (326 ind. visit $^{-1}$) (Figure 3.1.6B). In the breeding season, also the highest concentration of birds is found resting during high tide (5,856 – individuals/visit), and during low tide (2,048 – individuals/visit) (Figure 3.1.6C). In all the seasons exist association between the variables behaviour and tide (winter – chi-square = 1167, critic value = 3.8; pre-breeding – chi-square = 216, critic value = 3.8; breeding – chi-square = 145; critic value = 3.8).

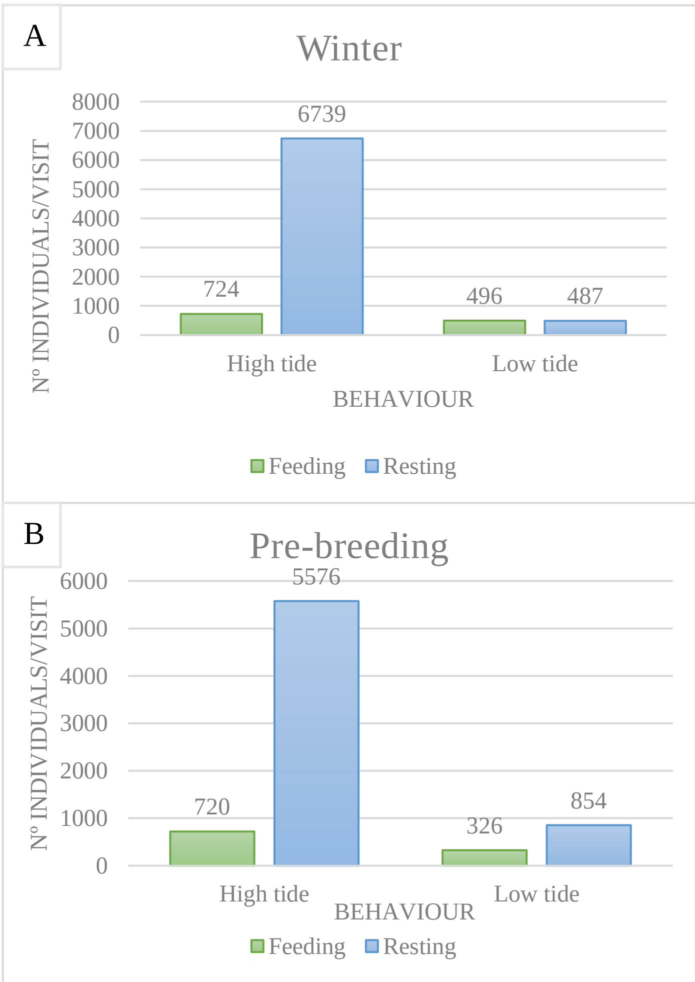

Figure 3.1.6. Relation between behaviour and tide in each season on saltpan. A) during winter period; B) during pre-breeding period, and C) during breeding season.

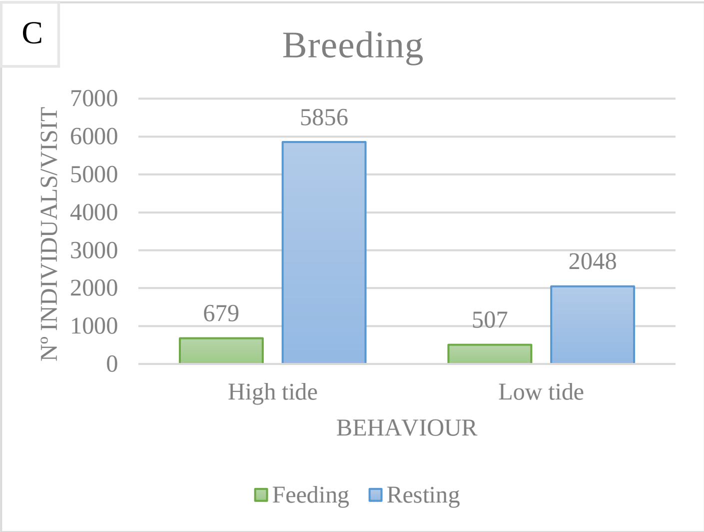

Figure 3.1.6. Relation between behaviour and tide in each season on saltpan. A) during winter period; B) during pre-breeding period, and C) during breeding season.

In a perspective more specific of the most abundant birds of the saltpan along all the months of the research were seen as the kentish plover (*Charadrius alexandrinus*) appeared in a high abundance in November, to then decreased it during the next months until reach in February the next big peak of population with an average of 30 ind. visit^{-1} observed. In May the population was in their lowest abundance with an average of 10 ind. visit^{-1} and started to increase in the next two months. It was always a species present on the saltpan (Figure 3.1.7A). For the avocet (*Recurvirostra avosetta)*, a frequent species in this saltpan, their population started to increase in abundance from November until reached the maximum in March with an average of 70 ind. visit^{-1}. Then decreased being the next month, April, the month with the smallest abundance of avocets (5 ind. visit^{-1}). In the three last months of the research the population began to increase again (Figure 3.1.7B). For the dunlin (*Calidris alpina)* the first and sharper peak happened in December (440 ind. visit^{-1}) and decreased in the January month. The population return to increase with a wide peak covering February, March and April months to then decreased faster in summer months (Figure 3.1.7C). For the black-winged stilt (*Himantopus himantopus*), another species that was always present on the saltpan, the first peak appeared in December, the second one, the highest, appeared in February with 15 ind. visit^{-1} and the third one covering April and May with 11 ind. visit^{-1}. Also, appeared a small peak in the saltmarsh during May (Figure 3.1.7D). For the common ringed plover (*Charadrius hiaticula*) appeared three intense peaks, one in December (139 ind. visit^{-1}), another in February (120 ind. visit^{-1}), and the last one in April (110 ind. visit^{-1}). After April the abundance decreased to reach between May and June the lowest rate of the nine months. At the same time, in the saltmarsh appeared a little peak in May (Figure 3.1.7E). For the black-tailed godwit (*Limosa limosa*) the abundance started in November with highest average of individuals (110 ind. $visit^{-1}$) and was decreased slowly until April when disappeared from saltpan (Figure 3.1.7F). For the common redshank (*Tringa totanus*), two big peaks appeared in saltmarsh, one in January (15 ind. $visit^{-1}$), and another in June, the highest with 17 ind. $visit^{-1}$. Also, this species appeared in the saltpan in January, decreasing but decreased during next months until disappeared in April (Figure 3.1.7G). For the grey plover (*Pluvialis squatarola*) the peak in the saltpan happened in January with 30 ind. $visit^{-1}$ and disappeared in March meanwhile in saltmarsh appeared a little peak in December (10 ind. $visit^{-1}$) and huge abundance peak in March with 100 ind. $visit^{-1}$. Then the observations were constant during the summer months (Figure 3.1.7H).

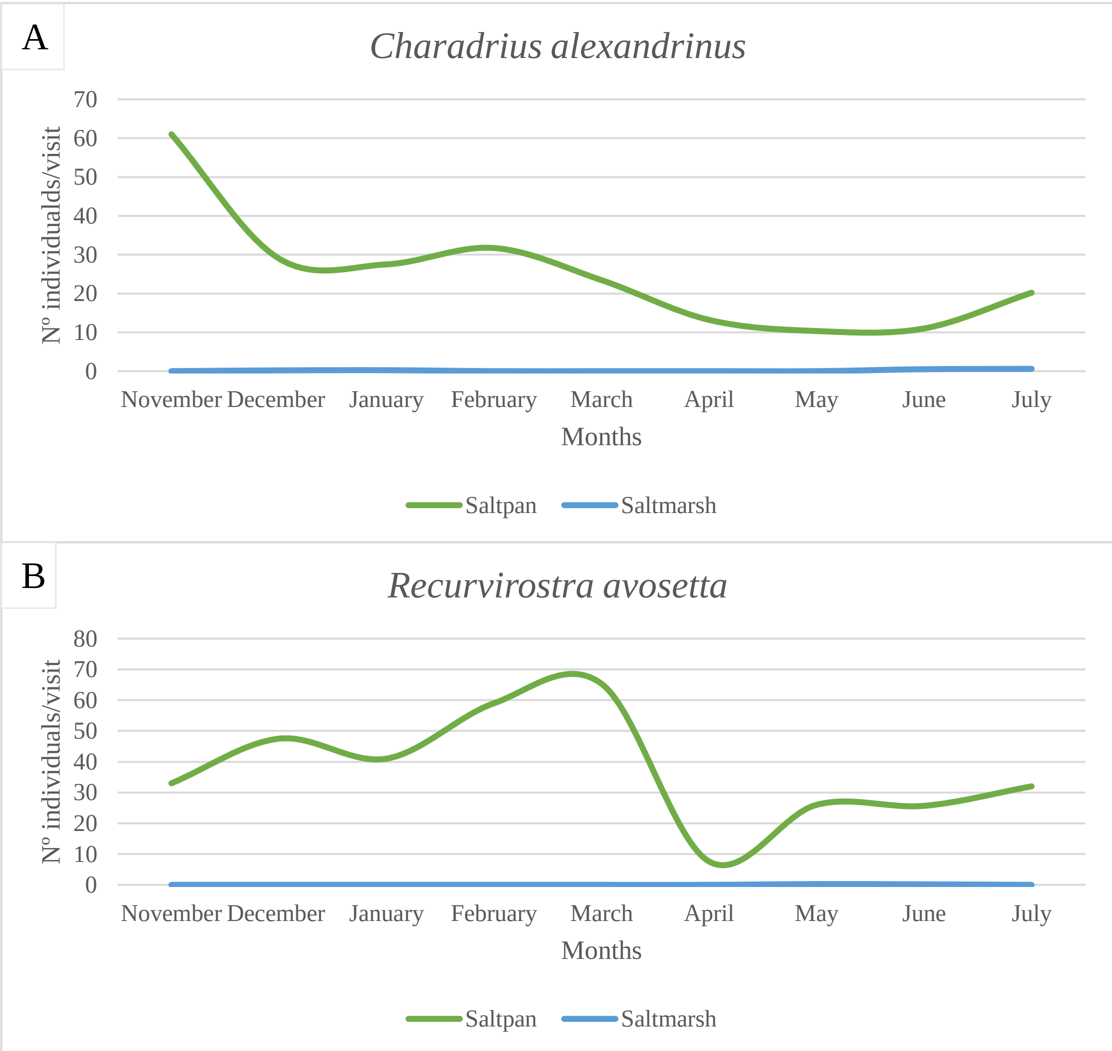

Figure 3.1.7. Comparison between observations in saltmarsh and saltpans of the most abundance species in number of individuals per visit. A) *Charadrius alexandrinus*; B) Recurvirostra avosetta, C) *Calidris alpina*, D) *Himantopus himantopus*, E) *Charadrius hiaticula*, F) *Limosa limosa*, G) *Tringa totanus*, and H) *Pluvialis squaarola*.

