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Changes in Community structure and dominance triggered by seasonal and abiotic differences in saline lagoons

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1 Abstract

The geographical distribution of species across habitats depends on the environmental conditions and biotic interactions. In coastal saline lagoons environmental conditions are highly variable due to influxes of both salt and freshwater. Despite this, many species periodically enter saline lagoons, dependant on the conditions, marine, estuarine and freshwater species have all been recorded in these habitats. Lagoonal communities are characterised by euryhaline lagoonal specialist that are adapted to tolerate the environmental variation. However little is known about how fish and invertebrate communities react to environmental change, specifically over short term changes during different periods of salt water flooding. Here we show how the community as a whole and how fish and invertebrate species individually respond to these changes.

Seasonality was the only temporal influence on community structure, however species abundance was impacted by both month and flooding phase. Temperature, dissolved oxygen, pH and turbidity all influenced community structure, however invertebrate and fish communities were impacted differently. Fish abundance increased by an average of 202% when dissolved oxygen concentration increased from 3 to 8 mg l-1, but fish diversity decreased with increasing oxygen. Temperature and fish diversity were positively correlated increasing by 49% from 10 to 15°C. Invertebrate abundance was positively correlated with salinity, increasing by 55% between 2 and 4 PSU, but negatively correlated with dissolved oxygen. Increase invertebrate diversity was only significantly linked to a decrease in chlorophyll fluorescence. There was a negative correlation between fish and invertebrate abundance, but this was not significant.

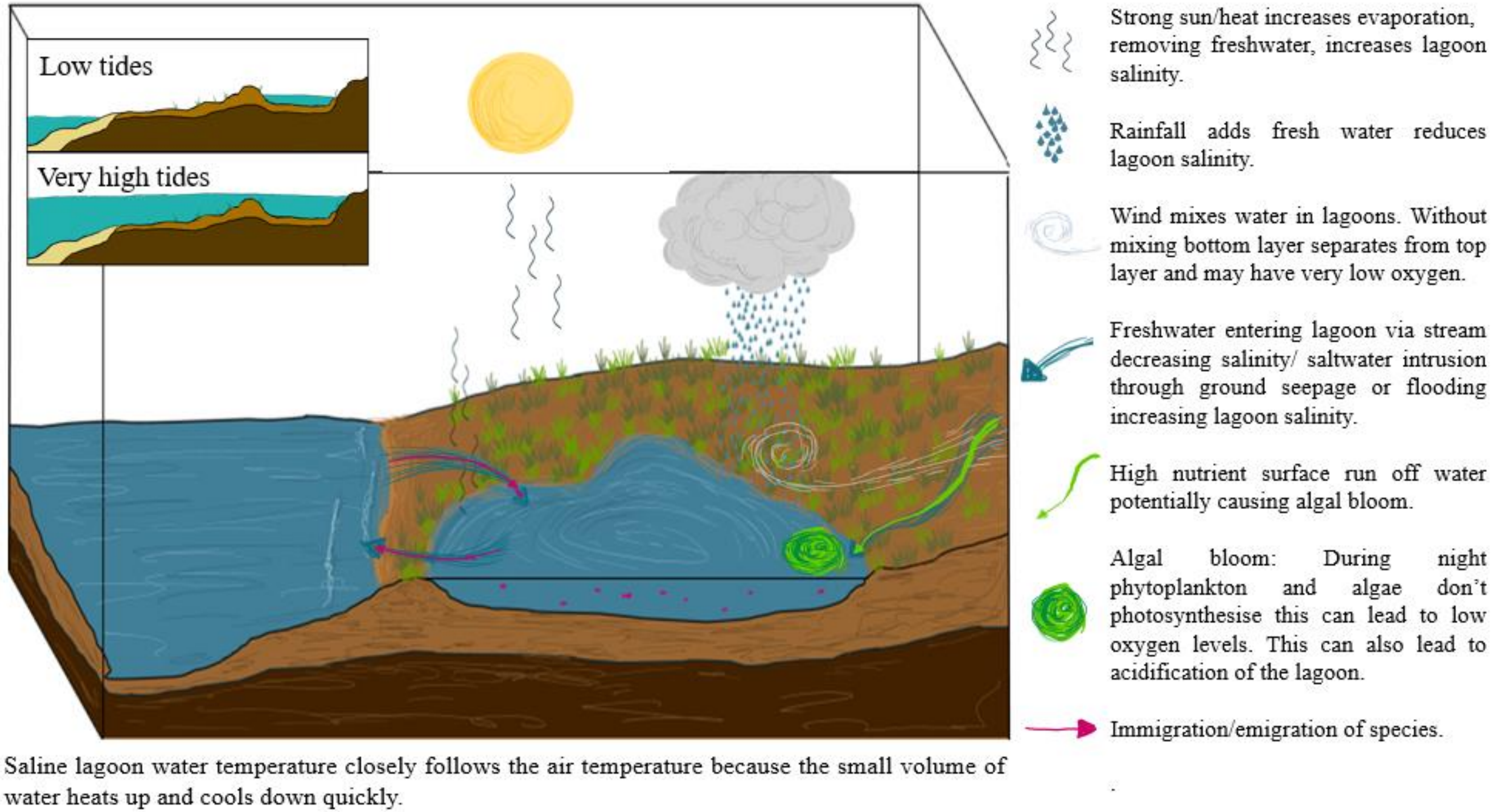
This study highlights the varied impact of environmental factors on community structures, emphasising the need for tailored management strategies in naturally stressed saline lagoons. These ecosystems are particularly vulnerable to climate change and eutrophication due to their small volume and isolated nature. By understanding how communities respond to environmental change, we can manage these habitats more effectively and restore the biodiversity of specialised and protected species.

2 Lay summary

Saline lagoons are unique coastal habitats that are irregularly flooded by seawater, often only a few days a month. This periodic flooding causes significant variability in environmental conditions such as temperature, salinity, and oxygen availability, creating a challenging environment for the organisms that inhabit them. The processes affecting the aquatic environment in saline lagoons is shown in Figure 2.2.1. Despite these harsh conditions, many species, including marine, estuarine, and freshwater organisms, are found in saline lagoons. The community present often depends on the environmental conditions; for example, freshwater species only appear when salinity levels are low. Some species, known as lagoonal specialists, are highly adapted to these variable environments and remain in the lagoons year-round. Lagoonal habitats provide important ecosystem services, these are benefits or resources from nature that are needed to sustain human life, such as nutrient recycling or carbon sequestration. Despite their importance, little is known about how these communities react to short-term environmental changes during flooding.

This study explores how the overall community, as well as individual fish and invertebrate species, respond to environmental changes. We found that seasonal variation was the primary temporal factor influencing community structure, with species abundance affected by both the month and the flooding phase. Environmental factors such as temperature and dissolved oxygen had distinct impacts on fish and invertebrate communities. Fish abundance increased significantly, by 202%, as dissolved oxygen levels rose from 3 to 8 mg l^{-1}, though fish diversity decreased with higher oxygen levels. Temperature had a positive effect on fish diversity, which increased by 49% as the temperature rose from 10°C to 15°C. Invertebrate abundance was positively correlated with salinity, increasing by 55% when salinity rose from 2 PSU to 4 PSU, but dissolved oxygen levels negatively impacted invertebrate abundance. An increase in chlorophyll levels resulted in an observed decrease in invertebrate diversity. Although fish and invertebrate abundances were negatively correlated, this relationship was not statistically significant.

Our findings highlight the varied impacts of environmental factors on community structure. Saline lagoons are particularly vulnerable to climate change and eutrophication due to their small size and isolation. This study underscores the importance of tailored management strategies that consider the complex interactions between environmental conditions and species in these fragile habitats.



Strong sun/heat increases evaporation, removing freshwater, increases lagoon salinity.

Rainfall adds fresh water reduces lagoon salinity.

Wind mixes water in lagoons. Without mixing bottom layer separates from top layer and may have very low oxygen.

Freshwater entering lagoon via stream decreasing salinity/ saltwater intrusion through ground seepage or flooding increasing lagoon salinity.

High nutrient surface run off water potentially causing algal bloom.

Algal bloom: During night phytoplankton and algae don't photosynthesise this can lead to low oxygen levels. This can also lead to acidification of the lagoon.

Immigration/emigration of species.

Saline lagoon water temperature closely follows the air temperature because the small volume of water heats up and cools down quickly.

Figure 2.2.1 Diagram of saline lagoon processes

Fresh water input from rivers and rainfall decreases salinity, evaporation and salt water intrusion increases salinity. Individuals can only immigrate/emigrate during very high tides when the lagoon is connected to the sea, Individuals can also enter via streams when connected. Polluted water that runs off of farm land encourages algal blooms leading to low oxygen levels in lagoons. Mixing by water or wind ensures the water does not separate into layers, when this happens the bottom layer can become anoxic.

3 University declarations and statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed............................[redacted]...

Date: 05/09/2024

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed............................[redacted]...

Date: 05/09/2024

I hereby give consent for my thesis, if accepted, to be available for electronic sharing

Signed............................. [redacted] ....

Date: 05/09/2024

The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

Signed...............................[redacted]...................................

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5 Acknowledgement

I would like to take this opportunity to thank everyone who has helped me throughout this project. Without you I would not have been able to complete it.

First of all my primary supervisor, Miguel Lurgi who has helped me through every aspect of this project, spent numerous hours working with me, exploring different methods of analysis and discussing the outcomes of our research. I am very grateful for everything you have done and the appreciation for community ecology that you have given me, I hope we will work together in the future.

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Finally I would like to thank my friends and family for their support over this last year and for listening to me talk about “the cool fish I found” for the last 9 months.

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8 Abbreviations and nomenclature and conversions

LSL - Lookout side lagoon
SSL - Sea side lagoon
BF - Before flooding
DF - During flooding
AF - After flooding
REC - Recovery
RFU - Relative fluorescence units
PSU - Practical salinity units
DO - Dissolved oxygne
Mesohaline: Water with a salinity greater than that of freshwater but lower than that of sea water (typically between 0.5 and 30 PSU).
Euhaline: Water of sea level salinity (typically between 30 and 35 PSU).
Hyperhaline: Water with a salinity greater than that of sea water (typically 35 PSU and above).
Stenohaline: Individuals that can only tolerate a small range of salinities.
Euryhaline: Individuals that can tolerate a wide range of salinities.

1RFU = 1 ug l^{-1} Chlorophyll

9 Introduction

9.1 Formation and characteristics of saline lagoons

Saline lagoons are shallow intertidal habitats of reduced water exchange with the sea (Kjerfve, 1994). Lagoons are naturally formed when wave action causes sediment to build up over time, creating a barrier between the sea and land. When water fills this area a lagoon is created, as sediment is constantly shifting, these habitats are geologically short lived (Bird, 1994; Kjerfve and Magill, 1989). The barrier protects the lagoon and its inhabitants from wave action. Sea water can still infiltrate the lagoon by flowing thorough inlets, percolating through the barrier or by overtopping the barrier on certain high tides or during storms (Castañares and Phleger, 1969). It is estimated that over 50% of UK saline lagoons were lost between 1980 and 2010 due to climate change and rising sea levels (Natural England, 2010; WWT, 2017). In order to preserve the rare and valuable biota, many manmade lagoons were built to help compensate for the loss of habitat (WWT, 2017).

Saline lagoons can be classified into five principal sub-types: isolated, percolation, silled and sluiced lagoons, and lagoonal inlets. These categories differ in several key aspects, including sediment type, lagoon morphology, size, and the frequency of seawater infiltration. Such variations lead to distinct environmental conditions. For instance, isolated lagoons exhibit extremely low salinity levels, whereas percolation and silled lagoons often have much higher salinity (Downie, 1996; Joint Nature Conservation Committee, 2019). Across Europe, lagoons vary significantly in their ecological and conservation importance. Notably, silled lagoons are predominantly located in Scotland and support numerous rare and protected species (Brown et al., 1977; Joint Nature Conservation Committee, 2019). The formation of different lagoon types is determined by their physical settings and the interaction of geological, hydrological, and ecological factors. Consequently, the type of lagoon influences its abiotic characteristics and the species that are able to colonise it (Wanless, 1976).

Saline lagoon habitats provide fundamental ecosystem services (these are benefits or resources from nature that are needed to sustain human life) from the production of organic matter to nutrient recycling (Fores' et al., 1994; Newton et al., 2018). The availability of high nutrient concentrations in both water and sediment supports productivity, associated with a high abundance of primary producers such as salt marsh grasses and macrophytes (Burkepile and Hay, 2006; Watanabe and Kuwae, 2015). In parallel, an abundance of decomposer organisms results in rapid nutrient recycling. The enhanced productivity provided by saline lagoons in turn supports surrounding habitats such as wetlands, mangroves, salt marsh and sea grass meadows (Basset et al., 2013). Despite their recognised importance for ecosystem services and biodiversity, the health of many coastal lagoons is declining due to ineffective management of critical threats (Chapman, 2012). There is a general lack of understanding surrounding how these lagoons and their communities are affected by intensifying weather conditions (extreme rainfall and drought) and eutrophication, leading to a decline in these habitats and their characteristic species (Barnes, 1981; Loureiro et al., 2006; Maddock, 2008).

9.2 Threats to saline lagoons

Due to their small size and shallow waters, the effects of climate change and excessive nutrient input are exacerbated in saline lagoon habitats. Droughts may cause salinity and temperature to increase rapidly, whereas excessive rainfall can have the reverse effect (Malta et al., 2017; Sousa et al., 2009). Eutrophication affects the entire ecosystem in similar ways to many other inland water bodies (Newton et al., 2003). Increased nutrient input from surface run off can lead to algal blooms, which block sunlight from reaching the vegetation below. Without sufficient light, the bottom layer of algae cannot photosynthesize and thus begins to consume oxygen for respiration, potentially leading to hypoxic conditions in the lagoon (C.E.C., 1991). Given that these water conditions are already subject to relatively large variations, these threats have the potential to disrupt the entire ecosystem.

9.3 Environmental variation

Owing to their low water volume, saline lagoons experience greater environmental variation than other intertidal habitats (Pérez-Ruzafa et al., 2019; Semprucci et al., 2019). Factors such as salinity, temperature, dissolved oxygen concentration (DO) and nutrients can vary both spatially and temporally (Chagas and Suzuki, 2005; D'Autilia et al., 2004; Medina-Gómez et al., 2014). Due to partial isolation, saline lagoons have the unique trait that these conditions not only change throughout the seasons but also over the month, this is caused by water mixing due to cyclical sea flooding events. Fluctuations in environmental conditions are reduced when a lagoon has a consistent freshwater input via a stream, or saltwater input through seepage or inlets (Carl, 1940).

Saline lagoons are characterized by a decrease in salinity in the winter and an increase in salinity during the summer. Frequency of rainfall, evaporation and sea water inundation are strong determinants of salt concentration in these habitats (Carl, 1940). Greater variation in salinities can occur in lagoons that are spatially separated and can range from almost freshwater >0.5 Practical Salinity Units (PSU) to hypersaline >35 PSU (Franco et al., 2019). Variation in temperature, pH as well as other physical characteristics are also highly associated with the input of fresh and salt water (Carl, 1940). These factors are predominantly what influences the species present in saline lagoons, but salinity specifically, is an important driver of species distribution and often accounts for disparities in community composition (Joyce et al., 2005).

9.4 Biodiversity in saline lagoons

Saline lagoons can support an array of different flora and fauna, with most organisms found in these habitats being opportunists or habitat specialists (Bamber et al., 1992a; Joyce et al., 2005). Opportunists are species that can take advantage of, or tolerate, lagoonal environments, but they are not restricted to them (Kanaya et al., 2016). Habitat specialists on the other hand, are organisms that have evolved and adapted to that environment and are thus rarely found in any other habitat. The former group can be broken down into freshwater, estuarine and marine species, while the latter can be split into stenohaline marine lagoonal specialists and euryhaline lagoonal specialists (Bamber et al., 1992b). It is important to recognise that these organisms are unlikely to reside simultaneously in the same lagoon due to their physiological differences in salinity tolerance.

Opportunists take advantage of the environment when it meets their requirements but can leave when it is no longer suitable, which is the case for freshwater species. Estuarine species are often euryhaline, meaning they have evolved tolerance to a wide range of salinities (Newton and Mudge, 2003; Tagliapietra et al., 2009). While not restricted to lagoons, these species are still important to these habitats as they support coastal and migratory bird populations including the endangered bittern (Cramp and Simmons, 1977). The families/orders of Gobidae, Mugilidae and Pleuronectiformes (Gobies, mullet and flatfish), among other species, may use mesohaline saline lagoons as nursery grounds due to their lower salinity levels, which reduces the energy expenditure on osmoregulation, thus facilitating enhanced growth potential (Stunz et al., 2001).