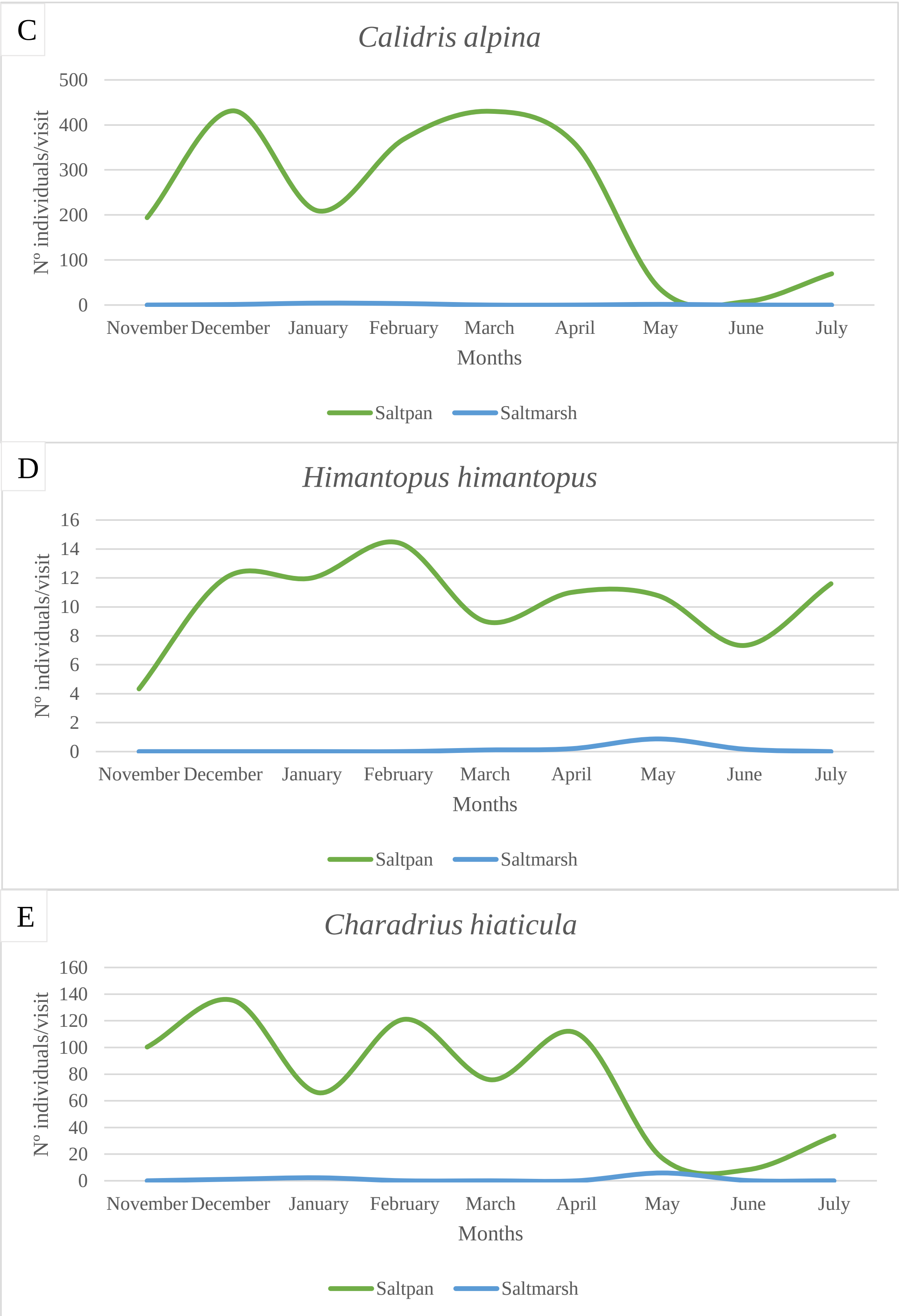

Figure 3.1.7. Comparison between observations in saltmarsh and saltpans of the most abundance species in number of individuals per visit. A) *Charadrius alexandrinus*; B) Recurvirostra avosetta, C) *Calidris alpina*, D) *Himantopus himantopus*, E) *Charadrius hiaticula*, F) *Limosa limosa*, G) *Tringa totanus*, and H) *Pluvialis squatarola*.

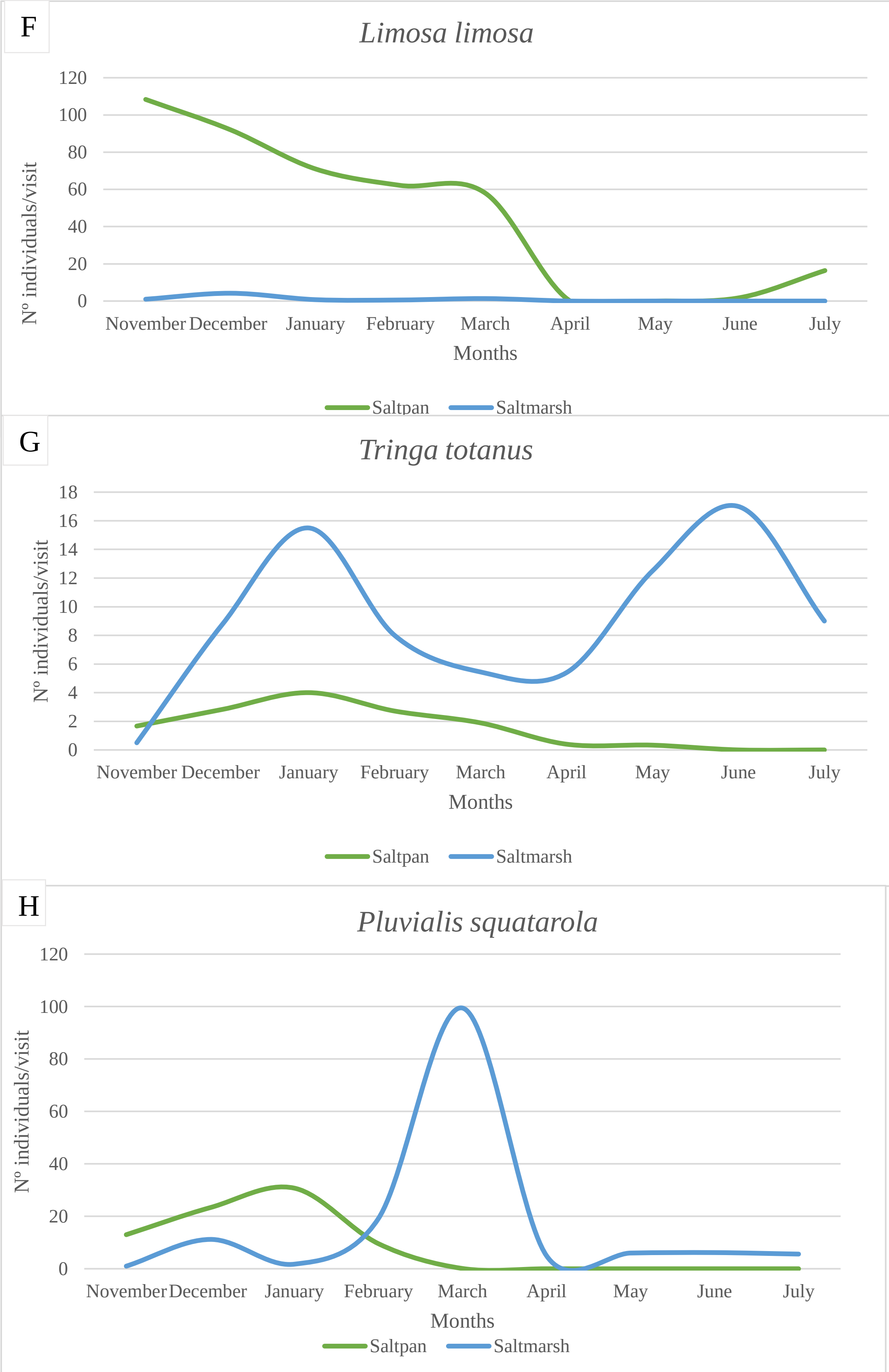

Figure 3.1.7. Comparison between observations in saltmarsh and saltpans of the most abundance species in number of individuals per visit. A) *Charadrius alexandrinus*; B) Recurvirostra avosetta, C) *Calidris alpina*, D) *Himantopus himantopus*, E) *Charadrius hiaticula*, F) *Limosa limosa*, G) *Tringa totanus*, and H) *Pluvialis squatarola*.

The avocet (*Recurvirostra avosetta*) was found in the tanks numbers 3 and 8 in more abundance where the depth is approximately 18 cm. Also, the abundance of this species was higher in the walls number 6 and 7. All the abundance remained in the cold-evaporator tanks (Figure 3.1.8A). The abundance of black-tailed godwit (*Limosa limosa*) was higher in the tanks number 3 and 4 with a water depth between 18 and 19 cm, and the wall number 3. This species was never observed in the hot-evaporator tanks (Figure 3.1.8B). The highest abundance of common ringed plover (*Charadrius hiaticula*) was specially observed in the walls number 16 and 17 belongs to hot-evaporator tanks and in the wall number 3 and 5 from the cold-evaporator tanks. Also, the average was higher in the tank 6 with a water depth of 14 cm (Figure 3.1.8C). The dunlin (*Calidris alpina*) was observed in all the saltpan because was the most abundant bird, appeared in more abundance in the tank number 6 for feed, in the tank less deep (14 cm), and in all the walls of the saltpan (Figure 3.1.8D).

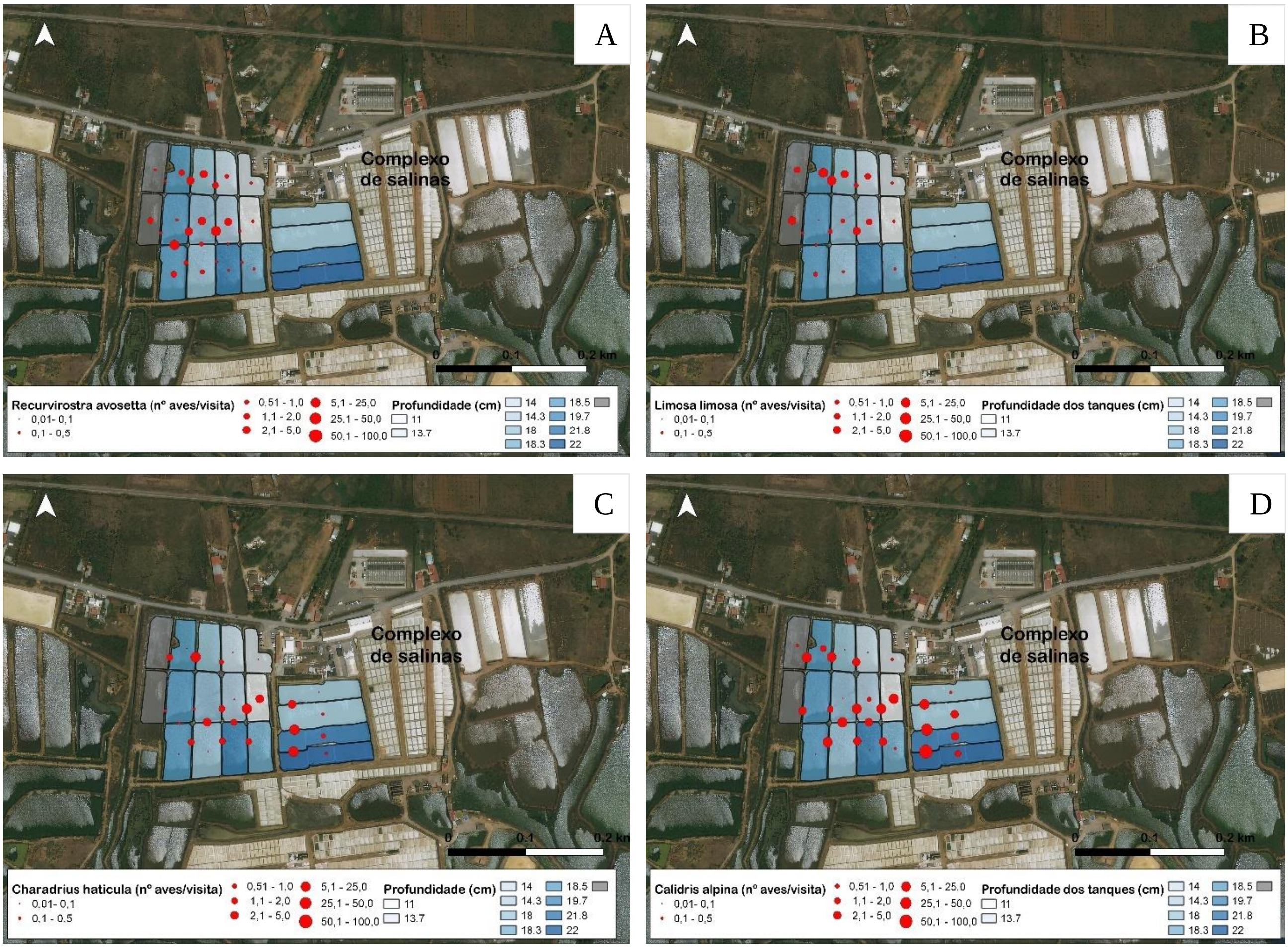

Figure 3.1.8. Favourite locations in the saltpan of different species, the size of red circle represent the abundances: A) *Recurvirostra avosetta*, B) *Limosa limosa*, C) *Charadrius hiaticula*, D) *Calidris alpina.*

- **Presence of wader's nest**

This saltpan was used as nesting area, chicks from three wader's species were observed using tanks and walls to rest and feed (Table 3.1.9).

Table 3.1.9. Number of chicks of the three species observed on the saltpans. The total of individuals is the maximum number of chicks observed during all the survey.

Species	Total individuals (N)
Himantopus	4
Recurvirostra avosetta	4
Charadrius alexandrinus	2

- **Legband's birds**

A total of 11 birds with legbands were observed. Most of them were from black-tailed godwit (*Limosa limosa*, n = 8), followed by avocet (*Recurvirostra avosetta*, n = 2) and lesser black-backed gull (*Larus fuscus*, n = 1). Unfortunately, just two story live were found (see annex).

3.1.2. Comparison between saltpan and saltmarsh

A total of 38 species were found in the saltmarsh. Both systems share some species but the abundance in each place seems totally different, being the most abundance for saltmarsh grey plover (*Pluvialis squatarola*) with a frequency of 42 %, followed by common redshank (*Tringa totanus*) with a frequency of 18 %. In the saltmarsh, species as little egret (*Egretta garzetta*) or eurasian spoonbill (*Platalea leucorodia*) were in higher number than in the saltpan and other species appeared only in the saltmarsh such as the great cormorant (*Phalacrocorax carbo*) and two raptor species, the osprey (*Pandion haliaetus*) and the peregrine falcon (*Falco peregrinus*) which were observed feeding. The grey heron (*Ardea cinerea*), four different species of ducks, and eight species of passerines were common to observe on saltmarsh too. Some wader species were seen only in the saltmarsh such as eurasian curlew (*Numenius arquata*) and whimbrel (*Numenius phaeophus*) that were not observed at the saltpan (Table 3.1.10).

Table 3.1.10. Frequencies of species of saltpan and saltmarsh.

Species	Number in saltpan (N)	Number in saltmarsh (N)	Frequency in saltpan (%)	Frequency in saltmarsh (%)
Calidris alpina	12,954	60	52	2
Charadrius hiaticula	3,832	63	15	2
Limosa limosa	2,211	42	9	1
Recurvirostra avosetta	2,135	3	9	<1
Pluvialis squatarola	370	1,253	1	42
Tringa totanus	79	535	<1	18
Charadrius alexandrinus	471	8	2	<1
Himantopus himantopus	570	11	2	<1
Phoenicopterus roseus	471	0	2	0
Calidris alba	386	2	2	<1
Egretta garzetta	23	200	<1	7
Sternula albifrons	248	15	1	1
Tadorna tadorna	171	30	1	1
Calidris minuta	110	0	<1	0
Chroicocephalus genei	80	0	<1	0
Platalea leucorodia	1	132	<1	4
Larus michahellis	36	179	51	6
Chroicocephalus ridibundus	51	17	<1	1
Larus fuscus	16	89	<1	3
Actitis hypoleucos	27	3	<1	<1
Phalacrocorax carbo	0	93	0	3
Numenius arquata	0	85	0	3
Motacilla alba	17	3	<1	<1
Ardea cinerea	5	40	<1	1
Tringa nebularia	15	11	<1	<1
Arenaria interpres	7	17	<1	1
Calidris ferruginea	7	3	<1	<1
Gallinago gallinago	7	0	<1	0
Larus spp.	0	31	0	1
Motacilla flava	4	18	<1	1
Pandion haliaetus	0	18	0	1
Spatula clypeata	2	0	<1	0
Alcedo atthis	2	1	<1	<1
Oenanthe oenanthe	0	9	0	<1
Larus audouinii	1	0	<1	0
Anas platyrhynchos	0	5	0	<1
Luscinia svecica	0	4	0	<1
Falco peregrinus	0	4	0	<1
Alauda arvensis	1	0	<1	0
Pluvialis dominica	1	0	<1	0
Larus delawarensis	1	0	<1	0
Numenius phaeopus	0	3	0	<1
Sylvia melanocephala	0	3	0	<1
Sylvia atricapilla	0	2	0	<1
Calidris pugnax	0	1	0	<1
Galerida cristata	0	1	0	<1
Podiceps cristatus	0	1	0	<1
Mareca strepera	0	1	0	<1

The most abundant species in this saltpan were dunlins (*Calidris alpina*), common ringer plover (*Charadrius hiaticula*), black-tailed godwit (*Limosa limosa*), and avocet (*Recurvirostra avosetta*) (Figure 3.1.11).