Lagoonal specialists are specifically adapted to saline lagoons and therefore are the characteristic flora and fauna of this habitat. In the UK there are approximately 40 lagoonal specialists, including 7 plant and 14 insect species (Davidson et al., 2014). Euryhaline lagoonal specialists are very tolerant of the temporal shifts in environmental conditions as they have adapted to deal with them (Bamber et al., 1992a). *Cerastoderma glaucum* (the lagoon cockle) for example has a much lower respiration rate than its marine counterpart (*C. edule*). This likely enables them to withstand the lower dissolved oxygen concentration during the summer months (Boyden, 1972). This species also shows reduced energy expenditure at increased temperatures which is a selective advantage in lagoonal habitats (Wilson and Elkaim, 1997). On the other hand, stenohaline marine lagoonal specialists can only tolerate a small salinity range (equivalent to marine salinities) and are rare habitat specialists, making saline lagoons important areas of conservation. It is important to note that many of these species may have evolved through allopatric speciation and thus are adapted to the specific conditions of a singular lagoon system (Dobzhansky, 1951; Porter et al., 2001).

As with most intertidal ecosystems, there are fluctuations in diversity and abundance of species throughout the year. Community composition is dependent on whether the environmental conditions being favourable to each species (Lauchlan and Nagelkerken, 2020). In the saline lagoon habitat these environmental conditions vary cyclically throughout the month, for example during flooding salinity might increase. Therefore we also expect some transient changes in community structure.

Many lagoonal specialists are now threatened by climate change and pollution as their adaptations to the specific conditions of lagoonal habitats make it difficult to inhabit other ecosystems (Angus, 2017; Bamber et al., 1992a). These adaptations prevent them from surviving outside these habitats and hence limit their ability to migrate to a more favourable environment (Bamber et al., 1992a; Barnes, 1981). Many of these species are now at risk of local extinction, and in some cases even global extinction for endemic individuals (Bamber et al., 1992a). This was the case for *Edwardsia ivelli* (Ivell's sea anemone), a euryhaline lagoonal specialist endemic to only one lagoon in West Sussex, UK that has not been recorded since 1983 (Bamber et al., 1992a; Manuel, 1975). The rapid loss of biodiversity within these environments is the reason increased conservation efforts are needed, the majority of lagoons are already protected but this is having minimal impact on the issue at hand.

9.5 Scope of the study

By recording species abundance data and taking water measurements in the months February to July, we aim to determine the cause of community change within saline lagoons. By understanding the environmental changes that cause loss of abundance and diversity, we can propose management strategies to prevent this occurring. Furthermore, we can identify the months or flooding phases where the ecosystem is most at risk. Understanding these dynamics is essential for assessing the broader implications for ecosystem health. Changes in community structure due to environmental change may result in gradual decrease in biodiversity. Where the habitat is no longer suitable for many species (for example low oxygen) their abundance will decline. Some of these species play a critical role in maintaining equilibrium within the ecosystem and a reduction in numbers can lead to further decline in habitat health and diversity (Johnson, 2000; Power et al., 1996). This study will address the gap in research in this environment. Prior studies in the UK have only recognised two fish species, *Atherina presbyter* and *Gasterosteus aculeatus* (sand smelt and three-spined stickle back), across 166 surveyed saline lagoons (Bamber et al., 1992a). Where conditions are appropriate there are likely to be many more fish species in these environments that have not yet been identified. Furthermore, seasonal variation in communities have been recognised but short-term changes have not. In a habitat that is isolated for the majority of the month, significant environmental variability is likely to occur. While some species are adapted to these conditions, it cannot be assumed that the rest of the community does not go through changes over this period, especially when they transition from isolation to connection with the marine environment.

The main aims and hypotheses of this thesis are:

1. To understand how the community changes throughout the year from one month to the next. (9.5.1)

We predict there will be an increase in juvenile marine/estuarine fish species between May and July which correlates with the spawning period of multiple species between March and May. This may also result in a decrease in invertebrates.

2. To determine if community structure changes over the course of the month, relating to different phases of flooding (before, during, after flooding and during the no flooding phase). (9.5.2)

We expect an increase in marine species during and after flooding resulting in an increase in total abundance predominantly of fish.

3. To quantify the influence of environmental conditions on the structure of saline lagoon communities. (9.5.3)

We hypothesise that salinity, temperature and dissolved oxygen concentration will have the greatest effect on community structure in these habitats.

4. To understand the effects of environmental conditions on fish abundance and diversity in saline lagoons. (9.5.4)

We predict lower salinities should be related to higher fish abundance. Salinities around 30 PSU will have the greatest diversities but salinities above this would limit both abundance and diversity. Fish abundance and diversity is predicted to increase with dissolved oxygen and temperature.

5. To understand how the environment impacts invertebrate abundance and diversity in saline lagoons. (9.5.5)

We predict invertebrate abundance and diversity to increase with dissolved oxygen concentrations, and to decrease as the environment becomes fore acidic (lower pH).

9.5.1 Investigating the seasonal changes in community structure

We hypothesise that Euryhaline species will be dominant in these lagoons due to the prolonged periods without sea water influx, resulting in variable salinities this could include estuarine species and euryhaline lagoonal specialists. It is predicted that the majority of fish in this community are likely to be juveniles due to the shallow depth of the lagoons, limiting the size of the individuals that can reside here. An expected increase in juvenile fish abundance from May through July correlates with the spawning period of multiple species between March and May. This rise in juvenile fish populations may result in a decrease in invertebrate abundance, as invertebrates are more likely to be predated upon or may burrow deeper into the substrate, thereby reducing their representation in the collected samples. This will be determined by sampling two lagoons at four different flooding phases each month to identify how the community structure changes over time.

Previous studies on saline lagoons have identified the biota present. UK based studies have focused on the invertebrate and plant communities, emphasising that many rare and protected species inhabit these environments (Barnes, 1981; Joint Nature Conservation Committee, 2019). Differences in location and habitat characteristics have been used to identify the key aspects of a lagoon that support the uncommon species (Bamber et al., 1992a). There is a lack of knowledge surrounding the fish community in these habitats, as only two species have been recorded in these studies (Angus, 2017; Bamber et al., 1992a; Barnes et al., 2008; Barnes, 1981; Healy, 1997; Herbert et al., 2018; Joyce et al., 2005; R. N. Bamber, 1991). A greater number of studies on UK fish communities have been conducted on salt marsh, a similar intertidal habitat. Salt marshes display seasonal differences in communities, showing a greater diversity during the spring to being dominated by *Dicentrarchus labrax* and *Pomatoschistus microps* (European seabass and common Goby) in autumn and low diversity during the winter months (Green et al., 2009).

9.5.2 Investigating whether there are differences in community between flooding phases

Less regulation from rainfall and greater evaporation leads to greater environmental variability during the summer. Shallow water and reduced mixing during non-flooding phases means predation from birds is more likely. We predict there will be an increase in marine species abundance and diversity during and after flooding, which will increase total abundance of fish. While there is no current knowledge to base this hypothesis on, it has been documented that the environmental conditions of saline lagoons can change rapidly between flooding (Newton and Mudge, 2003). Similar disturbances have caused shifts in dominance in other communities, for example saltwater intrusion on freshwater marshes resulted in a change in dominant vegetation as one species did not recover, leaving more space for other species to proliferate (Flynn et al., 1995).

9.5.3 Investigating what factors cause changes in community structure and dominance

We hypothesise that salinity, temperature and dissolved oxygen concentration will have the greatest effect on community structure. Many of the organism groups that may reside in these habitats do not coexist, this separation is predominantly due to different tolerances of water salinity (Bamber et al., 1992a). We expect this would result in temporal variations in community composition and structure as salinity levels fluctuate. Temperature is a well-documented driver of species distribution. Since the lagoons are subject to large temperature changes, it is expected that this will influence the presence and abundance of species. Finally, dissolved oxygen concentrations are expected to vary greatly due to high nutrient levels within these habitats (Watanabe and Kuwae, 2015). High nutrient levels can lead to algal blooms which dramatically reduce oxygen availability (C.E.C., 1991). This comparison will be made by taking measurements of temperature, dissolved oxygen concentration, salinity, pH, Turbidity and chlorophyll concentration. One water sample will be taken in each lagoon on each sample date (4 per month) to determine which factors have the greatest effect on community structure.

Previous research has indicated that changes in juvenile fish abundance are largely influenced by seasonal variations in water temperature and salinity (Iotti et al., 2023). Salinity changes in lagoonal habitats can trigger a change in dominance, where some lagoons have low mesohaline salinities, daphnia are dominant, this results in a less turbid environment. An increase in salinity can lead to the replacement of Daphnia by calanoid copepods and rotifers, subsequently resulting in reduced water clarity. The shift in zooplankton dominance can also cause a ripple effect throughout the community by altering the availability and type of food resources provided by the zooplankton (Jeppesen et al., 2007).

9.5.4 Investigating how the fish community is impacted by environmental change

It is expected that low salinities will be associated with high fish abundance, salinities closer to sea level will have increased biodiversity, but high salinity environments will limit both factors as this is what was found in a study of tropical saline lagoons (Franco et al., 2019). Fish abundance and diversity is expected to be positively correlated with dissolved oxygen concentration as higher oxygen availability allows a greater number of individuals to inhabit an area. Some species are known to deal better with low oxygen availability such as gobies and flat fish, many fish also have the adaptation to gulp air in order to survive in low oxygen environments (Gee and Gee, 1995). In hypoxic conditions (< 2 mg l^{-1}), the low respiratory distress reaction develops faster at higher temperatures, at 20°C the response is almost immediate, random movements allow the animal to return to the oxygenated water (Jones, 1952).

9.5.5 Investigating how the invertebrate community is impacted by environmental change

We predict that as invertebrate abundance and diversity will increase with dissolved oxygen concentration, at hypoxic levels (< 2 mg 1-1), oxygen has been known to limit invertebrate biomass and diversity, significantly lowering the abundance of equilibrium species such as long lived bivalves (Dauer et al., 1992). Low pHs are expected to significantly limit invertebrate abundance, specifically those that have calcium carbonate exoskeletons. Lagoons with a mean pH below 5.5 results in mollusca, malocrustacea and emphemerptera being characteristically absent due to the low abundance of dissolved carbon and calcium in the water making it difficult to maintain their calcium carbonate exoskeleton (Barnes, 1987; Fryer, 1980).

10 Methods

10.1 Study site

The study site comprises a system of saline lagoons that are part of the Llanelli Wildfowl and Wetlands Trust (WWT) Centre at 51.6650° N, 4.1252° W. This site was chosen as there were two lagoons that were appropriate to sample, also to observe the community composition of a managed lagoon system. A conservation area designated for the protection of habitats that support bird diversity within the Burry inlet on the Loughor estuary, South Wales, UK (Figure 10.1). Saline lagoons where the sampling was conducted were artificially created from salt marsh habitat in 1998 to improve fish stocks in the area and attract coastal and migratory bird populations. These lagoons are classified as isolated as they are separated from the sea for the majority of the month. Sea water only enters the lagoons by overtopping during high spring tide (> 8.2 m) or ground water seepage, they also typically have variable salinity that is often low (Downie, 1996; Joint Nature Conservation Committee, 2019). The lagoons are surrounded by saltmarsh habitat and to the north is a 2km sea wall, which prevents any landward migration of marsh vegetation.

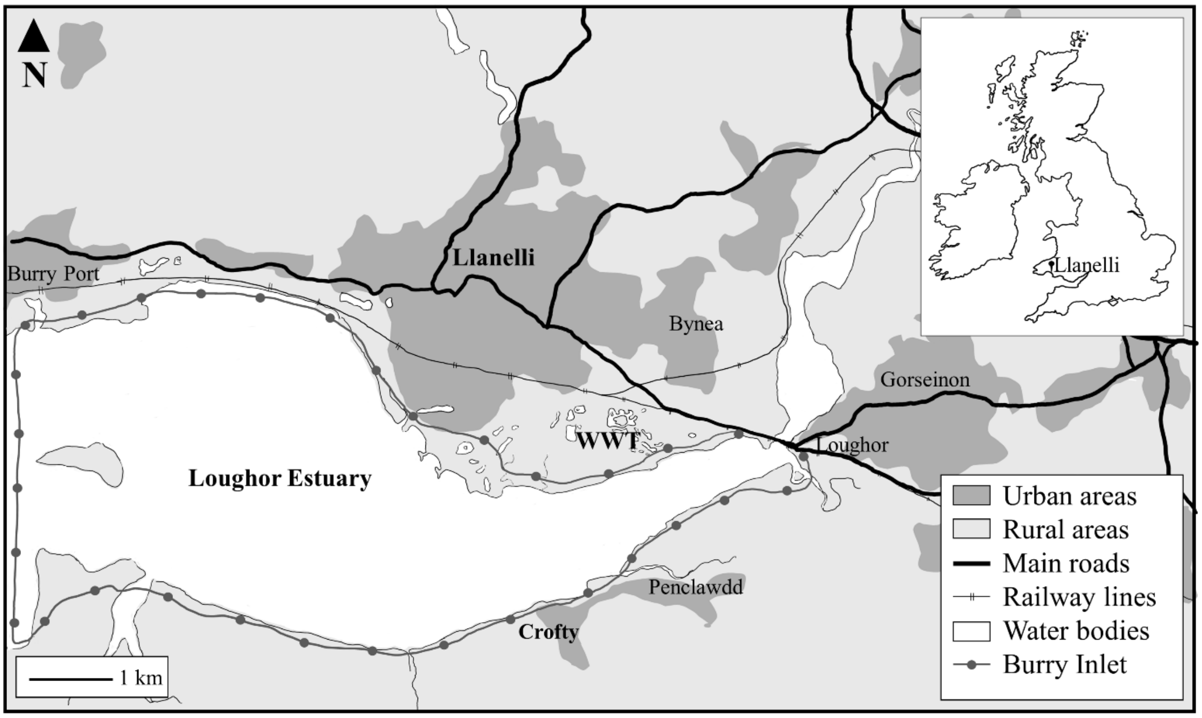

Figure 10.1 Map of Llanelli WWT and surrounding area

Our study site, the Llanelli Wildfowl and Wetland Trust (WWT) is located in Llanelli, on the Loughor estuary, South Wales, UK (51.6650° N, 4.1252°W). The wetlands here are part of the Burry Inlet Site of Special Scientific Interest, indicated by the spotted line at the sea-land connection of the Loughor estuary.

The three lagoons studied have a combined area of 45,600m2. Two larger lagoons: the lookout side lagoon and the sea-side lagoon (LSL and SSL respectively), are both approximately 20,000m^2 and have a drainage point (Figure 10.2). They are also connected by a small gap in the barrier between them that formed due to erosion. The smaller lagoon is approximately 5,000m^2 but was not sampled due to excessive debris. Depth varies greatly predominantly due to tidal variation, at the highest spring tides of 9.5m the lagoons have an approximate depth of 1.5m and all barriers separating the lagoons are also submerged. When the tide recedes, water drains out over the top of the lagoons or via the drainage points in the two larger lagoons leaving between 10-40cm of water depending on the time of year. The drainage points are controlled by staff at the wetland centre allowing control over the amount of water to be drained.

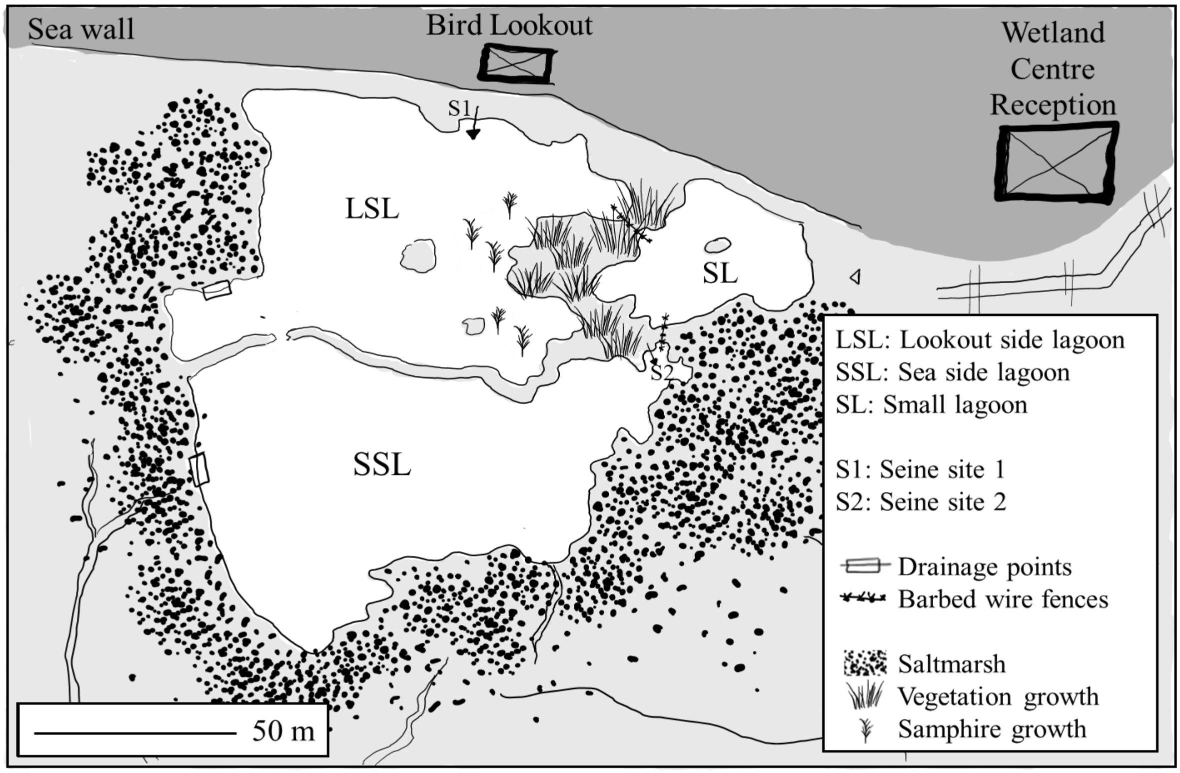

Figure 10.2 Sample site and characteristics of Llanelli saline lagoons

There are three saline lagoons, the lookout side lagoon (LSL), the seaside lagoon (SSL) and the small lagoon (SL). LSL and SSL are connected due to a break in the wall separating them. SL is isolated except during high spring tides, this however was not sampled due to debris that would rip the net. Seine deployment sites are shown in the top centre of LSL, and top right corner of SSL. Seines were deployed perpendicular to the shore from a bank that was sloped and covered an approximate area of 25m.

The tidal cycle is diurnal consisting of two neap tides and two spring tides each month, one spring tide has a greater high tide than the other and it is during this stage of the month that the saline lagoons usually flood (JNCC, 2019; US Department of Commerce, 2012). From a community ecology perspective this flooding has been treated as a perturbation of the community as it disturbs the water causing mixing and increasing salinity as well as potentially introducing predators to the habitat (Alcérreca-Huerta et al., 2019; Hairston et al., 1960). This may cause a shift in the community structure. The tidal cycle for the sampling period (February to July) is shown in Figure 10.3 where lagoonal flooding only occurs when the tide height is greater than 8.1m. During the time the lagoons are not flooding, the community may revert to its original structure.

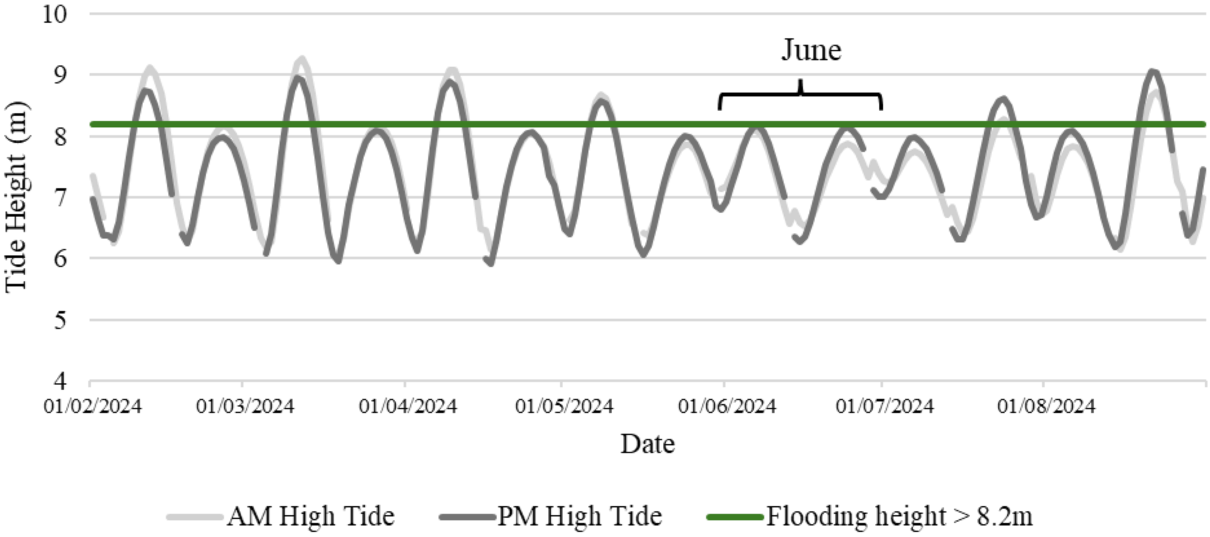

Figure 10.3 Llanelli high tide dates and heights

Llanelli high tide heights for entire sampling duration (February to August), each peak represents a spring tide and each trough a neap tide. The horizontal line symbolises the tide hight that needs to be exceeded for the lagoons to flood. June is highlighted where the tide hight does not exceed the flooding height (POLTIPS, 2022).

10.2 Sampling methodology

Aquatic communities comprising fish, malocrustaceans and bivalves, polychaetes, insects and plant species (see Table 10.1 for species list) were sampled monthly between February and July 2024 (excluding June as the lagoons did not flood, see Figure *10.3*. The two larger lagoons, LSL and SSL, were sampled four times per month: approximately 24 hours before flooding; the halfway point during flooding (this varied depending on the number of days the lagoons flooded); approximately 24 hours after the final flooding; and approximately 48 hours after that during the recovery phase (named BF, DF, AF and REC respectively) shown in Figure 10.4. This sampling design allowed us to determine the impact of a suspected environmental perturbation (flooding) on the community and the timeframe of these changes in structure. The community was sampled using a seine net, to ensure all species that inhabit both pelagic and benthic environments were surveyed (Franco et al., 2022).

10.2.1 Seine

The sample design consisted of 120 sampling events (2 lagoons x 5 months x 4 days x 3 replicates). Seine nets were chosen as the preferred catching method based on their potential to maximise catch in saltmarsh habitats (Franco et al., 2012, 2019; Verdiell-Cubedo et al., 2013). The seine net used was 15m x 2m with 3mm mesh, attached to 1.5m poles, an effective net for targeting smaller benthic-demersal species (predominantly between 20–100mm) (Franco et al., 2022, 2012). For each pond all three replicates were taken from the same location throughout the study (shown in Figure 10.2). This was because different microhabitats may occur within the lagoon may have varied communities and also because there were a limited number of places the seine net could be deployed as the lagoon banks were too steep at most points. Seine hauls were completed by two people, deployed perpendicular to the shore, each covering an area of approximately $20m^2$.

Once a seine has been completed fish and invertebrates (excluding crabs which were placed in a separate bucket) were transferred from the net to a filled 40l bucket to be processed. After all specimens had been placed in the bucket, individuals of each species were counted using a hand net then placed into a second filled bucket. Seines one and two for each lagoon remained in covered buckets until the third seine was completed to avoid recatch. After processing the catch was released in the same location it was captured.

During June when no flooding occurred the water almost completely evaporated from the lagoon. Due to this, on the before flooding sample in July, deploying the seine net was not possible. As a replacement, three 1litre grab samples were taken (per lagoon) and placed onto a white tray to analyse. Abundances of each species found for each sample were recorded.

Table 10.1 Taxonomic classifications of species observed at Llanelli saline lagoons

Taxonomic classification of species recorded during sampling. The first column shows the name used during field work, where species were given the same recorded name multiple species were observed but due to high volume recorded under the same category. Species were recorded to the highest taxonomic level possible (Class, order and species). Species without a recorded name were observed but their abundance was not recorded, and they were excluded from the analysis (Cramp and Simmons, 1977; Franco et al., 2022).

Recorded name	Class	Order	Species	Common name
	Teleostei			
		Gobiiformes		
Goby spp.			*Pomatoschistus microps*	Common goby
Goby spp.			*Pomatoschistus minutus*	Sand goby
		Mugiliformes		
Mullet spp.			*Chelon spp.*	Grey mullet
TH mullet			*Chelon ramada*	Thin lipped grey mullet
Gold mullet			*Chelon auratus*	Golden grey mullet
Flatfish		Pleuronectiformes		Flatfish
Flounder			*Platichthys flesus*	European flounder
Sole			*Buglossidium luteum*	Solenette
		Anguiliformes		
E. eel			*Anguilla anguilla*	European eel
	Malocostraca			
Amphipod		Amphipoda		Amphipod spp.
Mud scud			*Corophium volutator*	European mud scud
		Decapoda		
Shrimp spp.			*Palaemon varians*	Atlantic ditch shrimp
Shrimp spp.			*Palaemon elegans*	Rockpool shrimp
Shrimp spp.			*Crangon fabricius*	Brown shrimp
EG crab			*Carcinus maenas*	European green crab
	Bivalvia			
		Cardiida		
Cockle spp.			*Cerastoderma edule*	Common cockle
	Polychaeta			
		Spionida		
Polychaete		*Polydora spp.*		Bristle worms
	Insecta			
		Diptera		
Blood worms			*Chironomid spp.*	Chironomidae midges
Larvae			*Tipula spp.*	Cranefly larvae
		Coleoptera		
			Gyrinidae spp.	Whirligig beetles
	Liliopsida			
		Cyperales		
			Spartina spp.	Cordgrass spp.
	Ulvophyceae			
		Ulvales		
			Ulva lactuca	Sea lettuce
	Magnoliopsida			
		Apiale		
			Crithmum maritimum	Rock samphire

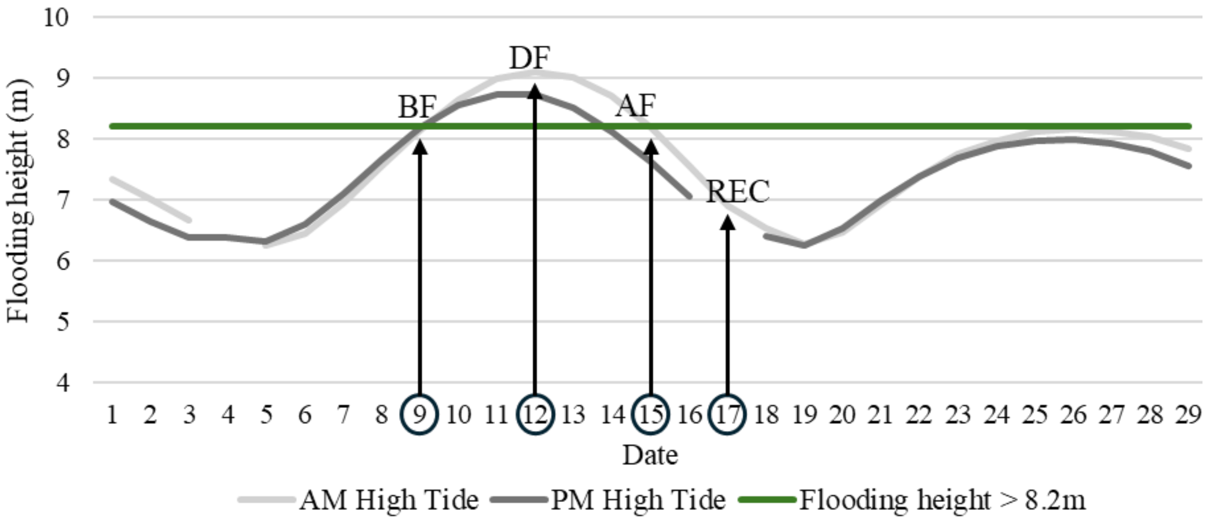

Figure 10.4 Example of a sampling schedule for the month of February
Sample schedule for February based on high tide heights and approximate flooding period of six days. The graphs shows the different sample dates: 09/02 ~ before flooding, 12/02 ~ during flooding, 15/02 ~ after flooding and 17/02 ~ recovery (POLTIPS, 2022).

10.2.2 Water Assessment

Water measurements were taken during the sampling period, at the same locations where seine nets were deployed, prior to seine hauls to avoid water mixing. A total of 80 measurements were taken (2 ponds x 5 months x 4 days x (1 measurement + 1 water sample)). Temperature and dissolved oxygen (DO) were measured in the field using a DO probe (consistently submerged by 10 cm during all measurements). Water samples were collected from each lagoon to measure chlorophyll concentration in the lab. For this, 100 ml of water was collected and added to a container already containing 300 ml of 99% ethanol, resulting thus in a 75% ethanol solution that allowed us to euthanise zooplankton and prevent change in chlorophyll concentration (Black and Dodson, 2003; Joyce et al., 2005). Water samples were then tested in the lab using a multiparameter sonde (insitu device) to measure pH, salinity, turbidity, and chlorophyl-a Fluorescence. Two measurements from each sample were taken and an average calculated. Since three quarters of the water samples was almost pure ethanol, obtained measurements were multiplied by four to approximate the true values.

10.3 Data Analysis

Information from the sampling data were summarised as abundances of individual species per sample (all three seines were combined). The data were transformed using a Hellinger transformation, converting species abundances to relative values and applying a square root. To address our first two hypotheses about how community structure varies between months and flooding phases, we used Non-metric Multidimensional Scaling (NMDS) to visualize the differences. Pairwise Permutational Analysis of Variance (PERMANOVA) and two-way Analysis of Variance (ANOVA) were then applied to quantify these differences in community structure. First an NMDS, using Bray-Curtis distances was used to quantify the dissimilarity in species composition between samples. This was applied to community abundance data to visualize the differences in community structure between months using the R vegan package (Oksanen et al., 2024). We focused on the first two dimensions of the NMDS as these explained the majority of the variation in the data and assessed the differences along these dimensions between the analysed communities. Pairwise PERMANOVA was used to quantify these differences across months and flooding phases, in order to determine the temporal influences of community composition. We used the 0.05 cut off for the p-value to establish significance in the differences across groups. Community differences were also tested using pairwise PERMANOVA for significance between flooding phases.

Two-way ANOVAs were conducted on two response variables: total species abundance (square root transformed) and alpha diversity (using Shannon Weaver diversity index). We used month and flooding phase as the explanatory variables to determine if they were significant predictors of total abundance and diversity. The lagoons were not treated as separate variables in the ANOVA due to multiple breaks in the divide, allowing migration and preventing their independence. Interactions between factors were also not used due to the small sample size that could potentially lead to errors. The residuals of the model were tested for normality using the Shapiro-Wilk test for normality, where the p-value was greater than 0.05 the model was accepted. To test which groups within the month and flooding phase variables were significant, we used Tukey's Honest Significant Difference (HSD) test.

A Pairwise PERMANOVA was performed on Hellinger transformed environmental variables (dissolved oxygen concentration, temperature, pH, salinity, turbidity and chlorophyll). Two models were created: the first using month as the explanatory variable and the second with flooding phase. This was to determine whether each month or flooding phase had a significantly different environment from the rest, the p-value cut off was 0.05 here. As each variable can respond differently to temporal change a two-way Analysis of Variance (ANOVA) was conducted for each to determine if changes were associated with month or flooding phase. No interactions between predictor variables were incorporated into the model due to the small sample size of groups. The residuals of the model were tested for normality using the Shapiro-Wilk test for normality, where the p-value was greater than 0.05 the model was accepted.

To address our third hypothesis, we assessed the relationship between community composition and environmental parameters by performing a Redundancy Analysis (RDA). RDA was conducted using the Hellinger-transformed community data and the standardised water parameters as response and predictor variables respectively. Water data was standardised using the scale() function in R, which centres each variable by subtracting its mean and scales it by dividing by its standard deviation, resulting in a mean of 0 and a standard deviation of 1. We tested all possible combinations of variables and chose the model with the highest R^2. An Analysis of Variance for Constrained Correspondence Analysis (ANOVA.CCA) was then performed on the outcome of the RDA to determine which environmental variables had a significant impact on community composition.

Subsequently, the community was partitioned into three distinct groups: fish, invertebrates, and shrimp. This allowed us to address the final two hypotheses investigating the effect of environmental parameters on fish and invertebrates separately. The decision to separate shrimp from the invertebrates was due to the typically larger abundance of shrimp compared to other invertebrates. Generalised Linear Models (GLM) were used to assess the effect of environment on abundance and diversity of each group (only abundance was assessed for shrimp). Abundance data were square root transformed and diversity was calculated using Shannon Weaver diversity index. All GLMs were fitted using Gaussian distribution on abundance and Shannon diversity (separately). The dredge function from the MuMIn package in R was used to compare all possible combinations of the explanatory variables (dissolved oxygen concentration, temperature, pH, salinity, turbidity and chlorophyll) within the model. This function selects the model with the lowest AIC value and the best fit (Barton, 2024). Residuals were tested for normality using the Shapiro-Wilk test for normality, where the p-value was greater than 0.05 the model was accepted.