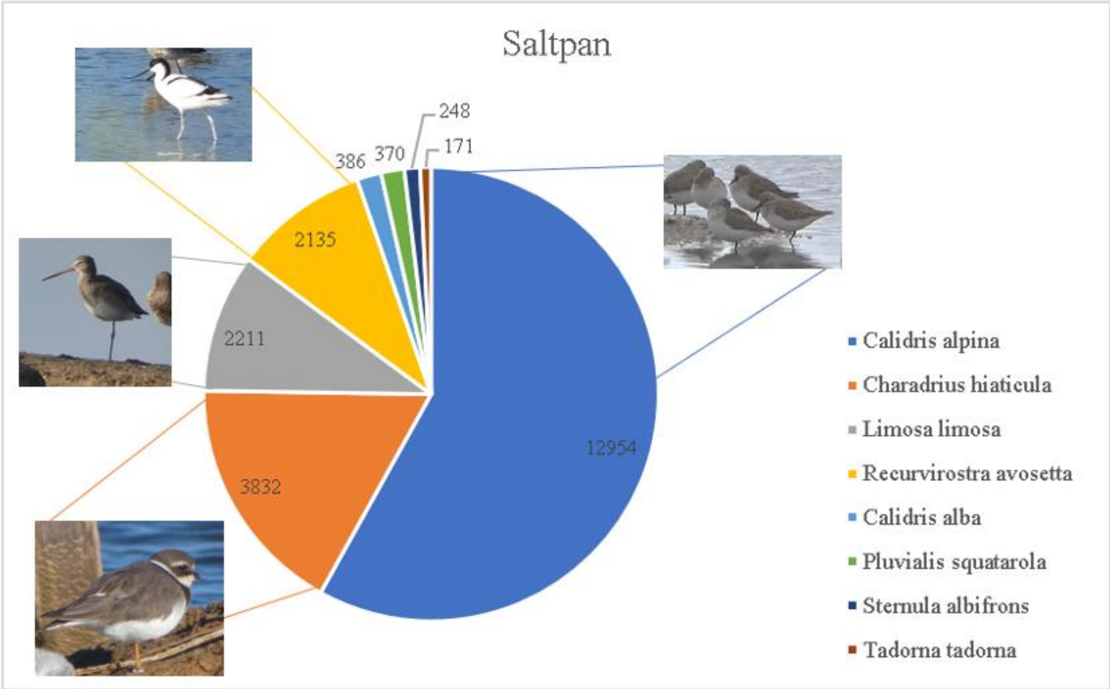

Figure 3.1.11. Total number (N) of individuals of the most abundance species observed in the saltpan. Photos taken by me in Necton saltpan

The most abundant species in the saltmarsh were grey plover (*Pluvialis squatarola*), common redshank (*Tringa totanus*), little egret (*Egretta garzetta*), and yellow-legged gull (*Larus michahellis*) (Figure 3.1.12).

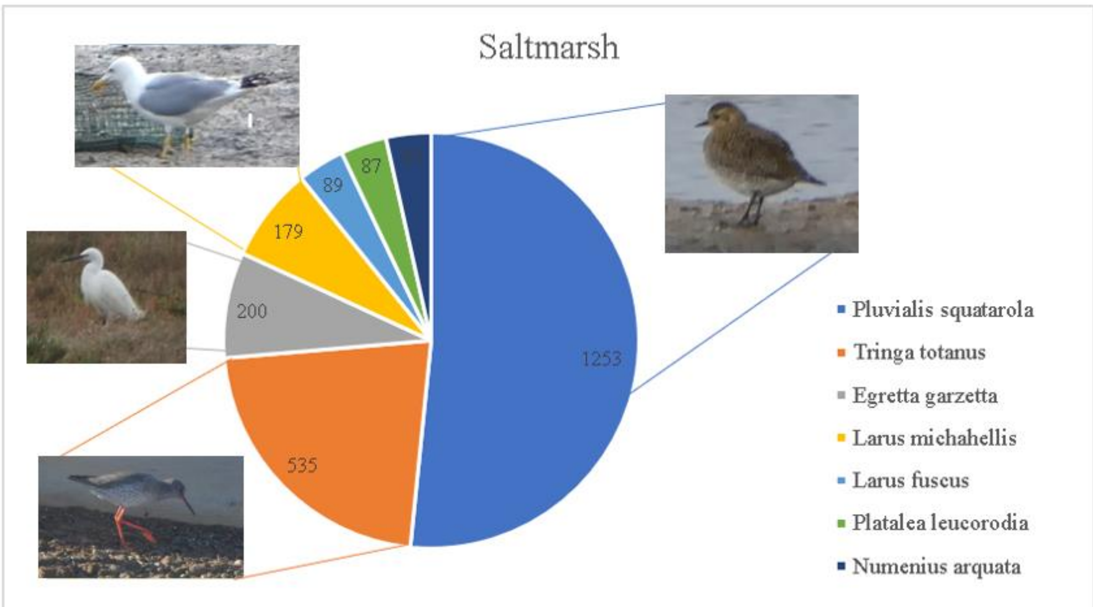

Figure 3.1.12. Total number (N) of individuals of the most abundance species observed in the saltmarsh. Photos taken by me in saltmarsh and Necton saltpan.

The different groups on the saltpan and the saltmarsh were studied to know which one present more abundance in each place and know the diversity. Both ecosystems presented great frequencies of waders, being this group the most abundance in the two places. For saltmarsh another two groups presented higher frequencies: the herons and egrets, and the seagull (Figure 3.1.13).

Table 3.1.13. Total number of individuals (N) and frequency (%) per each group present in both ecosystems.

Groups	Saltpan (N)	Saltmarsh (N)	Frequency Saltpan (%)	Frequency Saltmarsh (%)
Waders	23937	2177	95	71
Wildfowl	171	36	1	1
Passerines	29	42	0	1
Herons and Egrets	500	372	2	12
Raptors	0	22	0	1
Seagulls	432	332	2	11
Cormorant	0	94	0	3
Total	25069	3075	1	1

This saltpan was mostly used by small body size waders as *Calidris* spp. or *Charadrius* spp., with a big difference over the second more common that were the big body size waders such as *Limosa limosa*, *Recurvirostra avosetta* or *Himantopus himantopus*. As for the saltmarsh it was mostly used by medium body size waders such as *Tringa totanus*, *Pluvialis squatarola* or *Arenaria interpres* (Figure 3.1.14).

Table 3.1.14. Total number of individuals (N) and frequency (%) per body size into groups of waders. Small (10 – 20 cm body size), Medium (21 - 30 cm body size), Large (30 – 50 cm body size).

WADERS	Saltpan (N)	Saltmarsh (N)	Frequency in saltpan (%)	Frequency in saltmarsh (%)
Small	18542	215	77	10
Medium	464	1806	2	83
Large	4931	156	21	7

3.2. Blue carbon assessment

3.2.1. Saltpan age reconstruction and areas

The analysis of the historical aerial images of the saltpan showed that the configuration of the tanks was substantially changed since the earliest photograph record in 1947. An important redistribution of the tanks was done in 1972, which modified the functions of the tanks (J. Narvalho from Necton, S.A., personal communication). Based on the aerial images (Figure 3.2.1) the final evaporator tank was already built in 1947, and it was functioning as a decanter tank until 1972, when it started to act as a final evaporator, yet without any modification on its structure (Figure 3.2.1). The first evaporator was acting as a final evaporator from 1947 until 1969, when it was converted to a crystallizer, and it was transformed again in 1972 into its current structure and function (Figure 3.2.1). The decanter tank was a crystallizer in 1947, an evaporator tank in 1968, and a crystallizer again from 1969 to 1972, when the conformation changed to its current structure of decanter (Figure 3.2.1). Based in this historical analysis, the estimated age for the studied tanks acting nowadays as decanter, first and final evaporator are of 49 years for the decanter and first evaporator (both being rebuilt in 1972) and of at least 74 for the final evaporator (which has not been rebuilt since 1947).