All statistical analyses were performed in R and RStudio (R Core Team, 2021).

11 Results

11.1 Dominant and rare species in saline lagoons

Sampled individuals were distributed among a total of 13 identified animal Orders belonging to eight different Classes (Table 10.1). Seven fish (teleost) species were observed, including the endangered *Anguilla Anguilla* (European eel) that was captured on two occasions in February and March. The most abundant fish species were species in the family Gobidae (*Pomatoschistus microps and P. minutus*) during the winter months with a mean abundance of 285 in February. Towards the spring-summer months (May and July) their numbers declined and abundance of Mugilidae species increased (this can be seen in the Supplementary Results Figure 15.1 and Figure 15.2). Both *Chelon ramada* and *Chelon auratus* were identified in this genus of mullets, with a mean of 265 individuals captured per sample in May decreasing to 30 in July. Pleuronectiformes including *Platichthys flesus* and *Buglossidium luteum* (European flounder and Solenette, respectively) were predominantly found in May, present in small numbers in April but missing from other months.

Five orders of invertebrate species were identified during sampling events, the most abundant group among invertebrates were the shrimp species with a mean abundance of 300 individuals captured per sample. *Palaemon varians, Palaemon elegans* and *Crangon fabricius* were observed, however the abundance of each species is not known as the majority were too small to identify accurately. Abundance of *Carcinus maenas* (European green crab) started low but increased into the summer months, while amphipod abundance including *Corophium volutator* (European mud scud) remained low from February to May then significantly increased in July (predominantly *C. volutator*). All data is available in the Supplementary Results, Table 15.1.

11.2 Temporal dynamics of community composition

Using pairwise Permutational Analysis of Variance (PERMANOVA), differences in community structure were observed between most months, with the largest differences found between February and May (F = 28.03, P adj. = 0.01), February and July, (F = 14.37, P adj. = 0.01) and March and July (F = 11.39, P adj. = 0.01). During the before flooding (BF) survey in July, the lagoons almost completely dry, creating larger variability between samples (Figure 11.1). No significant differences in community structure were found between flooding phases (see Supplementary Results Table 15.2 for full results). Further analysis revealed that total species abundance (sum of all individuals) differed significantly across both months and flooding phases (Month: Df = 4, F = 5.03, p = 0.003; FP: Df = 3, F = 3.55, p = 0.025). Total abundance increased significantly from March to May, and then decreased from April/May to July (March-May: diff = 11.5, p adj = 0.045; May-July: diff = -15.6, p adj = 0.003; April-July: diff = -12.3, p adj = 0.029). Within months, total abundance increased significantly from before to after flooding (diff = 11.0, p adj = 0.019). Total diversity did not significantly change across months or flooding phases. Full results in Supplementary Results, Table 15.4, Table 15.5 and Table 15.6.

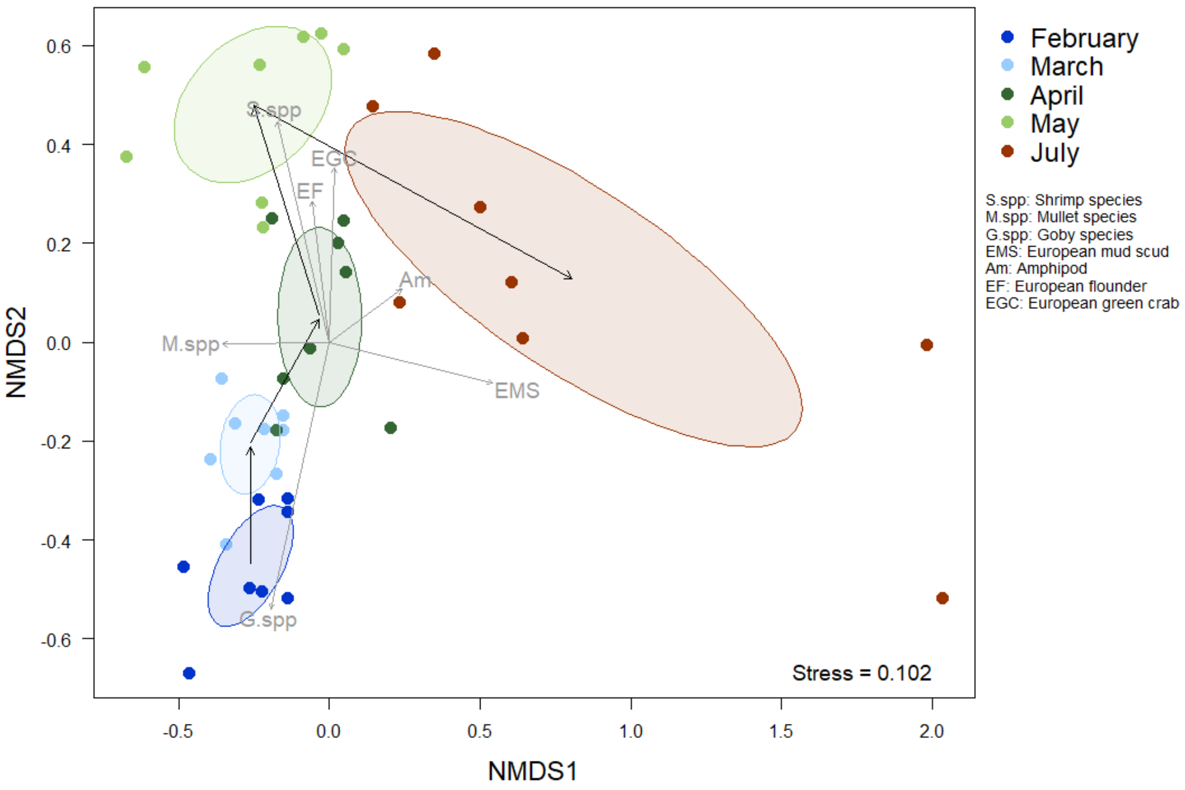

Figure 11.1 Seasonal changes in community structure

NMDS showing sample points of community structure, each colour represents a month, eight samples were taken per month, and arrows show temporal direction. Axes represent reduced dimensions of the community abundance matrix, an accurate representation of the multidimensional model as a stress value of 0.101 is exhibited. Grey labels represent species that were significantly associated with each direction and axis. The two outliers in July on the far right were 11 grab samples as on this day there was no water in the lagoon.

11.3 Distinctive difference in environment between months and flooding

Using pairwise Permutational Analysis Of Variance (PERMANOVA), differences in environmental conditions were identified between multiple months (February-July: Df = 1, p adj = 0.01; March-May: Df = 1, p adj = 0.02; April-May: Df = 1, p adj = 0.03; May-July: Df = 1, p adj = 0.01), but showed no significant differences across flooding phases (months combined).

Two-way Analysis Of Variance (ANOVA) were used to determine if changes in environmental factors (individually) could be linked to month or flooding phase.

Water temperature and dissolved oxygen concentration varied greatly over the study, ranging from 7.00 to 24.50 C (12.39 ± 4.06 SD) and 2.56 to 13.00 PPM (7.86 ± 2.19 SD) respectively. As expected, water temperature increased significantly from the winter, colder months to the warmer, spring/summer ones (Df = 4, F = 31.36, p = 3.93 x 10^{-11}), with the highest temperatures observed in May and July (Figure 11.2). Dissolved oxygen varied greatly over both months and flooding phase (M: Df = 4, F = 4.16, p = 0.001; PF: Df = 3, F = 7.18, p = 0.007), a wider range of values was observed in April and May, coinciding with the onset of macroalgae growth in the lagoons.

Turbidity and pH by month (Tur: Df = 4, F = 10.00, p = 1.66 x 10^{-5}; pH: Df = 4, F = 4.36, p = 0.006). Turbidity stayed relatively low (usually between 3 and 200 NTU) except for in July when turbidity reached 496 NTU. pH ranged between 7.64 and 8.75 but had greater variability in February, May and July.

Salinity and chlorophyll fluorescence month and flooding phase (Sal:M: Df = 4, F = 26.51, p = 0.000; Sal:FP: Df = 3, F = 5.93, p = 0.002; Chlor:M: Df = 4, F = 10.20, p = 1.94 x 10^{-5}, Chlor:FP: Df = 3, F = 10.03, p = 8.22 x 10^{-5}). Salinity was not as high as expected only ranging from 0.11 to 8.61 PSU, increases were observed during and after flooding, as well as a significant rise in July. Chlorophyll fluorescence ranged from 0.03 to 4.6 RFU, this was much lower in May when macroalgae abundance was at its greatest and was also highest before flooding.

There was likely an interaction between month and flooding phase here however due to a small number of samples this was not able to be tested.

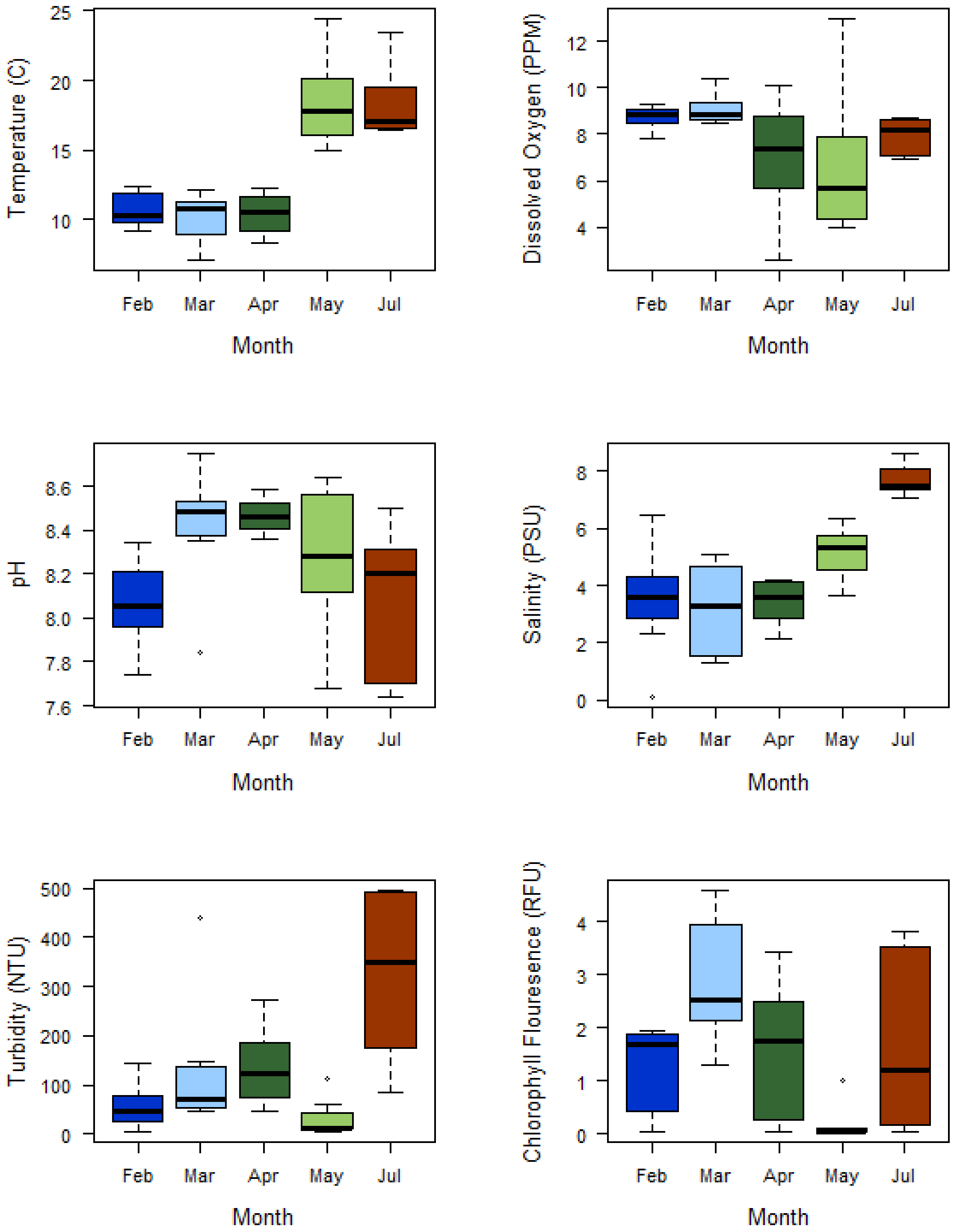

Figure 11.2 Seasonal variation in environmental conditions

Monthly variation in temperature, dissolved oxygen concentration, pH, salinity, turbidity and chlorophyll fluorescence in the water. The central black line in each box shows the median value of the distribution, while the vertical limits of the boxes show upper and lower quartiles. The whiskers show the range and points are outliers. Each month consisted of eight water samples (i.e. n=8 per box).

11.4 Water temperature accounts for the greatest community change

Analysis of Variance on the distance-based Redundancy Analysis revealed that environmental differences across samples were able to account for almost 48% of variation in community structure of saline lagoons through time. Residuals accounted for 52% of variation, this is variation that is unexplained in the model suggesting variables not recorded also influence community structure. Amongst environmental factors, water temperature was the strongest predictor, accounting for 16.95% of community variation (Df = 1, p = 0.001), dissolved oxygen however, only accounted for 6.23% of community variation which was less than expected (Df = 1, p = 0.005). Turbidity and pH accounted for 14.44% and 10.29% of the variation in community composition, respectively. (Tur: Df = 1, p = 0.001, pH: Df = 1, p = 0.001; Figure ***11.3***)

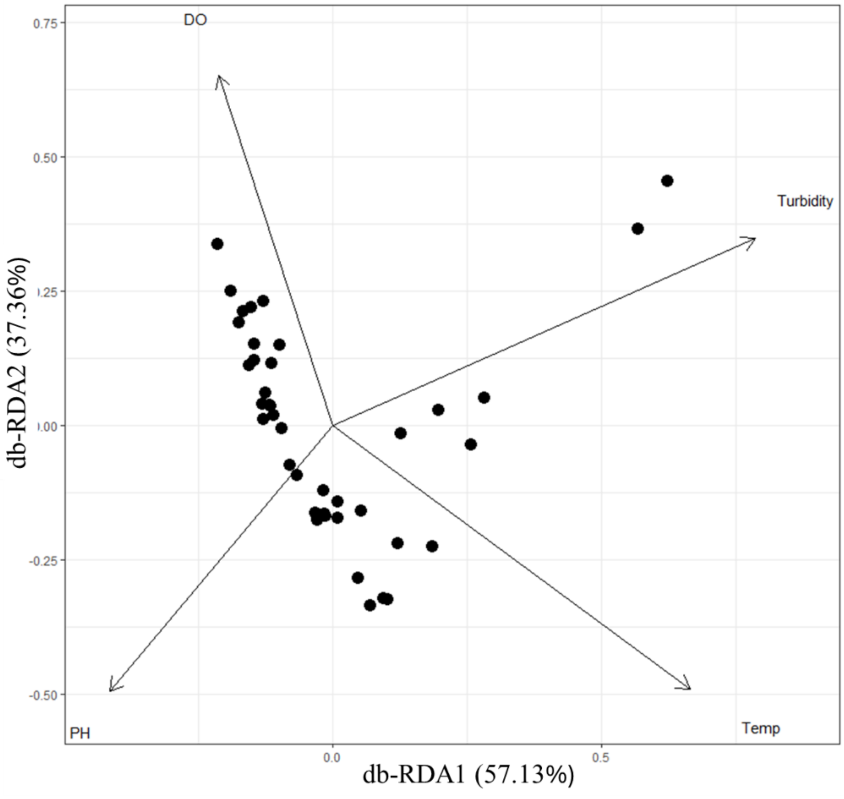

Figure 11.3 Influence of temperature, turbidity, pH and oxygen on community structure

Distanced based Redundancy analysis visualising the impact of environmental factors on community structure. Axis db-RDA1 explaining 57.13% of the variation in community structure and axis db-RDA2 explaining 37.36%. The direction of the arrows indicates the gradient of each environmental parameter, with longer arrows representing stronger gradients. Points represent community samples, and those positioned closer to an arrow suggest that the community was associated with higher levels of the corresponding environmental parameter. Water temperature accounted for 16.95% of community variation, turbidity for 14.44%, pH for 10.29% and dissolved oxygen for 6.23%.

11.5 Oxygen availability linked to changes in abundance and diversity

Generalised Linear Models with a Gaussian distribution were used to identify the impact of environment on invertebrate and fish abundance and Shannon diversity.

Abundance of fish increased significantly with increased oxygen availability (Est = 2.33, p = 1.34 x 10^{-5}). When dissolved oxygen concentration (DO) increased from 3mg/l to 8mg/l fish abundance increased by an average of 202%, Figure 11.4. Temperature, Turbidity and chlorophyll were all negatively correlated with fish abundance (Temp: Est = -0.85, p = 0.003; Turbidity: Est = -0.02, p = 0.003; Chlor: Est = -2.47, p = 0.004). DO and chlorophyll were potentially negatively correlated here as high chlorophyll concentration due to phytoplankton abundance can lead to a decrease in water oxygen levels over night, but no interaction was found between these variables.

Temperature was found to be strongly related to fish diversity (Estimate = 0.04, p = 0.001). Mean species biodiversity (richness and evenness) rose by an average of 50% when temperature increased from 10°C to 15°C. Fish diversity was also positively correlated with chlorophyll fluorescence (Est = 0.10, p = 0.018). Chlorophyll fluorescence elevated species biodiversity by an average of 55% when an increase from 0.5 RFU to 2.5 RFU was observed. Increases in both oxygen concentration and turbidity were negatively related to fish species richness and evenness (DO: Est = -0.07, $p < 0.003$; Tur: Est = -0.001, $p < 0.001$).

In Figure 11.4 the relationships between variables (water temperature, DO and chlorophyll) and fish abundance appear to contrast with those observed between the same variables and Shannon diversity. The relationship between fish abundance and fish diversity was tested using Pearsons correlation, however this was not significant.

Invertebrate abundance was negatively correlated with dissolved oxygen concentration (Est = -0.26, p = 0.024), but positively correlated with salinity (Est = 0.43, p = 0.017). An elevation in salinity of 4 PSU (from 2 PSU to 6 PSU) increased invertebrate abundance by an average 60%. Invertebrate diversity, on the other hand, was only negatively correlated with chlorophyll fluorescence (Est = -0.14, p = 0.02), while shrimp abundance was negatively correlated with both chlorophyll and turbidity (Chlor: Est = -2.35, p = 0.018; Tur: Est = 0.02, p = 0.049). A negative correlation was observed between invertebrate and fish species however this was not statistically significant (z = -1.7963, $p > 0.05$).

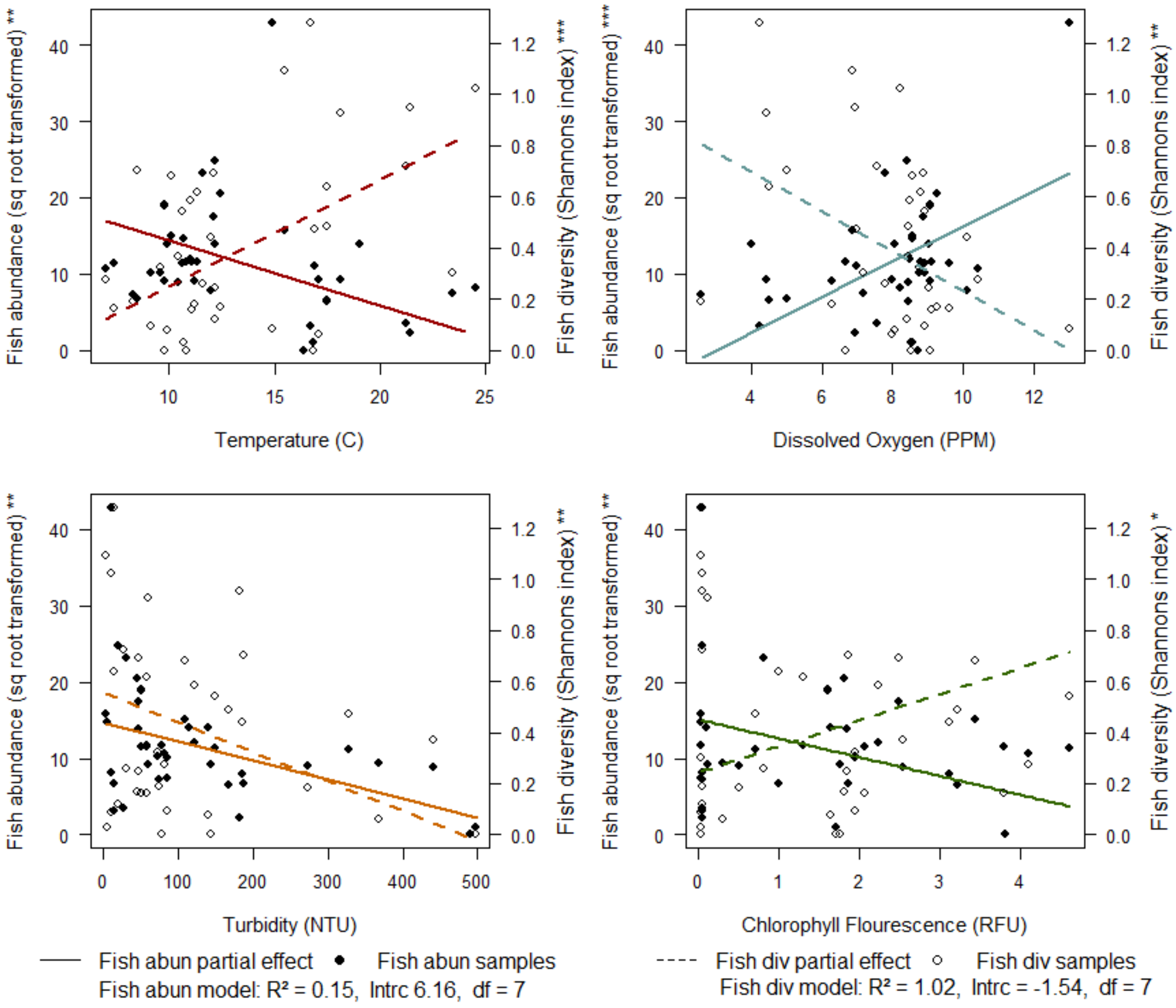

Figure 11.4 Correlation between fish abundance and diversity and water parameters.

Variation in fish abundance and Shannon diversity explained by water temperature, dissolved oxygen concentration, turbidity and pH. Samples are indicated by solid or outlined points and solid or dashed lines show partial effect of the model for each variable. Contrasting correlations can be seen between water temperature and fish abundance and water temperature and Shannon diversity (Est = -0.85, Est = 0.04 respectively). This was also seen with oxygen concentration (Est =2.33, Est=0.07) and chlorophyll fluorescence (Est = 2.47, Est = 0.10).

12 Discussion

Seven Teleost species were observed including Mugiliidae, gobidae and Pleuronectiforms species, *Anguilla Anguilla* and *Gasterosteus aculeatus*, in comparison only two species were found in previous studies *G. aculeatus* and *A. presbyter* (Bamber et al., 1992a). High seasonal variation in species composition and abundance shows the community changes significantly throughout the year.

The short term variability of community structure in saline lagoons can be linked to a number of environmental parameters. In this study all variables linked to at least one aspect of community structure. Despite these variables explaining much of the change in community structure, there are variables that were not considered during this study that may also impact the community. These include; depth, nitrogen and phosphorus concentration, as well as details on habitat complexity, in particular macroalgal cover and substrate type. The inclusion of these variables may result in a more comprehensive understanding of the factors affecting community composition and structure in saline lagoons. Another variable that was partially considered was flooding, to better understand the impact of intermittent flooding the volume of water exchanged and flood duration should also be taken into account.

Dissolved oxygen concentration appears to be one of the greater influences of abundance and diversity in saline lagoons. However, the relationship between environmental variables and invertebrate abundance and diversity may not be accurate. This is due to the use of seine nets which are predominantly designed to sample the water column and catch fish. Many invertebrate species live within the sediment, therefore the abundances obtained were likely an underestimate of the true population. The addition of sediment samples may provide better insight into the effect of environment on invertebrate communities. Furthermore, as invertebrates were not always able to be identified to the species level this reduced the accuracy of our conclusions about diversity in saline lagoons. Identification difficulties also limited our ability to confirm the presence of lagoonal specialists, however residence in this location is unlikely. This arises from the fact that specialists are usually found in mature lagoons, whereas the Llanelli lagoons might be considered “new” as they were completely drained of water for a prolonged period in March 2023 (Bamber et al., 1992a).

Our objectives were to identify seasonal variation in community structure and link these to environmental change. We found the greatest differences in community structure were between February and May, and February and July. Temperature increased considerably from February, March and April to May and July which could account for these variations. Furthermore, temperature was associated with the largest amount of community variation. Other significant variables indicated in our analysis were dissolved oxygen, turbidity and pH.

Additionally, we sought to assess whether significant differences in community structure occurred throughout the flooding cycle. Total abundance significantly increased from before to after flooding, however community structure did not consistently change in the same way over the four flooding phases. This is likely due to the changes that occurred between months resulting in inconsistent changes between flooding phases over the whole sample period. We expect that community structure does significantly change over flooding, throughout each month, however there were not enough samples to test this theory.

Finally we aimed to investigate the differences in fish and invertebrate communities and how they respond differently to changes in environment. While fish abundance increased with oxygen availability, invertebrate abundance decreased. Similarly where fish diversity was negatively correlated with chlorophyll fluorescence, invertebrate diversity was positively correlated. Despite these patterns, the correlation between fish and invertebrate abundances and diversity was not significant. Fish abundance and diversity were also linked to changes in temperature and turbidity, and invertebrate abundance was associated with changes in salinity.

12.1 Temperature as the main driver of change in community structure

Water temperature had the greatest influence on community structure, turbidity, pH and dissolved oxygen also were linked to changes in community. Shifts in diversity and dominance can occur in response to changes in water temperature, the nature of these changes depend on the degree and rate of warming. Intertidal habitats are typically the most diverse during the Autumn, as warmer temperatures along with greater nutrient and light availability, influence fish migration and breeding periods (Scrosati et al., 2011). However, in areas experiencing unnatural warming due to climate change the opposite can be true. In estuarine habitats, warmer waters often result in fewer species dominating the community (Ilarri et al., 2022). Dominant species often included *Chelon* or *Pomatoschistus* species, although prolonged warming may lead to an increased presence of invasive species (Ilarri et al., 2022; Lauchlan and Nagelkerken, 2020). Warming may not lead to a net loss or gain in diversity of invertebrates, just change in the present species. Long term trends in benthic invertebrates were tracked in areas of Shetland that showed overall temperature increase. This resulted in a net loss of cold-affinity species and gain in warm-affinity ones such as Nematoda and Nemertea, this change in dominance had a showed a general increase in ecosystem functioning. Sediment stability, lower and higher trophic production increased across all depths (0-300m+), while nutrient recycling was found to increase between 0 and 30m and bioturbation intensity between 15 and 30m (Armitage et al., 2024).

Numerous other factors can impact the community structure, variations in species' tolerance to low oxygen, for example, make dissolved oxygen concentration a determining factor. Increased fluctuations in oxygen levels tend to occur in saline lagoons during the summer, this results in dominance of more resilient species such as those in the genus *Pomatoschistus* (Maes et al., 1998). The community structure of macroinvertebrates is also impacted by oxygen availability, this along with salinity, pH and coarse grain size explained 40% of variation in macroinvertebrate community structure in a Brazilian lagoon (Bevilacqua et al., 2022).

Unexpectedly, salinity did not influence community structure. This is likely explained by the low levels of salinity throughout the study period. Salinity had the greatest impact on fish community structure in a group of tropical lagoons that showed high variation in salinity (from 8 to 54 PSU). In the same study depth was also found to impact community structure along with turbidity and temperature to a lesser extent (Franco et al., 2019). Salinity has also been reported to influence invertebrate community structure in saline lagoons. Where marine, brackish and freshwater species can inhabit these ecosystems the salinity gradient determines the proportion of each of these types (Barnes et al., 2008; Bevilacqua et al., 2022).

12.2 Oxygen and temperature as key predictors of change in fish communities

Our results revealed that dissolved oxygen concentration was positively correlated with fish abundance, increasing from approximately 10 individuals to 100 between 3 and 8 mg l^{-1}. For the majority of species, dissolved oxygen levels below 3mg l^{-1} are life threatening and can cause death if exposure is prolonged. However, fluctuating levels can also cause stress and damage to fish gills and tissues (Bajaj, 2017; Copping et al., 2021). Oxygen concentration in confined areas often varies diel cyclically, increasing throughout the day due to photosynthesis of algae and vegetation. During the night respiration continues but photosynthesis stops, leading to a gradual decrease in oxygen availability throughout the night (Christian, 1981). Throughout the flooding period, if oxygen depletion is too severe, fish populations may migrate to areas of higher oxygen concentration, however direct responses have only been recorded in hypoxic conditions that trigger the low respiratory distress reaction (Jones, 1952). Dissolved oxygen levels never dipped below 2mg l^{-1} but samples were usually taken at 7:30 AM or later at which point DO would have started to increase again. It is thus plausible that individuals might have left the area when the water became hypoxic before sampling commenced. Furthermore, given that there were differences observed between the two lagoons it is possible that some areas were hypoxic while others were not.

Water chlorophyll concentrations tend to mirror phytoplankton abundance (Søndergaard et al., 2017). In our study site, Chlorophyll was negatively correlated with fish abundance. This might be due to larger phytoplankton abundance resulting in more oxygen usage overnight, which has been observed to lead to oxygen depletion in lagoons (Christian, 1981; Søndergaard et al., 2017). Therefore, the observed relationship between low chlorophyll and high fish abundance may be a secondary effect, driven by low oxygen levels rather than the direct influence of chlorophyll concentration on fish. We found lower chlorophyll concentrations during May. This was likely due to increases in abundance of the algae *Ulva lactuca* which is able to monopolise nutrient absorption. However, this period was also when the greatest variation in dissolved oxygen concentrations occurred as a result of more photosynthesis during the day and more respiration at night. The increased habitat complexity brought by macroalgal cover may mitigate the oxygen depletion in some cases, as where vegetative cover is greater this can increase abundance and species richness for teleosts (Franco et al., 2019; Iotti et al., 2023).

Surprisingly, dissolved oxygen concentration resulted in a decrease in fish diversity. Lagoon systems typically have a strong dominance of few species, more resources are used by these species resulting in low species numbers (Nicolidou et al, 1985; Arias and Drake, 1994). When oxygen levels were high, we observed large abundances of a few species (shrimp, gobies and mullet). When oxygen was low, on the other hand, no single species was able to dominate, allowing a greater number of species to coexist. Chlorophyll fluorescence increased fish diversity, this may be due to the relationship between oxygen and chlorophyll lagoons (Christian, 1981; Søndergaard et al., 2017)..

The negative relationship observed between temperature and fish abundance does not align with prior research on temperate environments (Maciej Serda et al., 2013). Warmer, shallow areas are where energy expenditure is greatest as they constitute common foraging grounds for teleosts. Energy expenditure and acceleration typically increase in warmer areas up to 30°C and decrease there after (Brownscombe et al., 2017). During spring and summer, lagoon temperatures were considerably warmer than sea temperatures. While flooding caused a drop in lagoon temperature, the gradient still increased from outside to inside the lagoon, potentially explaining the negative correlation between fish abundance and water temperature.

Conversely, water temperature appeared to significantly increase fish diversity, showing a rise of 49% when temperature rose by 5°C. Warmer waters have been linked to faster metabolic rate and growth in juvenile fish as energy expenditure is reduced (Orlowski, 2003; Whitfield, 2021). Furthermore, the highest water temperature was recorded in May, coinciding with increased growth of aquatic plants and macroalgae, potentially enhancing habitat complexity and contributing to greater diversity. Increased temperature could indicate higher UV promoting macroalgal growth and primary productivity at this time (Pihl et al., 1996). This relationship could also be linked to the concept that diversity is limited by high abundance of a few species, similar to how dissolved oxygen increases abundance but decreases diversity (Arias and Drake, 1994; Reizopoulou and Nicolaidou, 2004).

Turbidity was negatively correlated with fish abundance and diversity. This relationship could be attributed to the reliance of fish on vision for foraging and predator avoidance as increased turbidity reduces water clarity and limits the visual range (Lunt and Smee, 2020). High turbidity areas may favour benthic species such as crabs that rely more on mechanoreception and chemoreception (Hornung, 2024; Lunt and Smee, 2020). Turbidity also reduces photosynthesis and primary production as light cannot penetrate the water as well, this can also lead to a decline in fish productivity (Giacomazzo et al., 2023).