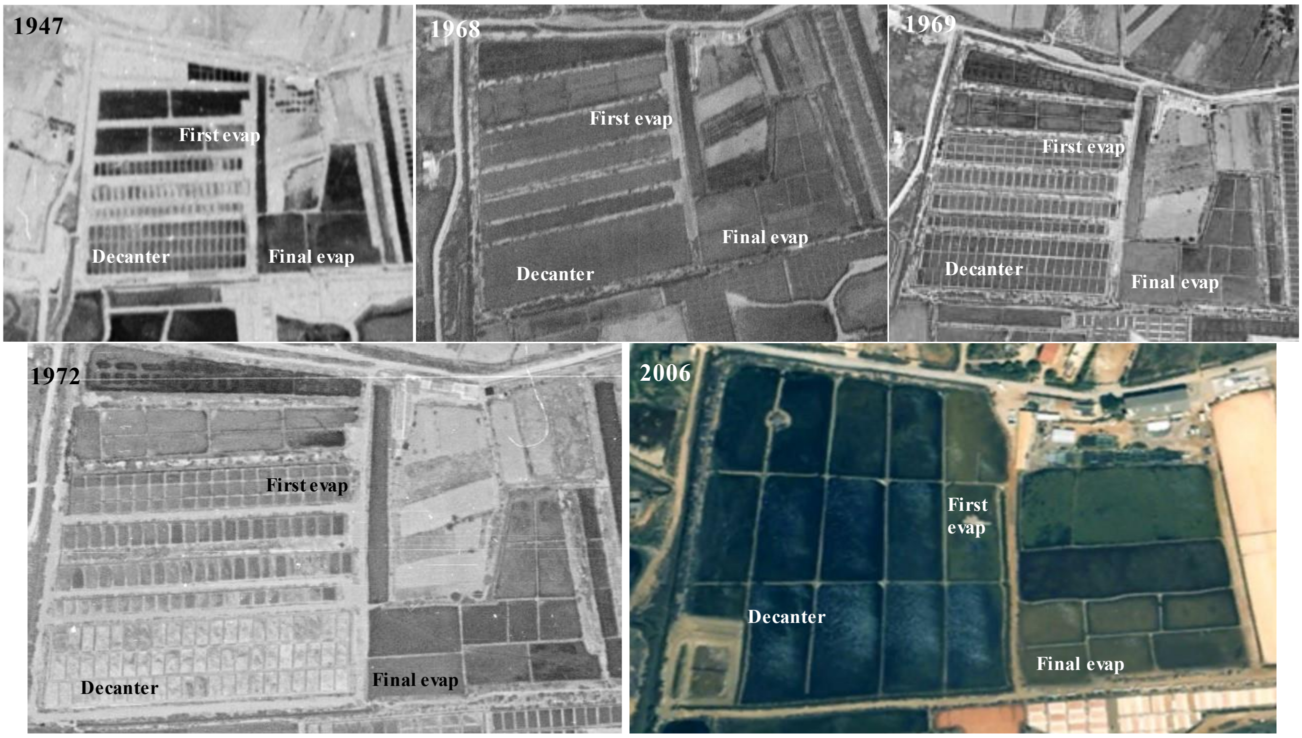

Figure 3.2.1. Historical images of the Necton saltpan obtained by the Portuguese Army Geospatial Information Centre (aerial images in black and white) and Google Earth^{TM} (satellite image in colour) that show the structural changes in the study area from 1947 to 2006. The present position of the studied tanks is shown on each image: decanter, first evaporator (first evap), and final evaporator (final evap).

The total areas of the three parts of saltpan system in the current conformation are: 2.346 m^2 for the decanter, 26.876 m^2 for all the tanks acting as first evaporator, and 11.813 m^2 for the tanks acting as final evaporators (Table 3.2.2).

Table 3.2.2. This table shows the estimated age (y) and the area of each part of the system of the saltpan (ha).

Tank type	Estimated age (y)	System part area (ha)
Decanter	49	0.2
First evaporator	49	2.7
Final evaporator	74	1.2

3.2.2. Sediment profiles and stocks

All the cores presented the same structure consisting of a superficial black muddy layer and a deeper light sandy layer (Figure 3.2.3). The black superficial layer was deeper in the final evaporator tank (~ 20 cm), followed by the decanter (~15 cm), and the first evaporator (~11 cm) (Figure 3.2.3, Figure 3.2.4)

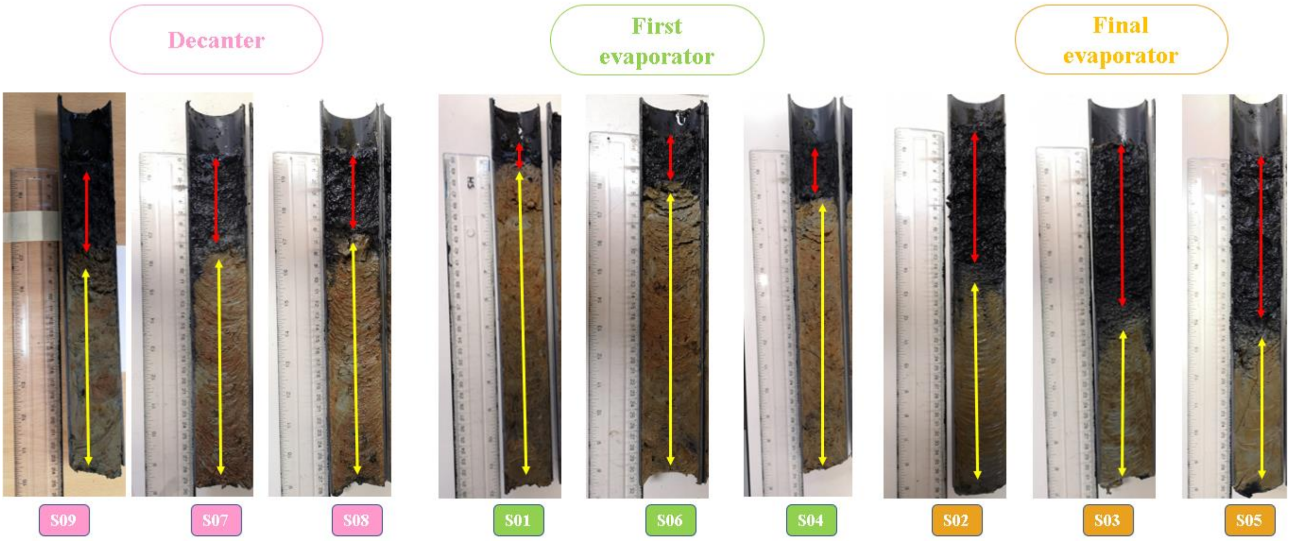

Figure 3.2.3. Photographs of the sampled soil sediment cores from the three types of tanks. Red arrows mark the superficial muddy black layers, and yellow arrows show the deep sandy layers. Code of each core is given in the bottom.

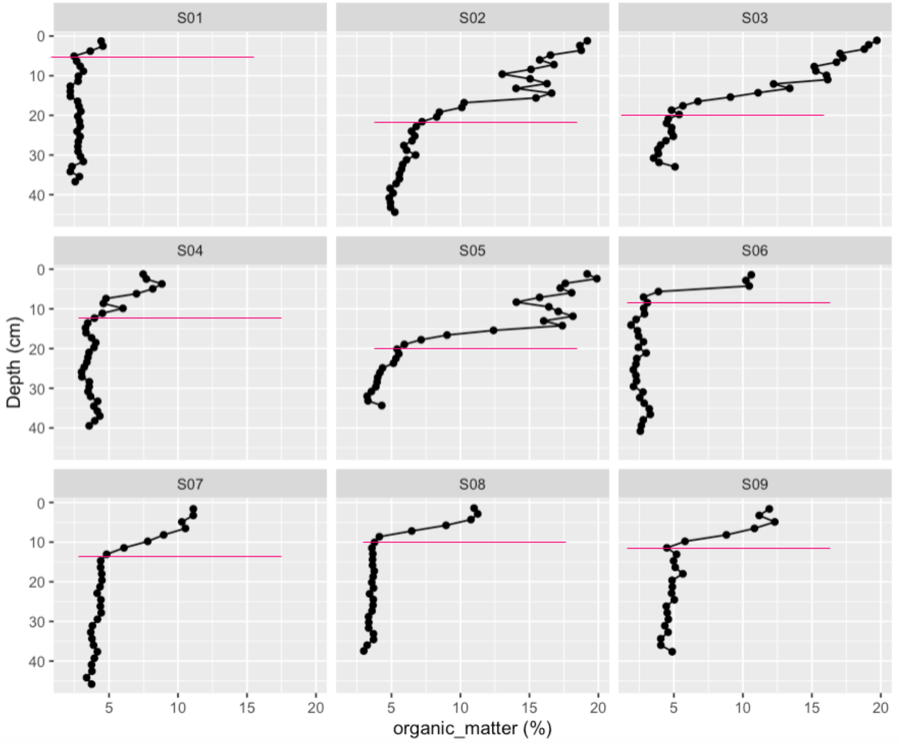

Figure 3.2.4. Depth profile of the organic matter content of each core. The pink line shows the first point where the amount of OM starts to be constant with depth, which was defined as the depth of the OM rich layer.

Similar patterns of DBD for decanter (mean = 14.2 ± 2.9 g dw cm^{-3}) and final evaporator (mean = 24.6 ± 5.6 g dw cm^{-3}) were observed, with special differences in the upper layer where decanter tank had less DBD than the cores of final evaporator (Figure 3.2.5). In the first evaporator tank (mean = 34.5 ± 6.7 g dw cm^{-3}), the sediment density was higher along all the layers of the three cores in comparison to the other tanks, with most of their values ranging between 1 to 1.3 g dw cm^{-3} (Figure 3.2.5). The DBD for the decanter and the final evaporator tanks ranged from 0.5 and 1.0 g dw cm^{-3} (Figure 3.2.5). The three tanks present significant differences between them ($p < 0.05$), being the first evaporator tank the one presenting the denser sediment, and the decanter and final evaporator showing similar sediment densities.

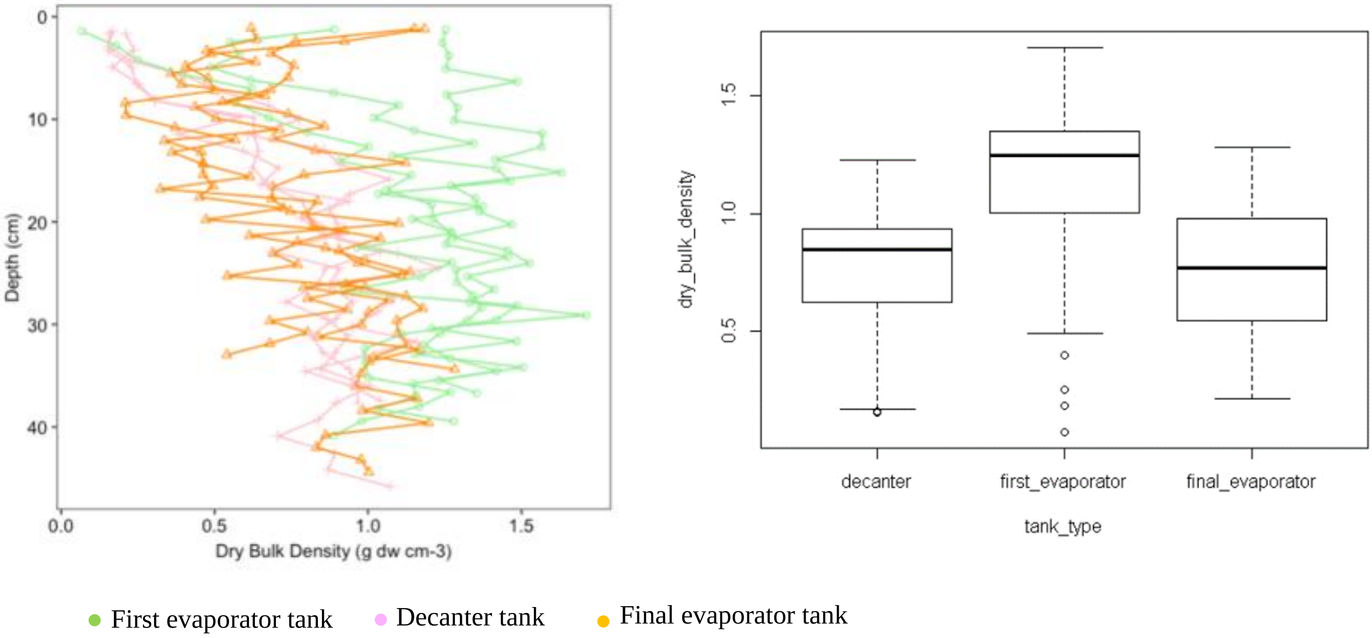

Figure 3.2.5. Left panel shows the sediment dry bulk density (DBD, g dw cm^{-3}) along depth of each core in the three tank types of the saltpan. Right panel shows boxplot of the dry bulk density per tank. The whiskers represent the minimum and maximum values, the box represent the interquartile range where the inferior part is the first quartile, and the upper part is the third quartile of the sample. The gross line represents the median.

The percentage of organic matter (OM, % dw) and organic carbon (OC, % dw) were higher in the first layer of all the cores and decreased with depth (Figure 3.2.6). In the decanter tank, the values ranged from 1 to 4 % dw and 3 to 11 % dw for OM (mean = 6.0 ± 0.8 % dw OM; mean = 1.8 ± 0.2 % dw OC) and decreased until the depth of 10 cm where it become constant. In the first evaporator tank, the range was from 1 to 3 % dw for OC and from 2 to 10 % dw for OM (mean = 3.7 ± 0.9 % dw OM; mean = 1.1 ± 0.3 % dw OC), presenting some variability in the layer until the 10 cm depth and becoming constant in the deeper layers. In the final evaporator, the values ranged from 1 to 6 % dw for OC and 4 to 20 % dw for OM (mean = 11.2 ± 0.8 % dw OM; mean = 3.4 ± 0.3 % dw OC). The final evaporator was the tank with the highest contents of OM and OC ($p < 0.05$, Figure 3.2.6), and with the deeper OM-rich layer, up to 20 cm. The other two tanks presented similar OC and OM percentage contents (Figure 3.2.6).

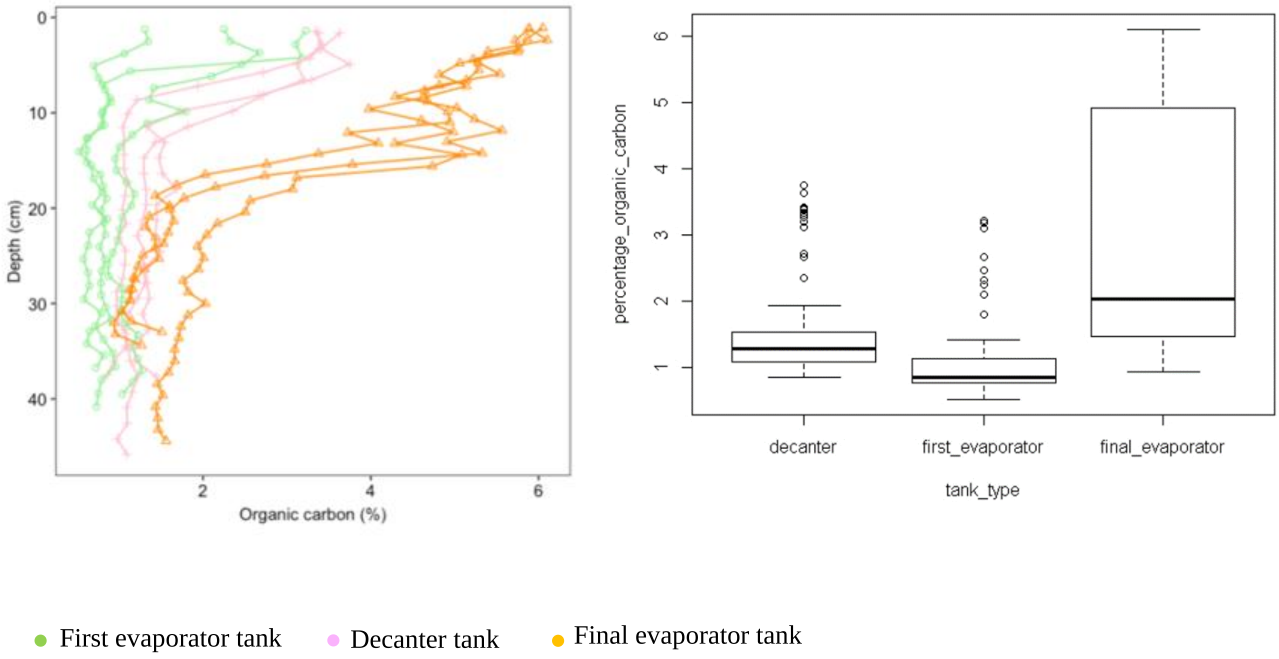

Figure 3.2.6. Organic carbon (OC, % dw) content percentage profiles (left) and boxplot of organic carbon (OC, % dw) (right) in the three types of tanks of the saltpan. The whiskers represent the minimum and maximum values, the box represent the interquartile range where the inferior part is the first quartile, and the upper part is the third quartile of the sample. The gross line represents the median.

The OM and OC stocks in the top 30 cm of the sediment varied among the tank types of the saltpan, being lower for the decanter tank (OM = 95.2 ± 5.5 Mg OM ha^{-1} ; OC = 28.3 ± Mg OC ha^{-1}) and the first evaporator tank (OM = 108.5 ± 35.5 Mg OM ha^{-1} ; OC = 23.6 ± 10.7 Mg OC ha^{-1}) and higher for the final evaporator tank (OM = 225.6 ± 52.3 Mg OM ha^{-1}; OC = 51.4 ± 16.0 Mg OC ha^{-1}) (Figure 3.2.7, Table 3.2.8, Table 3.2.9).

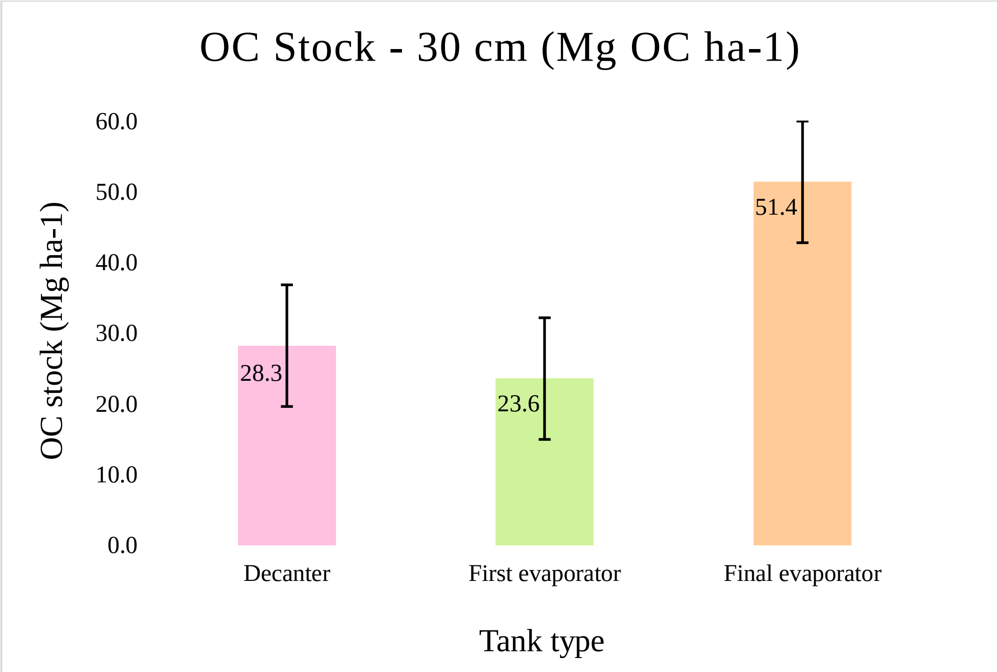

Figure 3.2.7. Average of organic carbon stock in 30 cm cores for the three cores obtained in the study with SD.

The total amount of OM and OC in each part of the system was calculated to know the scale of the stocks at the level of the saltpan. The stocks of OM and OC in three part of the system presented significant differences between them (OM, $p < 0.01$; OC, $p < 0.01$). The decanter part presented stocks of 23.3 Mg OM and 6.9 Mg OC, being the part of the saltpan with the smaller stock. The area of Necton saltpan covered by the 13 first evaporator tanks presented stocks of 292.9 Mg OM and 63.7 Mg OC. The area covered by the final evaporator part presented stocks of 270.8 Mg OM and 61.7 Mg OC, lower than in the first evaporator part, despite having the higher stocks per unit area, explained by the lower area covered by them (Table 3.2.8, Table 3.2.9).

Table 3.2.8. The table show the average in organic matter stock for each tank along the first 30 cm (g OM ha^{-1}), then the area belonging to each part of the system (ha) and the organic matter stock in each part of the saltpan system (Mg OM).