Salinity did not influence fish abundance or diversity. This finding was unexpected as previous work has shown that fish distribution can be highly impacted by water salinity. Low salinity waters result in reduce energy expenditure for osmoregulation in fish, allowing faster rate of growth and increased biomass (Boeuf and Payan, 2001; Orlowski, 2003; Pombo et al., 2005). This is likely the reason why such large abundances of juvenile fish aggregate in this area as salinity remained below 9 PSU. Fish abundance is typically greater at lower salinities, while species richness peaks at approximately 35 PSU. Salinities that exceeded 35 PSU (hypersaline) showed a rapid decrease in both abundance and richness (Franco et al., 2019). These differences are predominantly observed across spatial scales opposed to temporal ones, as individual lagoons rarely transition from mesohaline to hyperhaline. This could indicate why the fish community was not impacted by salinity here, given that salinity stayed within the mesohaline boundaries.

While the salinity remained low a variety of freshwater, marine and estuarine species were still observed in the lagoons. *Chelon ramada, Platichthys flesus, Anguilla anguilla* are all catadromous fish, meaning they spawn in marine or coastal areas then as juveniles travel to brackish or freshwater environments to develop. *Gasterosteus aculeatus* are anadromous fish that are born in freshwater environments then may migrate to brackish and marine environments. *Pomatoschistus microps* and *P. minutus* can inhabit both marine and estuarine environments however do not travel into freshwater rivers. What these species have in common is they can tolerate a wide range of salinities allowing them to utilise the saline lagoon habitat for reduced energy expenditure, foraging and shelter.

12.3 Chlorophyll and salinity as influences of invertebrate community

Our results revealed negative correlations between invertebrate abundance and dissolved oxygen concentrations. Amongst the possible explanations for this relationship, two are worth discussing. Firstly, in low oxygen concentration conditions there tends to be lower fish abundance and, in turn, fewer invertebrates are predated on (Barnes, 1987; Copping et al., 2021; Diehl, 1992). In ecosystems with fish present, habitat complexity has been related to increases in invertebrate abundance. However, in that same study, where fish were not present habitat characteristics had no effect of invertebrate communities, highlighting the influence of fish presence on invertebrate abundance (Rennie and Jackson, 2005). Alternatively, this could be due to stratification in the lagoons causing sediment to become hypoxic, forcing invertebrates into the open water (Dauer et al., 1992).

We observed a negative correlation between invertebrate diversity with chlorophyll fluorescence. As previously stated water chlorophyll levels tend to mirror phytoplankton abundance, and macroalgal growth tends to limit phytoplankton abundance (Søndergaard et al., 2017). Macrophyte cover and invertebrate diversity are positively correlated due to the increased habitat complexity creating shelter for a greater number of species (Yofukuji et al., 2021). Greater habitat complexity increases invertebrate abundance in habitats where fish are present as it reduces predation pressure (Rennie and Jackson, 2005). Furthermore, some lagoonal specialists have associations with certain species of algae, *Gammarus insensibilis* is one such species that is usually only found where *Chaetomorpha* is present. This is because it is an important food source for *G. insensibilis* (Sheader and Sheader, 1987; Bamber et al., 1992a). Other invertebrates may have a similar reliance on specific macrophytes and growth of these species could encourage a greater number of species to populate the lagoons.

We found invertebrate abundance increased with salinity. This is likely because the majority of invertebrates sampled were intertidal and estuarine species that are adapted to higher salinity environments. Invertebrate abundance and species richness were positively correlated with salinity, with both usually reaching a peak at euhaline levels (Barnes et al., 2008; Bevilacqua et al., 2022).

In our study pH did not impact invertebrate abundance or diversity, likely due to lagoon pH not dropping below 7 (becoming acidic). Environments where pH levels fall below 5.5 are characterized by the absence of invertebrates such as Mollusca, Malacostraca, and Ephemeroptera. This is due to the low concentrations of dissolved carbon and calcium in the water, which inhibit these organisms' ability to maintain their calcium carbonate exoskeletons (Barnes, 1987; Fryer, 1980). Low pH can be linked to eutrophication as the increased nutrient concentration often triggers algal blooms. Consequently, higher algal respiration rates increase carbon dioxide production which reacts with the water to form carbonic acid (Brush et al., 2020). The steady pH seen in the Llanelli lagoons are an indicator that there is not excess nutrients in the lagoons allowing them to remain healthy.

13 Conclusion

Here we have shown that many more teleost species inhabit these ecosystems than previously thought, and demonstrated how community composition and structure is linked to abiotic change in a highly variable environment.

Extreme fluctuations in saline lagoon environments can make it challenging for certain species to establish viable populations. However, it also offers certain advantages over other habitats that can be exploited by well-adapted species, such as reduced salinity and increased oxygen availability in some locations. The decline in coastal lagoons over the last 30 years due to eutrophication, sea level rise and erosion shows that management of these habitats needs to be improved. Saline lagoons are rare ecosystems only covering 0.02% of the UK, but they are critical to preserving coastal diversity as they act as a carbon sink and support surrounding ecosystems such as salt marsh (WWT, 2017). Rare and endemic species that depend exclusively on saline lagoon habitats could become extinct if these habitats disappear as their conditions are difficult to find elsewhere. This is especially true for stenohaline lagoonal specialists as they are not tolerant of salinity changes, making climate change (specifically increased temperature and rainfall) the biggest threats to these invertebrates.

The high abundance of juvenile mullet and shrimp caught shows the importance of these lagoons as fish nurseries and how they support fish stocks. This is also critical for bird conservation as many migrating and coastal birds rely predominantly on these habitats for food. More research needs to be conducted on the relationships between the species that share the lagoon and how they affect each other. This would enhance the understanding of the entire community and inform management of lagoons in poor condition that have been affected by eutrophication or climate change. The consistent pH and controlled growth of phytoplankton/algae shows that Llanelli saline lagoons are effectively managed. The high abundance of bird species that are drawn to the lagoons is evidence of its health and the consistently high abundance of fish, shrimp and other prey items shows that the ecosystem is in a state of equilibrium.

Further research on water quality at this site could be used to inform management at sites that are in poor condition and help restore temperate saline lagoons globally. Comparisons of multiple lagoons with a range of environmental trends would be useful in identifying how specific types of lagoon respond to environmental change and if this is consistent across all lagoons of a certain type.

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15 Appendices

15.1 Supplementary Results

All code is available at the github link below, the data set used is also available here. An abbreviated version is available on the next page.

https://github.com/AmeliaJones842/Saline-lagoon

Table 15.1 Community and environmental data from saline lagoons (February – July).

Month, flooding phase and pond were recorded, for each sample day for each lagoon (Pond) temperature, dissolved oxygen concentration, pH, salinity turbidity and chlorophyll fluorescence were recorded. Three seines per sample day per lagoon were taken and the sum of all three seines is recorded below.

Month	Flood	Pond	Temp	DO	PH	Sal	Turb	Chlor	G.spp	M.spp	S.spp	TLGM	Am	So	GGM	FF	EF	CFL	TSS	EGC	EE	EMS	C.spp	BW	P
February	BF	LSP	9.6	8.76	8.06	0.11	71.80	1.94	95	8	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0
February	BF	SSP	9.8	9.08	7.74	2.32	143.90	1.76	84	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	DF	LSP	9.8	9.08	7.95	4.46	51.40	1.61	285	76	56	2	6	0	0	0	0	0	0	0	1	0	0	0	0
February	DF	SSP	9.1	8.92	8.16	3.7	85.18	1.95	101	2	62	0	2	0	0	0	0	0	0	0	0	1	0	0	0
February	AF	LSP	11.6	7.79	7.97	3.39	29.79	0.81	500	39	280	0	2	0	0	0	0	0	0	0	0	1	1	0	0
February	AF	SSP	12.2	8.41	8.05	6.48	19.75	0.05	601	14	137	1	2	0	0	0	0	0	0	1	0	0	0	2	0
February	REC	LSP	10.7	8.56	8.34	4.18	5.05	0.03	214	1	136	0	1	0	0	0	0	0	0	0	0	0	0	0	0
February	REC	SSP	12.4	9.27	8.26	3.51	44.48	1.82	406	13	110	0	2	0	0	0	0	0	2	0	0	1	0	0	0
March	BF	LSP	7	10.4	8.46	1.46	80.84	4.1	105	9	92	0	0	0	0	0	0	0	0	0	0	1	0	0	0
March	BF	SSP	7.4	9.6	8.75	1.64	58.32	3.79	126	5	150	0	3	0	0	0	0	0	0	1	0	0	0	0	0
March	DF	LSP	10.4	8.44	8.53	4.3	440.56	2.54	72	5	73	0	1	0	0	0	0	0	1	1	1	0	1	0	0
March	DF	SSP	10.6	8.9	8.4	4.8	149.14	4.6	99	30	44	0	0	0	0	0	0	0	0	0	0	2	0	0	0
March	AF	LSP	11	8.49	7.84	5.06	122.07	2.23	109	34	103	1	3	0	0	0	0	0	0	1	0	0	1	0	0
March	AF	SSP	11.3	8.78	8.35	4.49	58.75	1.3	94	42	60	0	1	0	0	0	0	1	0	1	0	0	0	0	0
March	REC	LSP	11.1	9.12	8.51	2.26	50.99	2.06	128	5	164	0	4	0	0	0	0	1	0	0	0	0	0	0	0
March	REC	SSP	12.1	8.86	8.53	1.3	47.55	2.49	162	145	351	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	BF	LSP	12	10.1	8.59	2.49	184.76	3.11	55	5	107	1	3	0	0	0	0	0	0	0	1	0	0	0	0
April	BF	SSP	12.2	9.04	8.57	2.17	47.85	1.84	181	13	221	0	2	0	0	0	0	0	0	0	0	0	0	0	0
April	DF	LSP	10.1	8.55	8.43	3.27	109.02	3.43	58	163	1094	4	5	0	0	0	1	0	0	2	0	0	0	1	0
April	DF	SSP	9.9	8.05	8.38	4.21	139.95	1.64	193	3	458	0	1	0	0	0	0	0	0	6	0	0	0	0	0
April	AF	LSP	11.2	6.29	8.36	3.91	272.80	0.51	78	2	1031	0	1	0	1	0	0	0	0	4	0	1	0	0	0
April	AF	SSP	10.8	6.68	8.47	4.05	78.15	0.04	136	0	1140	0	3	0	0	0	0	0	0	7	0	0	0	0	0
April	REC	LSP	8.5	5	8.48	4.17	188.01	1.86	34	1	108	0	0	0	0	9	1	0	0	0	0	0	0	14	1
April	REC	SSP	8.3	2.56	8.46	3.18	73.50	0.06	50	1	257	0	5	0	0	1	0	0	0	6	0	1	0	7	0
May	BF	LSP	15.5	6.86	8.07	4	3.35	0.04	79	54	716	2	3	0	0	0	113	0	0	4	0	0	0	3	0
May	BF	SSP	24.5	8.21	8.57	5.56	9.69	0.05	35	17	198	0	9	0	0	0	15	0	0	14	0	0	0	1	0
May	DF	LSP	14.9	13	8.56	5.81	10.76	0.03	4	1814	1150	4	4	0	0	0	18	0	0	6	0	0	0	6	0

Month	Flood	Pond	Temp	DO	PH	Sal	Turb	Chlor	G.spp	M.spp	S.spp	TLGM	Am	So	GGM	FF	EF	CFL	TSS	EGC	EE	EMS	C.spp	BW	P
May	DF	SSP	21.2	7.54	8.64	3.64	27.18	0.05	2	0	450	0	10	0	0	0	9	0	1	16	0	0	0	0	0
May	AF	LSP	17.5	4.5	7.68	5.62	13.41	1	0	5	806	2	3	1	0	0	36	0	0	7	0	0	0	2	0
May	AF	SSP	16.7	4.23	8.32	5.04	13.32	0.05	0	4	729	0	28	2	0	0	1	0	3	10	0	0	0	1	1
May	REC	LSP	18.1	4.43	8.17	6.34	59.92	0.12	1	25	348	5	3	0	0	0	53	0	1	5	0	0	0	6	0
May	REC	SSP	19	4.01	8.25	5.02	114.35	0.11	0	173	139	18	4	3	0	0	0	0	1	12	0	0	0	2	0
July	BF	LSP	16.4	8.7	7.64	7.5	490.24	3.8	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
July	BF	SSP	16.4	8.7	7.64	7.5	490.24	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
July	DF	LSP	17.5	8.46	8.16	7.05	167.15	3.22	8	0	196	34	5	0	0	0	0	0	0	1	0	62	0	0	0
July	DF	SSP	16.8	8.54	8.35	7.49	496.51	1.71	1	0	12	0	0	0	0	0	0	0	0	3	0	9	0	0	0
July	AF	LSP	16.9	6.98	8.27	7.26	327.79	0.72	19	0	96	104	0	0	0	0	0	0	1	1	0	28	0	1	0
July	AF	SSP	17.1	7.97	8.24	8.46	367.99	0.3	1	0	225	86	0	0	0	0	0	0	0	6	0	4	0	0	0
July	REC	LSP	23.4	7.19	7.77	7.72	85.73	0.04	51	5	294	0	0	0	0	0	0	0	0	7	0	53	0	0	0
July	REC	SSP	21.4	6.94	8.5	8.61	182.25	0.05	1	3	338	1	0	0	0	0	0	0	0	4	0	6	0	0	0

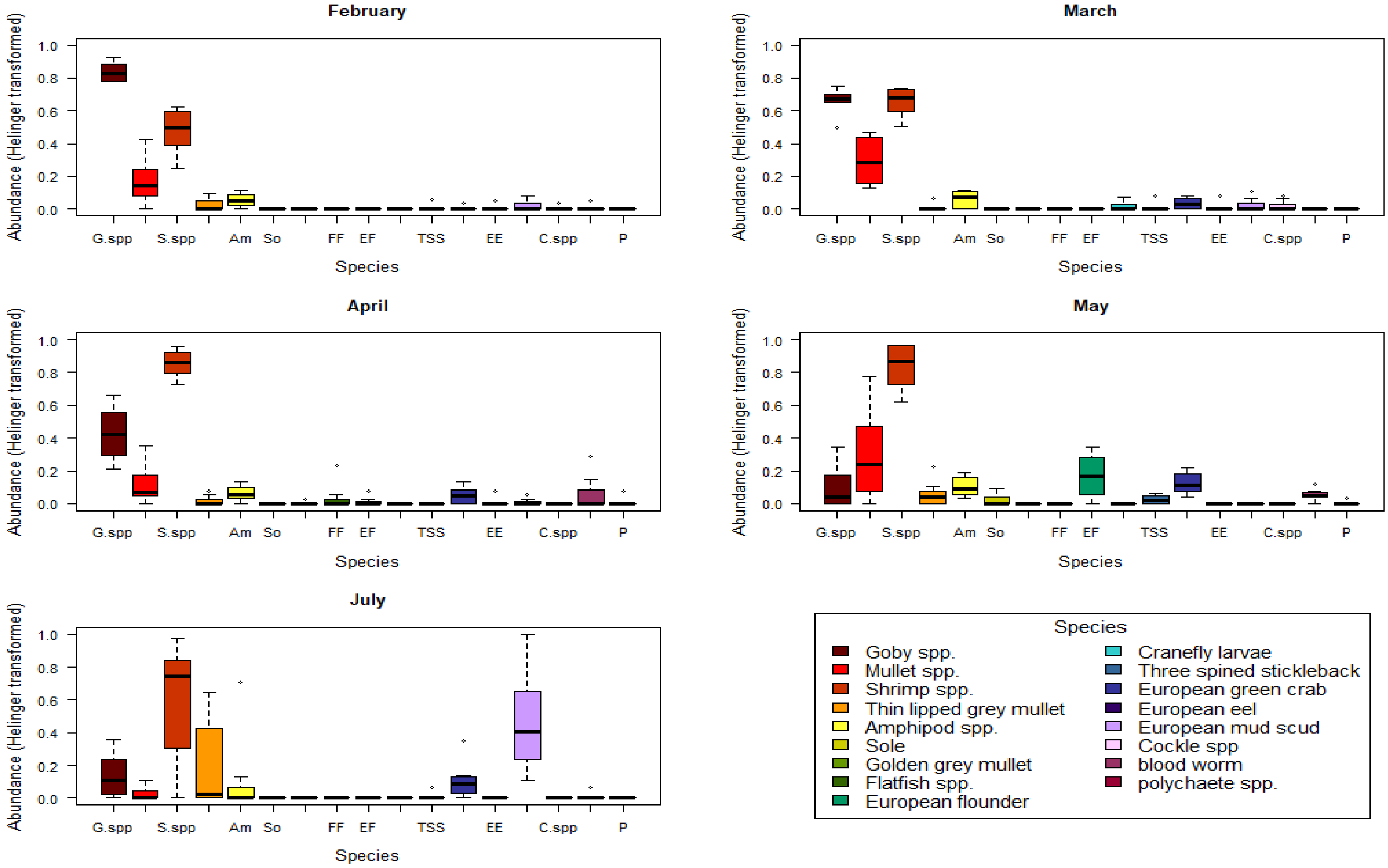


Figure 15.1 Monthly abundance of each species

Median, upper and lower quartiles and ranges of each species by month, during each month a total of eight samples were taken.