Tank type	Stock OM 30cm (Mg OM ha^{-1})	System part area (ha)	Stock OM/system part (Mg OM)
Decanter	95.2	0.2	23.3
First evaporator	108.5	2.7	292.9
Final evaporator	225.6	1.2	270.8

Table 3.2.9. The table show the average in organic carbon stock for each tank along the first 30 cm (Mg OC ha^{-1}), then the area belonging to each part of the system (ha) and the organic carbon stock in each part of the saltpan system (Mg OC).

Tank type	Stock OC 30cm (Mg OC ha^{-1})	System part area (ha)	Stock OC/system part (Mg OC)
Decanter	28.3	0.2	6.9
First evaporator	23.6	2.7	63.7
Final evaporator	51.4	1.2	61.7

3.2.3. Sediment accumulation rate and carbon sequestration

The sediment accumulation rates (SAR, cm y^{-1}) and carbon sequestration rates (CSR, g OC cm^{-2} y^{-1}) varied with the tank type ($p < 0.01$). In the decanter tank, SAR was 0.2 ± 0.04 cm y^{-1}, similarly to the first evaporator tank with a SAR of 0.2 ± 0.08 cm y^{-1}. The final evaporator tank presented a higher SAR of 0.3 ± 0.01 cm y^{-1} in comparison with the previous one. The pattern in the carbon sequestration rate (CSR) was similar, with statistically differences among them ($p < 0.01$). The decanter tank presented a CSR of 23 ± 3.91 g OC m^{-2} y^{-1}, the first evaporator tank presented similar CSR 20 ± 14.35 g OC m^{-2} y^{-1}, and the final evaporator presented the highest CSR of 63 ± 14.77 g OC m^{-2} y^{-1} (Table 3.2.10) (Figure 3.2.11).

Table 3.2.10. Organic carbon density (OCD, g OC cm^{-3}), sediment accumulation rate (SAR, cm y^{-1}) and carbon sequestration rate (CSR, g OC cm^{-2} y^{-1}) for the three types of tanks in the saltpan.

Tank type	OC density (g OC cm^{-3})	Sediment accumulation rate (cm y^{-1})	Carbon sequestration rate (g OC m^{-2} y^{-1})
Decanter	0.010	0.2	23
First evaporator	0.011	0.2	20
Final evaporator	0.023	0.3	63

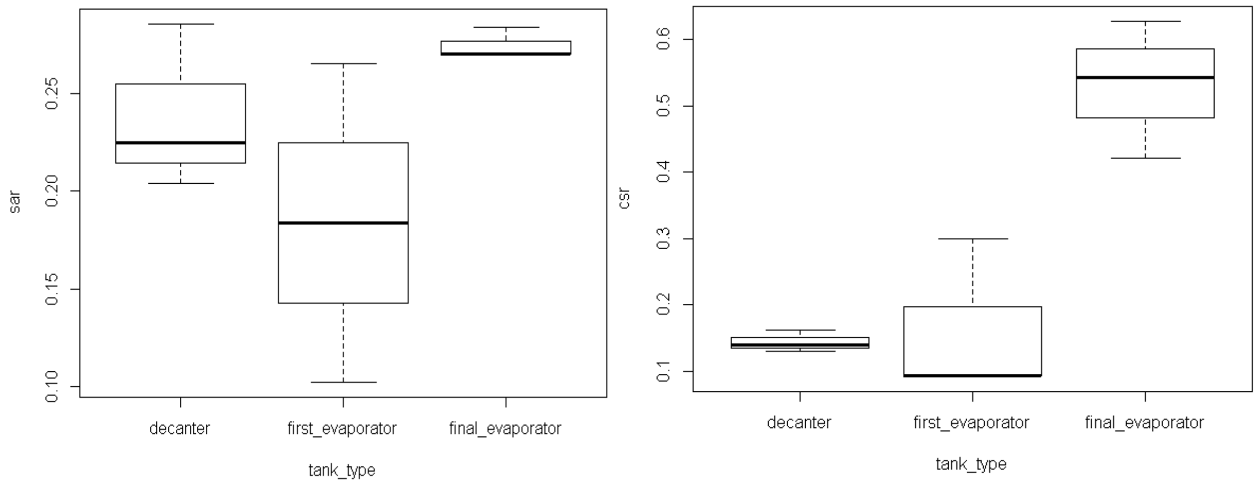

Figure 3.2.11. Boxplot of sediment accumulation rate (SAR, cm y^{-1}) and carbon sequestration rate (CSR, g OC cm^{-2} y^{-1}) in each part of the saltpan system. The whiskers represent the minimum and maximum values, the box represent the interquartile range where the inferior part is the first quartile, and the upper part is the third quartile of the sample. The gross line represents the median.

4. Discussion

4.1. Ornithological biodiversity support assessment

The Necton saltpan presented a high bird biodiversity, with 33 different species observed in nine months, and a high abundance of aquatic birds with a continuous presence of animals during the three epochs covered in the surveys. The species observed on the saltpans differed with those observed in saltmarsh, being most of the groups that belong to each one of them different. The more abundant species found on the Necton saltpan were waders. And most of the abundance waders seen on the saltpans present a decreasing in their populations worldwide (Red list of species IUCN). Waders used the saltmarsh or another natural coastal source to feed and the saltpan to rest or, as complementary feeding place where fulfil their energetic demanded if necessary (Múrias et al., 2002 and Sripanomyom et al., 2011). This is an explanation of what happened in this saltpan because the resting behaviour was the behaviour more observed during the survey. Most of the waders observed on the saltpan were waders of small body size such as *Calidris alpina*, being also one of the species with higher abundances of birds feeding. Another species with high abundance of individuals feeding was *Limosa limosa*, which body size is biggest than the previous species. Some publications show that species with small body size feed more on saltpans because need a continuous food intake and also this small type of birds consume the most abundant macroinvertebrates that are normally present on saltpans Pedro et al., 2009. This could be an explanation of why Necton saltpan presented higher abundances of small birds feeding, but also could be because the number of individuals counted of this species were far superior to any other species. The months with the highest abundances of birds were December, February, and March indicating that this saltpan is used by migratory waders in their way from high latitudes to the South to pass the Winter. It is for this that January present a lower concentration of birds because the higher concentration of the migration is already in the lower latitudes (Africa). Then during the pre-breeding migration (middle of February, March and April), in which the animals are going to the high latitudes to breed, the saltpans return to stay crowded again until the months of breed (May, June, July) where the saltpan presented the lower concentration of birds. It was observed that the saltpan was used more in high tide than in low tide. The explanation is that waders feed on the saltmarsh during the low tide and during the high tide they have to go to supratidal zones, such as the saltpans, to rest or to continue feeding in some cases, as was observed in other studies (Cruz et al., 2011). However, not all the species of waders went to the saltpan during the high tide. Normally, common redshank (*Tringa totanus*) and other big waders such as *Numenius* spp. preferred to stay on the saltmarsh, maybe looking for protection by the surrounding by vegetation. The long-leg species (*Limosa limosa*, *Recurvirostra avosetta*) were found feeding in deeper tanks meanwhile the waders with small legs (*Calidris alpina*, *Charadrius hiaticula*) were seen feeding or resting in the tanks with less depth, as previously observed in other saltpans (Rocha, 2013).

The most observed species in the saltpan were *Calidris alpina, Charadrius hiaticula*, *Limosa limosa*, *Recurvirostra avosetta, Charadrius alexandrinus, Himantopus himantopus,* and *Phoenicopterus roseus.* Most of them decreased in number during the breeding season but the Black-tailed godwit (*Limosa limosa*) disappeared completely from April to June when some individuals started to come but in lower concentration than during the big migrations. A plausible explanation is that they were the last individuals for the pre-breeding migration that were returning to the North or the first individuals of the pre-winter migrations. A high abundance of black-tailed godwit was observed in this saltpan. They have been seen often in other saltpans of the same region being a species common on the place. It is worth noting that this species is near threatened by IUCN, which is an added value to the service of biodiversity support. Eight individuals of this species were observed with legbands, but just the story life of one of them was found. This individual came from The Netherlands and was the second time that was seen in the same place. This could mean that the same individuals return to the same saltpan, year after year. The great flamingo (*Phoenicopterus roseus*) was seen in big flocks on the Necton saltpans, as also, isolated individuals that remained per months. This species came often to the saltpan to rest and feed over the *Artemia* spp. present on the Necton saltpan (Chefaoui, 2021).

The avocet (*Recurvirostra avosetta*), and black-winged stilt (*Himantopus himantopus*) are two species frequents in the saltpans of Portugal, and present a high proportion of non-migratory population (Zockler et al., 2003, Fonseca et al., 2005). They are two of the species that nest in this saltpan, together with kentish Plover (*Charadrius alexandrinus*) and likely little tern (*Sternula albifrons*). This last species is one of the common species that nest in Portugal saltpans (Cruz et al., 2011), I cannot saw any egg or chick of little tern but this species appeared on saltpan only in the breeding season, so we can assume that it is another of the species that nest in Necton saltpan.

In conclusion, saltmarsh and saltpans presents different biodiversity and species abundances. The Necton saltpan is an important area to different types of birds as wildfowl, seagulls, or egrets, but especially for waders, that come to rest in massive number during the two big migrations of their life, and acting as nesting site, also, for some wader's population. All of this makes that this saltpan having a key role in supporting bird biodiversity helping to waders in their fight against population losses.

4.2. Blue carbon assessment

Necton saltpan presented different characteristics according to the part of the system, this could indicate that abiotic factors as temperature and salinity exert controls over organic carbon and organic matter accumulations. The final evaporator tank which presented higher salinity and hot water, also presented the highest ranges in the percentages of OM and OC, highest OC and OM stocks and highest rates in sediment accumulation and carbon sequestration. In addition, this tank is the oldest tank, with a minimum age of 74 years without changes in their conformation. Thus, the sediment in this tank are the oldest sediments while the other parts of the system are younger since they were transformed in the past from crystallizers to evaporator tanks, probably involving dredging of the tanks. The principal explanation of this higher rates is that this high salinity has an influence over the remineralization of the carbon and the degradation of the organic matter (Li et al., 2019). Also, the salinity influences the sedimentary bacterial community in this type of ground by creating an extremophile environment. This question will be solved once we got the results of the environmental DNA, which will give us clues on the microbiome in the sediment and the sources of the organic matter over time. The first conformation for the final evaporator tank was a decanter, in this case, the water of Ria Formosa, rich in OM and OC, entered to the system in this tank for many years before the current structure. This could be another contributed to explain the high accumulation rate found in the final evaporator.

Comparing our results with a previous study of the carbon burial on Ria Formosa saltmarsh, we observed that the carbon sequestration on the Necton saltpan is so much higher than this obtained in the saltmarsh (Martins et al., 2021). So we can conclude that exists a sequestration and an accumulation rate of carbon in the saltpans. This is an important finding because many areas of saltpans exists around the world and they could be added to other coastal ecosystems that are considered nature-based solutions in the fighting of climate change. Saltpans could be considered then as another type of blue carbon ecosystem, or even a new term could be coined, the White Carbon, to referred to the organic carbon sequestered and stored by saltpans around the globe.

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Annex

Red list of species (IUCN) with species observed on our study are

Species name	Common name (English)	Common name (Portuguese)	Threat degree	Population (Last update)
Recurvirostra avosetta	Avocet	Alfaiate	Least concern (LC)	Unknown (2016)
Himantopus himantopus	Black-winged stilt	Pernilongo	Least concern (LC)	Increasing (2016)
Charadrius alexandrinus	Kentish plover	Borrelho-de-coleira-interrompida	Least concern (LC)	Decreasing (2016)
Charadrius hiaticula	Common ringed plover	Borrelho-grande-de-coleira	Least concern (LC)	Decreasing (2016)
Calidris alpina	Dunlin	Pilrito-comum	Least concern (LC)	Decreasing (2016)
Calidris alba	Sanderling	Pilrito-das-praias	Least concern (LC)	Unknown (2016)
Phoenicopterus roseus	Greater flamingo	Flamingo	Least concern (LC)	Increasing (2016)
Tadorna tadorna	Common shelduck	Pato-branco	Least concern (LC)	Increasing (2019)
Limosa limosa	Black-tailed godwit	Maçarico-de-bico-direito	Near threatened (NT)	Decreasing (2016)
Egretta garzetta	Little egret	Garça-branca-pequena	Least concern (LC)	Increasing (2016)
Sternula albifrons	Little tern	Chilreta	Least concern (LC)	Decreasing (2018)
Chroicocephalus genei	Slender-billed gull	Gaivota-de-bico-fino	Least concern (LC)	Unknown (2019)
Calidris minuta	Little stint	Pilrito-pequeno	Least concern (LC)	Increasing (2018)
Ardea cinerea	Grey heron	Garça-real	Least concern (LC)	Unknown (2019)
Tringa totanus	Common redshank	Perna-vermelha-comum	Least concern (LC)	Unknown (2016)
Larus michahellis	Yellow-legged gull	Gaivota-de-patas-amarelas	Least concern (LC)	Increasing (2019)
Pluvialis squatarola	Grey plover	Tarambola-cinzenta	Least concern (LC)	Decreasing (2019)
Chroicocephalus ridibundus	Black-headed gull	Guincho	Least concern (LC)	Unknown (2018)
Alcedo atthis	Common kingfisher	Guarda-rios-comum	Least concern (LC)	Unknown (2018)
Motacilla flava	Western yellow wagtail	Alvéola-amarela	Least concern (LC)	Decreasing (2018)

Pluvialis dominica	American golden plover	Tarambola-americana	Least concern (LC)	Decreasing (2016)
Tringa nebularia	Common greenshank	Perna-verde-comum	Least concern (LC)	Stable (2016)
Larus fuscus	Lesser black-backed gull	Gaivota-de-asa-escura	Least concern (LC)	Increasing (2018)
Larus delawarensis	Ring-billed gull	Gaivota-de-bico-riscado	Least concern (LC)	Increasing (2018)
Calidris ferruginea	Curlew sandpiper	Pilrito-de-bico-comprido	Near threatened (NT)	Decreasing (2016)
Actitis hypoleucos	Common sandpiper	Maçarico-das-rochas	Least concern (LC)	Decreasing (2016)
Pandion haliaetus	Osprey	Águia-pesqueira	Least concern (LC)	Increasing (2016)
Phalacrocorax carbo	Great cormorant	Corvo-marinho-de-faces-brancas	Least concern (LC)	Increasing (2018)
Gallinago gallinago	Common snipe	Narceja-comum	Least concern (LC)	Decreasing (2016)
Circus aeruginosus	Western marsh-harrier	Águia-sapeira	Least concern (LC)	Increasing (2016)
Numenius arquata	Eurasian curlew	Maçarico-real	Least concern (LC)	Decreasing (2017)
Motacilla alba	White wagtail	Alvéola-branca	Least concern (LC)	Stable (2018)
Numenius phaeopus	Whimbrel	Maçarico-galego	Least concern (LC)	Decreasing (2016)
Luscinia svecica	Bluethroat	Pisco-de-peito-azul	Least concern (LC)	Stable (2018)
Arenaria interpres	Ruddy turnstone	Vira-pedras	Least concern (LC)	Decreasing (2019)
Passer domesticus	House sparrow	Pardal-comum	Least concern (LC)	Decreasing (2016)
Anas clypeata	Northern shoveler	Pato-colhereiro	Least concern (LC)	Decreasing (2019)
Platalea leucorodia	Eurasian spoonbill	Colhereiro	Least concern (LC)	Unknown (2016)
Falco peregrinus	Peregrine falcon	Falcão-peregrino	Least concern (LC)	Stable (2016)
Spatula clypeata	Northern Shoveler	Pato-trombeteiro	Least concern (LC)	Decreasing (2019)
Alauda arvensis	Eurasian Skylark	Laverca	Least concern (LC)	Decreasing (2018)
Larus audouinii	Audouin’s gull	Gaivota-de-audouin	Vulnerable (VU)	Decreasing (2020)

Stories live by labels

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Dados de anilhagem para DEW N127179

Número de anilha	DEW N127179
Espécies	Gaivota-de-asa-escura (Larus fuscus)
Age/Sex	Ave no ninho ou não voadora [1] /Desconhecido [U]
Data de anilhagem	03/07/2020 **Time** ---- Exatamente na data
Local de anilhagem	AMRUM/ODDE (Germany, ,)
Coordinates	54°4200N, 008°2000E Algures num raio de 5 Km
Estatuto	Ave em crescimento [-]
Catching_method	No ninho [N]
Ringer/group	/
Comments	Yellow H180E

Dados de recuperação para DEW N127179

Espécies	Gaivota-de-asa-escura (Larus fuscus)
Age/Sex	Voador de idade
Recovery data	02/03/2021 **Time** ---- Exatamente na data
Recovery site	SALINAS DE OLHÃO (Portugal, Faro,)
Coordinates	36°5400N, 007°5400W Algures num raio de 5 Km
Estatuto	Desconhecido ou não registado [U]
Condition	Vivo e provavelmente saudável mas com destino desconhecido [9]
Circumstances	Ave identificada por combinação de anilhas ou anilha de cor com caracteres [81]
Finder	Saray Perez, ()
Ringer/group	/
Comments	Yellow H180E - PDF p/ O em 22/03/2021 PF

Distance: 2332 km **Direction:** 219 **Elapsed** 242 Dias (0 Anos, 7 Mês (es) e 27 Dia (s)) **Nos. Controls:** 1

Overview Black-tailed Godwit Resightings

Observer: Saray Perez

Colourcode: **1LLPVB**

Ringnr: 1LLPVB **Ringing Date:** 16-5-2014

Age (in days; 50 = juv.; 99 = ad.): 1

Name Ringer: Haije Valkema

Name 2nd Ringer:

Ringing site: Gaastmeer, De Lange Hoek

The Netherlands 52.95000 N 5.53333 E

Resightings of this bird:

Date	Site			Observer(s)
29-4-2015	Gaastmeer, De Lange Hoek	52.95000 N 5.53333 E	The Netherlands	Haije Valkema
3-5-2015	Pikesyl, Hisse- en Pikemar	53.00111 N 5.57222 E	The Netherlands	Egbert van der Velde
30-3-2017	Gaastmeer, De Lange Hoek	52.95000 N 5.53333 E	The Netherlands	Egbert van der Velde
6-6-2017	Gaastmeer, De Lange Hoek	52.95000 N 5.53333 E	The Netherlands	Tim van der Meer
5-6-2018	Pikesyl, Hisse- en Pikemar	53.00111 N 5.57222 E	The Netherlands	Egbert van der Velde
9-1-2019	Olhão, Olhão saltpans	37.01667 N -7.85000 W	Portugal	Georg Schreier
3-5-2019	Gaastmeer, De Lange Hoek	52.95000 N 5.53333 E	The Netherlands	Egbert van der Velde
27-3-2020	Gaastmeer, De Lange Hoek	52.95000 N 5.53333 E	The Netherlands	Egbert van der Velde
17-6-2020	Harich, Trophorne	52.93889 N 5.57222 E	The Netherlands	Jos Hooijmeijer
28-2-2021	Olhão, Olhão saltpans	37.01667 N -7.85000 W	Portugal	Saray Perez