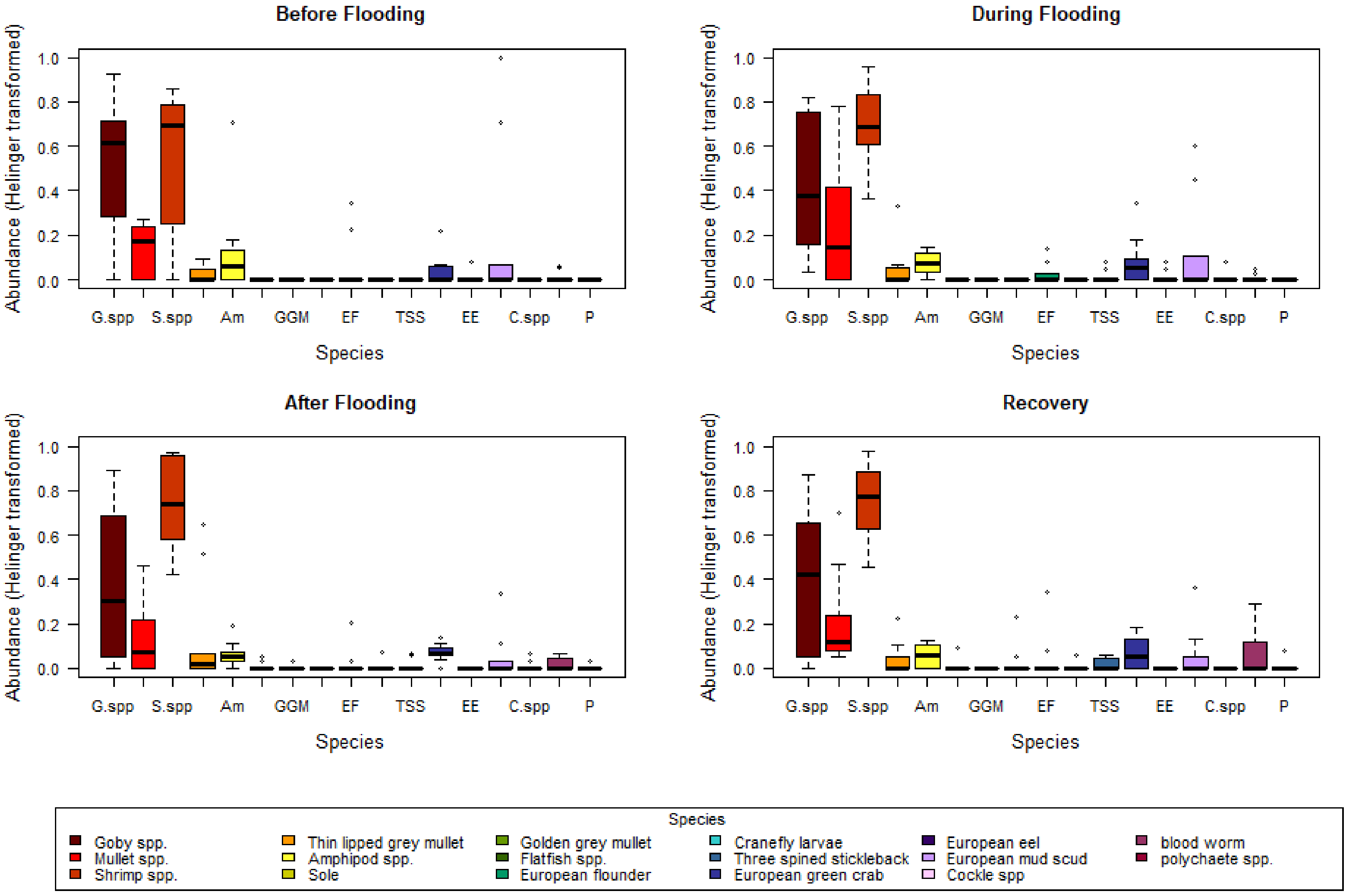


Figure 15.2 Abundance of each species during each flooding phase

Median, upper and lower quartiles and ranges of each species by flooding phase, during each month a total of eight samples were taken.

Table 15.2 Differences in community structure between months

Pairwise PERMANOVA result.

Pairs	Df	SumsOfSqs	F.Model	R2	p.adjusted
February vs March	1	0.1060136	6.509303	0.3173830	< 0.05
February vs April	1	0.4390262	18.015114	0.5627065	< 0.01
February vs May	1	1.0201035	28.029595	0.6669014	< 0.01
February vs July	1	1.2898128	14.368430	0.5064937	< 0.01
March vs April	1	0.2000023	8.414811	0.3754130	< 0.01
March vs May	1	0.5894279	16.468232	0.5405050	< 0.01
March vs July	1	1.0152031	11.385650	0.4485073	< 0.01
April vs May	1	0.2815220	6.416424	0.3142776	< 0.01
April vs July	1	0.7532237	7.745346	0.3561841	< 0.01
May vs July	1	0.7990459	7.312417	0.3431059	< 0.01

Table 15.3 Differences in community structure between flooding phases

Pairwise PERMANOVA result.

Pairs	Df	SumsOfSqs	F.Model	R2	p.adjusted
BF vs DF	1	0.09611574	0.6474453	0.03472032	> 0.05
BF vs AF	1	0.21061230	1.4243121	0.07332626	> 0.05
BF vs REC	1	0.17573403	1.2414144	0.06451783	> 0.05
DF vs AF	1	0.04666086	0.4830038	0.02613232	> 0.05
DF vs REC	1	0.02954254	0.3271758	0.01785195	> 0.05
AF vs REC	1	0.02366434	0.2637834	0.01444298	> 0.05

Table 15.4 Temporal influences of total abundance

Two way ANOVA (Total species abundance ~ Month + Flooding phase), significant results shown in bold.

Source	df	Sum sq	Mean sq	F-value	p-value
Month	4	1251.6	312.90	5.033	< 0.01
Flooding phase	3	661.5	220.52	3.547	< 0.05
Residuals	32	1989.6	62.17		

Table 15.5 Temporal influences of total abundance (Post hoc)

Tukey multiple comparison of means result (Total species abundance ~ Season * Flooding phase * Pond), significant results only.

Source	Mean difference	95% Cl	p-value (adj)
February-April	-5.370893	[-16.7624278 6.0206408]	> 0.05
July-April	-12.294643	[-23.6861772 -0.9031086]	**< 0.05**
March-April	-8.262214	[-19.6537487 3.1293200]	> 0.05
May-April	3.280554	[-8.1109804 14.6720882]	> 0.05
July-February	-6.923749	[-18.3152838 4.4677849]	> 0.05
March-February	-2.891321	[-14.2828552 8.5002134]	> 0.05
May-February	8.651447	[-2.7400870 20.0429817]	> 0.05
March-July	4.032429	[-7.3591058 15.4239629]	> 0.05
May-July	15.575197	[4.1836625 26.9667311]	**< 0.01**
May-March	11.542768	[0.1512339 22.9343025]	**< 0.05**
BF-AF	-10.969801	[-20.523847 -1.415755	**< 0.05**
DF-AF	-2.568239	[-12.122284 6.985807]	> 0.05
REC-AF	-5.161172	[-14.715218 4.392874]	> 0.05
DF-BF	8.401562	[-1.152483 17.955608]	> 0.05
REC-BF	5.808629	[-3.745417 15.362675]	> 0.05
REC-DF	-2.592934	[-12.146980 6.961112]	> 0.05

Table 15.6 Temporal influences of total diversity

*Two-way ANOVA result (Total biodiversity ~ Season * Flooding phase), significant results shown in bold.*

Source	df	Sum sq	Mean sq	F-value	p-value
Month	4	0.4365	0.10912	1.383	> 0.05
Residuals	35	2.7624	0.07893		

Table 15.7 Environmental fluctuations over the study

Dates of minimum and, maximum recorded values for environmental variables and mean and standard deviations.

Variable	Minium	Maximum	Mean
Temperature (°C)	7.00 (09/03)	24.50 (07/05)	13.56 (± 4.47SD)
Dissolved oxygen (mg l^{-1})	2.56 (14/04)	13.00 (09/05)	7.87 (± 1.98SD)
pH	7.64 (23/07)	8.75 (09/03)	8.26 (± 0.30SD)
Salinity (PSU)	0.11 (09/02)	6.48 (27/07)	4.59 (± 2.09SD)
Turbidity (NTU	3.35 (07/05)	496.51 (24/07)	135.34 (± 43.37SD)
Chlorophyll-a fluorescence (RFU)	0.03 (17/02)	4.60 (13/03)	1.52 (± 1.40SD)

Table 15.8 Comparison of environments over months

Pairwise PERMANOVA result on environmental variables showing that February and March are both significantly different from May at the 0.01 level, and April and March are significantly different at the 0.05 level.

Pairs	Df	SumsOfSqs	F.Model	R2	p.adjusted
February vs March	1	0.04628338	3.413039	0.19600478	> 0.05
February vs April	1	0.08227569	6.573470	0.31951197	> 0.05
February vs May	1	0.06340441	3.628524	0.20583254	> 0.05
February vs July	1	0.16925084	13.133372	0.48403023	**< 0.05**
March vs April	1	0.01138885	1.507567	0.09721491	> 0.05
March vs May	1	0.21092217	16.857565	0.54630250	**< 0.05**
March vs July	1	0.05632049	7.106493	0.33669701	> 0.05
April vs May	1	0.26289072	22.924669	0.62084968	**< 0.01**
April vs July	1	0.01694466	2.462604	0.14958778	> 0.05
May vs July	1	0.38847149	32.814675	0.70094847	**< 0.01**

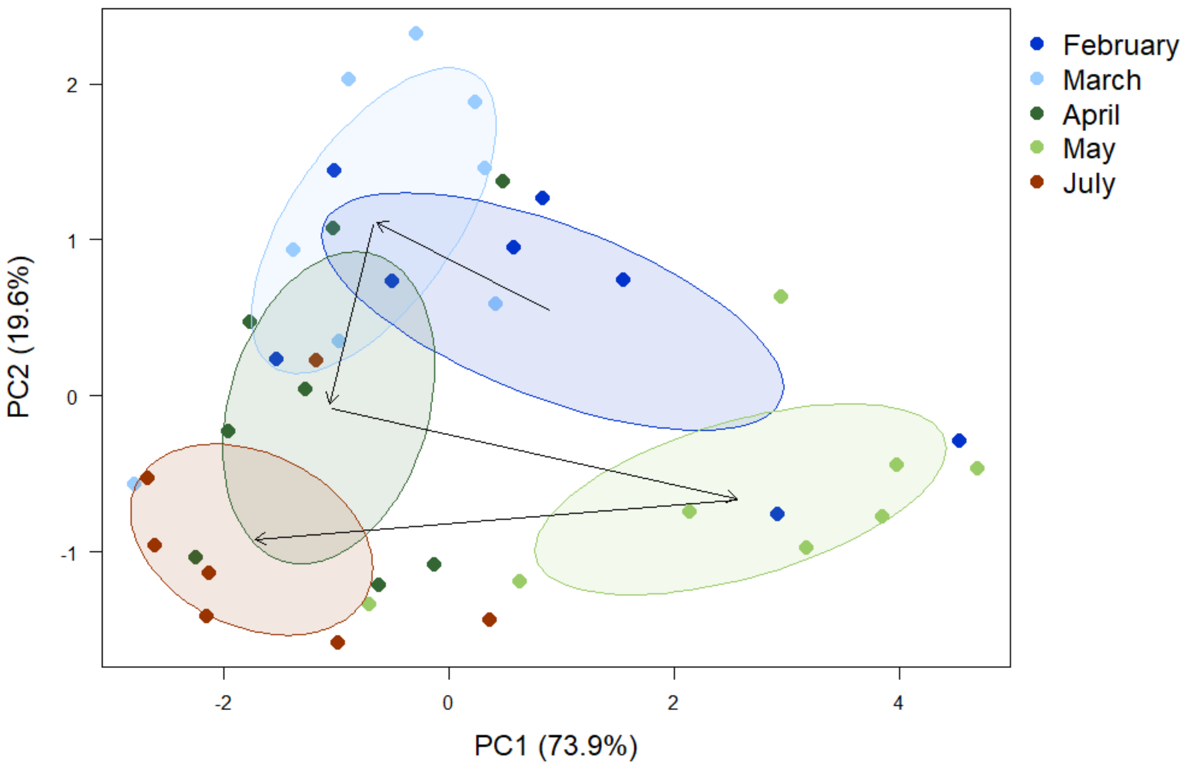


Figure 15.3 Environnemental variation in saline Lagoon

PCA result visualising environmental variability over February, March, April, May and July. Greater environmental variability can be seen in February and March (Compared to April and May) these points are predominantly positioned in the lower centre of the graph. April and May can be seen in the upper centre and right of the graph.

Table 15.9 Temporal variation in each water parameter

Two way ANOVA for temperature, dissolved oxygen, pH, salinity, turbidity and chlorophyll, temperature, pH, and turbidity were influenced by month while dissolved oxygen salinity and chlorophyll were influenced by month and flooding phase.

Parameter	Variable	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Temperature	Month	4	608.4	152.09	31.36	< 0.001
	Residuals	35	169.7	4.85		
Dissolved	FP	3	46.82	15.607	7.184	< 0.001
Oxygen	Month	4	36.14	9.036	4.159	< 0.01
	Residuals	32	69.52	2.172		
pH	Month	4	1.142	0.2854	4.358	< 0.01
	Residuals	35	2.292	0.0655		
Salinity	FP	3	19.43	6.475	5.928	< 0.01
	Month	4	115.83	28.958	26.510	< 0.001
	Residuals	32	34.96	1.092		
Turbidity	Month	4	427576	106894	10	< 0.001
	Residuals	35	374021	10686		
Chlorophyll	FP	3	22.28	7.426	10.03	< 0.001
	Month	4	30.21	7.553	10.20	< 0.001
.	Residuals	32	23.70	0.741		

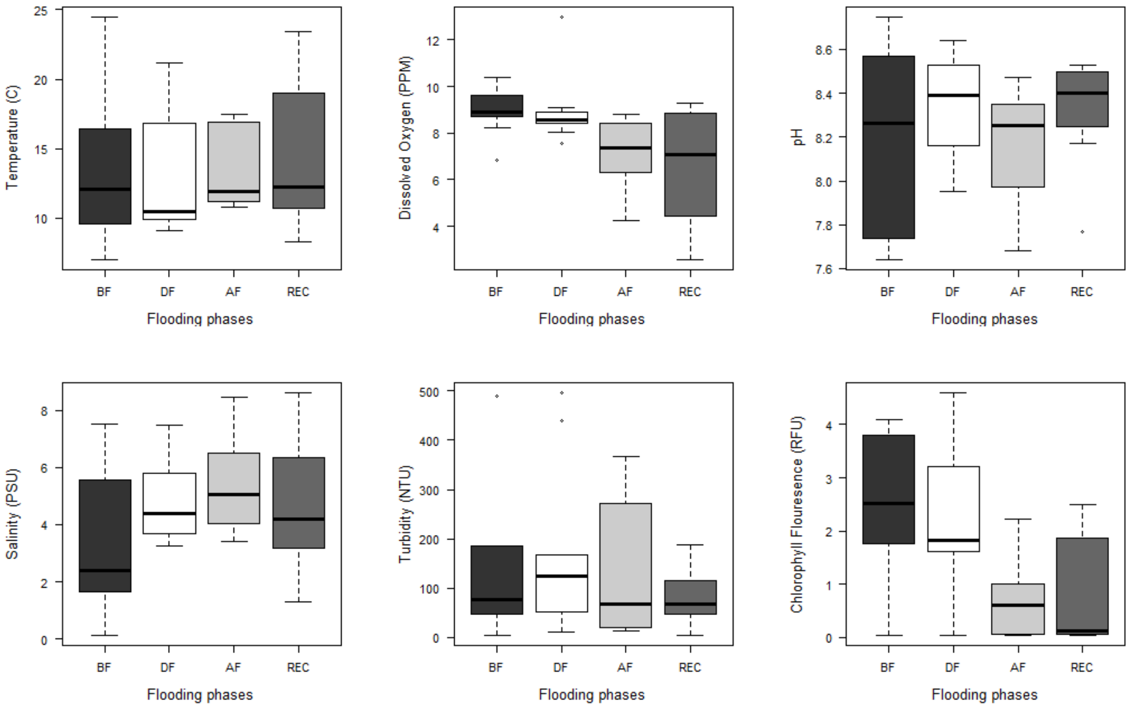


Figure 15.4 Differences in environmental parameters over flooding phases

Variation in temperature, dissolved oxygen concentration, pH, salinity, turbidity and chlorophyll fluorescence. Each flooding phase consisted of ten water samples. It is visible that each parameter do not follow the same temporal trend and vary differently over the course of the month.

Table 15.10 Drivers of change in community structure

ANOVA.cca result of RDA model (Transformed abundance matrix ~ Temperature + Dissolved oxygen + Ph + Salinity + TDS + Chlorophyll).

Variable	Df	SumOfSqs	F	p-value
Temperature	1	0.87174	11.3904	< 0.001
Dissolved Oxygen concentration	1	0.32058	4.1887	< 0.01
PH	1	0.52948	6.9183	< 0.001
Turbidity	1	0.74288	9.7067	< 0.001
Residual	35	2.67865		

Table 15.11 Influences of fish abundance

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	6.160440	4.671977	1.319	0.19612
Chlorophyll-a fluorescence	-2.470770	0.809151	-3.054	< 0.01
Dissolved Oxygen concentration	2.331228	0.458672	5.083	< 0.001
Salinity	1.195637	0.642927	1.860	> 0.05
Temperature	-0.852920	0.263545	-3.236	< 0.01
Turbidity	-0.024831	0.007785	-3.190	< 0.01

Table 15.12 Influences of fish diversity

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.5432433	1.2437367	-1.241	0.223169
Chlorophyll-a fluorescence	0.1023713	0.0412824	2.480	< 0.05
Dissolved Oxygen concentration	-0.0771668	0.0242827	-3.178	< 0.01
pH	0.2400546	0.1464758	1.639	> 0.05
Temperature	0.0418599	0.0110901	3.775	< 0.001
Turbidity	-0.0011565	0.0003329	-3.474	< 0.01

Table 15.13 Influences of invertebrate abundance

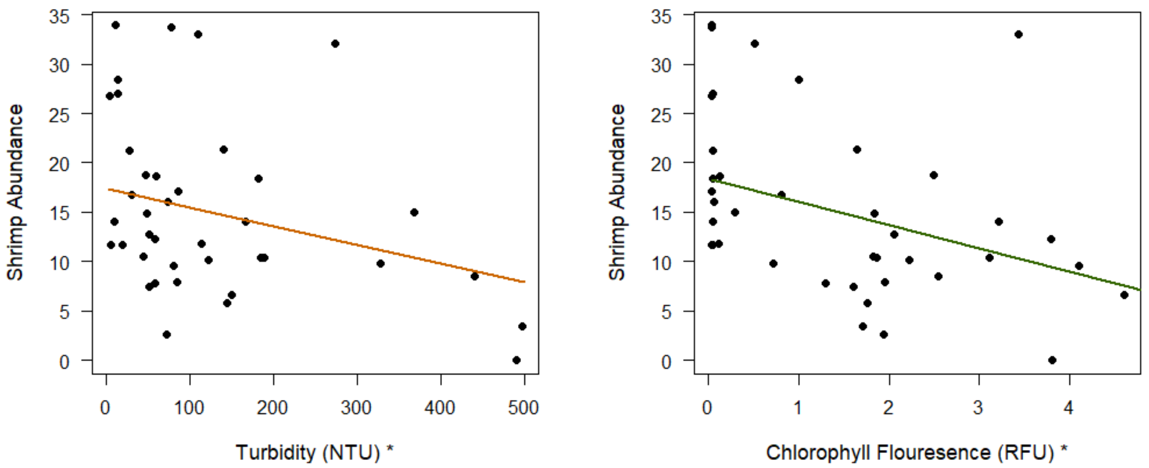
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-10.789816	6.469905	-1.668	0.1046
Dissolved Oxygen concentration	-0.262092	0.110740	-2.367	< 0.05
pH	1.511781	0.762956	1.981	> 0.05
Salinity	0.430840	0.170856	2.522	< 0.05
Temperature	0.127950	0.068657	1.864	> 0.05
Turbidity	-0.003575	0.001779	-2.009	> 0.05

Table 15.14 Influences of invertebrate diversity

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.77606	0.08606	9.017	5.57e-11
Chlorophyll-a fluorescence	-0.13682	0.04197	-3.260	< 0.01

Table 15.15 Influences of shrimp abundance

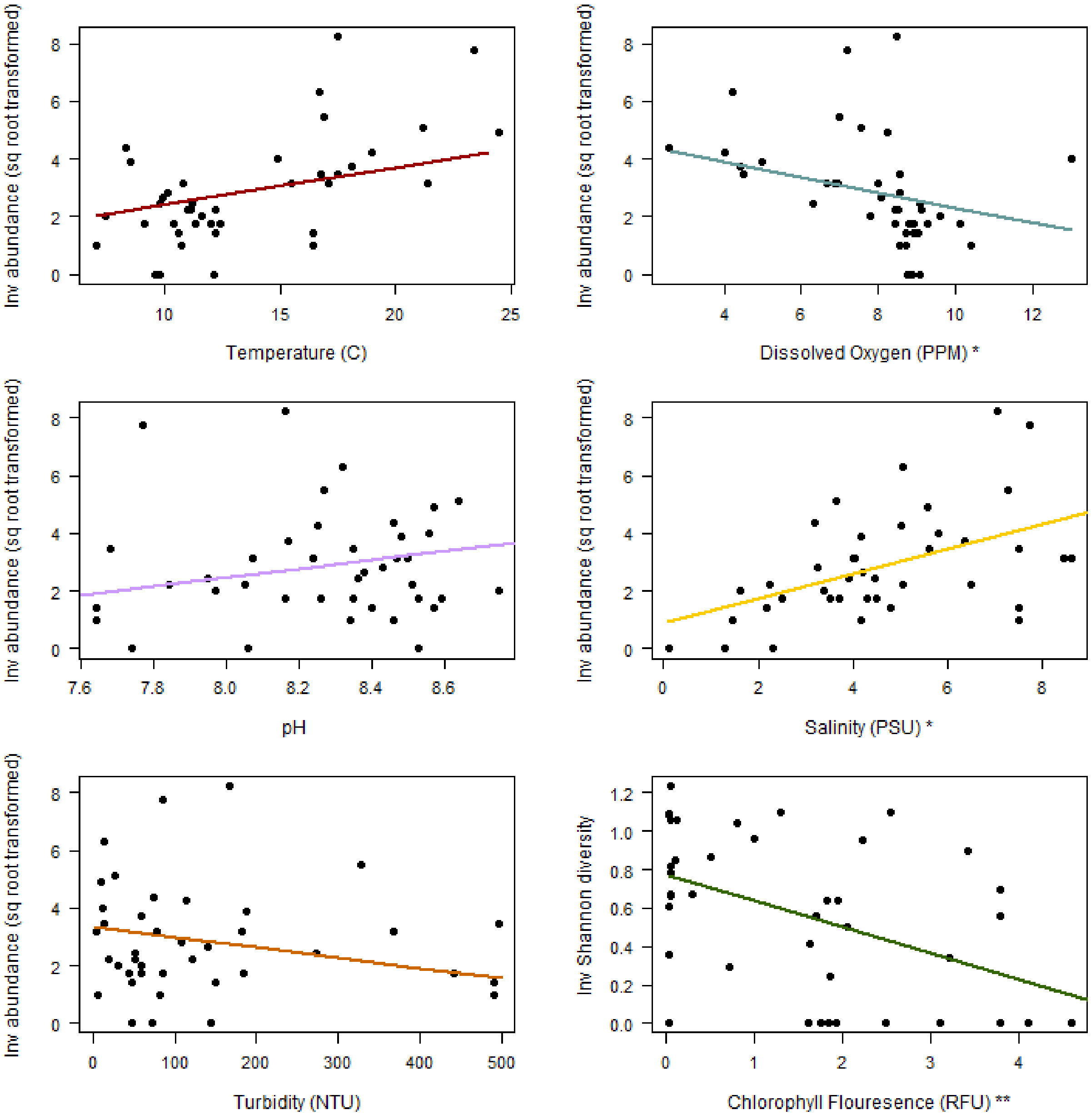
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	20.939646	1.977860	10.587	9.47e-13
Chlorophyll-a fluorescence	-2.351176	0.952783	-2.468	< 0.05
Turbidity	-0.018939	0.009289	-2.039	< 0.05



Shrimp abun model: glm(T.SHRIMP ~ Turbidity + Chlor). R² = 0.05, Intrc 20.94, df = 4

Figure 15.5 Environmental impact on shrimp abundance

Effect of turbidity and chlorophyll on shrimp abundance (included in the GLM), significance level is shown with asterisks (p < 0.05, ** p < 0.01, *** p < 0.001).*



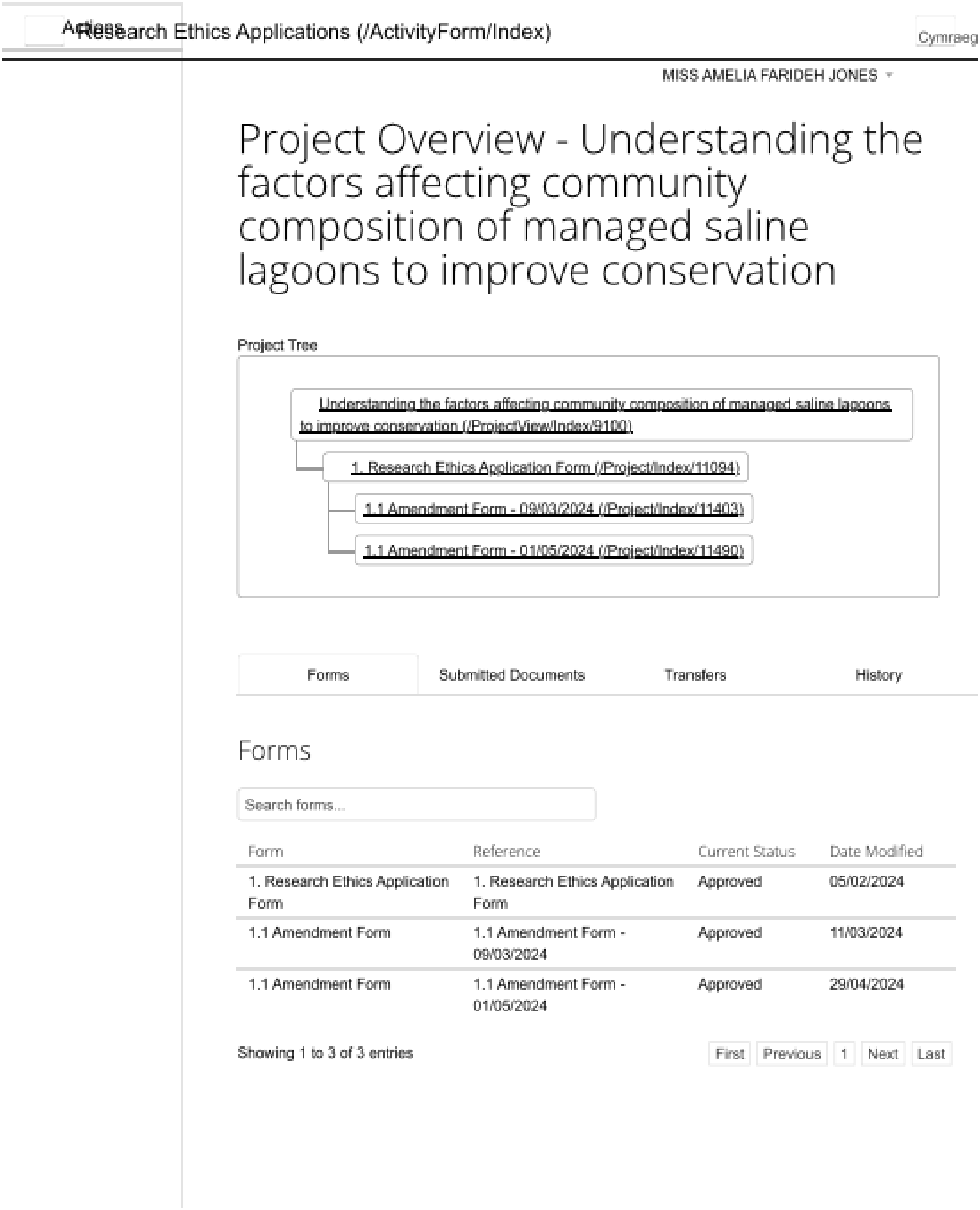
Inv abun model: glm(INV.abun ~ Temp + DO + PH + Salinity + Turbidity). R² = 0.21, Intrc -10.79, df = 7

Inv div model: glm(INV.Shan ~ Chlor). R² = 0.24, Intrc = 0.78, df = 3

Figure 15.6 Environmental impact of invertebrate abundance and diversity

All graphs except the bottom right show the relationship between invertebrate abundance and variables included in the GLM. The bottom right graph shows the relationship between invertebrate diversity and chlorophyll fluorescence, this is the only variable shown as no other variables were included in the GLM with the lowest AIC. Significance level of each variable is shown with asterisks (p < 0.05, ** p < 0.01, *** p < 0.001).*

15.2 Ethical Approval



Project Overview - Understanding the factors affecting community composition of managed saline lagoons to improve conservation

Project Tree

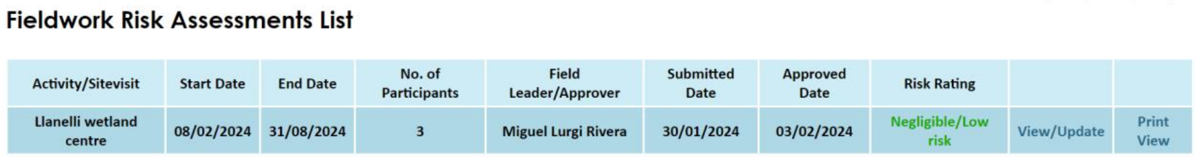
- Understanding the factors affecting community composition of managed saline lagoons to improve conservation (/ProjectView/Index/9100)
  - 1. Research Ethics Application Form (/Project/Index/11094)
    - 1.1 Amendment Form - 09/03/2024 (/Project/Index/11403)
    - 1.1 Amendment Form - 01/05/2024 (/Project/Index/11490)

Forms

Form	Reference	Current Status	Date Modified
1. Research Ethics Application Form	1. Research Ethics Application Form	Approved	05/02/2024
1.1 Amendment Form	1.1 Amendment Form - 09/03/2024	Approved	11/03/2024
1.1 Amendment Form	1.1 Amendment Form - 01/05/2024	Approved	29/04/2024

Showing 1 to 3 of 3 entries

15.3 Risk Assessments



Fieldwork Risk Assessments List

Activity/Sitevisit	Start Date	End Date	No. of Participants	Field Leader/Approver	Submitted Date	Approved Date	Risk Rating		
Llanelli wetland centre	08/02/2024	31/08/2024	3	Miguel Lurgi Rivera	30/01/2024	03/02/2024	Negligible/Low risk	View/Update	Print View

15.4 Statement of Expenditure

Item	Explanation	Cost per unit	Total cost
Petrol	Monthly to and from Llanelli wetland centre (10.1miles x 8) x 6 months	£36	£288
Waders	Waders for fieldwork x 3	£49	£147
Fish traps	Windemere perch traps for fieldwork	£10	£23
40l buckets	For placing captured fish and invertebrates x 4	£10	£40
Seine net bag	to carry seine net as old bag broke	£38	£53

15.5 Statement of Contributions

Contributor Role	Persons Involved
Conceptualisation	Miguel Lurgi, Nicole Esteban, Amelia Jones
Data Curation	Amelia Jones, Lauren Parlor, Samule Ludbrook, Daniel Aguirre, Scott Van Haren, Martina Reina-Cantirot, Sasha Shute, Paul Deacon, Peter Ludbrook
Formal Analysis	Amelia Jones, Miguel Lurgi
Funding Acquisition	N/A
Investigation	Amelia Jones
Methodology	Amelia Jones, Sasha Shute, Nicole Esteban, Miguel Lurgi
Project Administration	Amelia Jones, Miguel Lurgi
Resources	Sasha Shute, Nicole Esteban, Paul Deacon, Rob Smith, Rebecca Stringwell
Software	N/A
Supervision	Miguel Lurgi, Nicole Esteban
Validation	N/A
Visualisation	Amelia Jones, Miguel Lurgi
Writing – Original Draft Preparation	Amelia Jones
Writing – Review and Editing	Amelia Jones, Miguel Lurgi, Nicole Esteban