A Comparative Study: Impact of Salinity Dynamics on the Zonation of Halophytic Communities in Yeşilırmak Delta's (Türkiye) Coastal Dune and Salt Marsh

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Abstract

In this study, we conducted a comparative investigation into the impact of salinity parameters on the distribution patterns of wetland and coastal dunes plant communities in the Yeşilırmak Delta (Samsun, Turkey), as determined using the TWINSPAN technique based on a matrix of 74 species across 50 sample plots. The halophytic plant communities under examination included *Pancratium maritimum* L. and *Elaeagnus rhamnoides* (L.) A. Nelson, which distributed in the sand dunes, and *Salicornia perennans* Wild., *Juncus acutus* subsp. *acutus* L., and *Tamarix smyrnensis* Bunge, inhabiting the wetland ecosystem. This ecological investigation aimed to discern and compare the effects of salinity parameters on the spatial distribution of these distinct halophytic plant communities within the Yeşilırmak Delta region.

Significant variations in edaphic parameters among communities were determined using One-Way Analysis of Variance (ANOVA). According to the CCA ordination analysis, edaphic parameters responsible for the cumulative and subgroup differentiation of communities were identified as Ca^{+2}, Mg^{+2}, instantaneous soil moisture content (%), Cl^- and HCO_3^-. In the wetlands, parameters influencing the internal grouping of halophytic communities were found to be Mg^{+2}, instantaneous soil moisture (%), electrical conductivity (EC), and Cl^-. Conversely, in the coastal dunes, the parameters influencing the internal grouping of communities were determined to be pH and Ca^{+2}.

INTRODUCTION

In the global context, over 800 million hectares of land, constituting approximately 6% of the Earth's total land surface, experience salinity-related issues (Munns 2005). Indeed, in various regions across the globe, numerous distinctive halophytic ecosystems have developed as a result of unique environmental dynamics. These ecosystems exhibit a wide range of ecodynamics responsible for their formation, leading to the diversity of halophytic vegetation that accompanies them (Andersen et al. 2021; Lubińska-Mielińska et al. 2023). For instance, various saline ecosystems, such as coastal dunes (Du and Hesp 2020a), salt marshes formed by delta inundations (Debanshi and Pal 2020; Mumcu et al. 2023), the peripheries of inland lakes (Castañeda et al. 2020; Q. Cui et al. 2021; Q. Li et al. 2021), deserts in northern China (Xi et al. 2016; Nan and Guo 2018; J. ; Liu et al. 2022), oases (Zhang et al. 2003; Youcef et al. 2012; Zhao et al. 2019), and mangroves (Nazrul Islam et al. 2019; Biswas and Biswas 2021; Y. Wang et al. 2021), represents diverse salt-affected environments. These ecosystems exhibit distinct formation processes and ecological dynamics, and the factors affecting the structure and floristic composition of the developing vegetation vary from region to region.

Salt marshes are recognized as highly efficient carbon sinks with significant potential for carbon capture and storage, contributing to the mitigation of global warming. Coastal salt marshes, mangroves, and seagrass meadows, for instance, have demonstrated their exceptional capacity to absorb and sequester carbon, thus playing a vital role in reducing CO_2 emissions. Salt marshes excel in the effective accumulation and sequestration of blue carbon, estimated to range from 4.8 to 87.2 tera-grams of carbon per year. Despite their prowess in blue carbon storage, human activities have led to the destruction or alteration of extensive salt marsh areas (Cai et al. 2023).

Hence, the preservation of salt marsh ecosystems necessitates a comprehensive examination of the primary determinants governing the distribution and abundance of vascular plants within saline habitats (Maccioni et al. 2021). Salinity, as a major environmental stressor significantly constraining plant growth (Mahajan and Tuteja 2005), underscores the need for investigating its effects on soil nutrient dynamics, plant productivity, and the emergence of distinct halophytic plant communities, all of which are contingent upon the unique salinity formation processes across diverse habitat types.

Salinization, arising from region-specific dynamics and variabilities, assumes a paramount ecological role as a principal determinant influencing the zonation and floristic composition of distinct natural plant communities within saline environments. Salt stress in plants leads to ion toxicity and damages their photosynthetic system, as indicated by Munns in 2005. Throughout their long evolutionary period, plants have developed various mechanisms to adapt to salt stress. These mechanisms including genetic (R. Li et al. 2023) physiological (Lambers and Oliveira 2019; Schulze et al. 2019), morpho-anatomical (Grigore et al. 2014; R. Liu et al. 2018; F. X. Wang et al. 2018), and behavioural (Cao et al. 2014; Ma et al. 2018) adaptations, and they often interact with one another. These adaptations are crucial for the plant's survival and ability to distributed in saline environments.

We aimed to undertake a comparative analysis with the purpose of elucidating the influence of salinity parameters on the zonation of plant communities within the coastal salt marshes and coastal sand dunes ecosystems located in the Yeşilırmak Delta of Turkey. In pursuit of this objective, we conducted a comprehensive examination, focusing on the intricate dynamics of salinity and their effects on the spatial distribution and composition of plant communities in these specific ecological settings. Our study sought to contribute to the understanding of the intricate interplay between salinity parameters and the establishment of distinct plant community zones in these coastal environments within the Yeşilırmak Delta region.

MATERYAL METOT

2.1 Study area:

Situated in the Yeşilırmak Delta, which is the second-largest delta plain in Turkiye in terms of surface area (Fig. 1), the annual average temperature stands at 14.3°C, with an annual average precipitation of 1048.1 mm. Within the delta's expanse of 39,728 hectares, approximately 28.5% of the land experiences drainage issues, while an additional 2.1% of the area not only faces drainage problems but also exhibits salinity and sodicity concerns (İç 2015).

Especially in areas where drainage is impaired within the delta plain, the accumulation of soluble salts on the soil surface and their subsequent concentration occurs due to seasonal inundations from channels and lakes, coupled with a high groundwater table. This concentration results from the leaching of these soluble salts through capillarity, eventually mixing with groundwater and emerging onto the soil surface. Consequently, the ions accumulate on the soil surface and lead to salinization (Kwiatkowski and Pittman 1997; Bui 2017; Stavi et al. 2021).

Furthermore, unregulated utilization of aquifers in the Yeşilırmak Delta plain has led to a critical decline in water levels, particularly during the summer months. This decline facilitates seawater intrusion into the aquifers, serving as a source of localized salinization (Werner et al. 2013). The filling of aquifers with seawater through penetration (Konikow and Kendy 2005; Konikow 2011) is a significant contributor to this phenomenon due to uncontrolled aquifer usage. Whereas, in coastal dune habitats, the primary source of salinity stems from the invasion of seawater through marine wave action and spray from tidal surges (Redondo-Gómez et al. 2011; van Puijenbroek et al. 2017).

2.2. Methods

2.2.1. Floristic Methods

In the Yeşilırmak Delta Plain, halophytic communities dominated by species with salinity indicator values (Ellenberg et al. 1992; Ellenberg and Leuschner 2010) of ≥ 3 were selected based on floristic and structural homogeneity criteria as defined by van der Maarel. These communities were examined across ten continuous sample plots, and monthly floristic assessments were conducted to determine species cover-abundance values, following the methodology outlined by van der Maarel (E. van der Maarel 1979; Eddy van der Maarel and Franklin 2013). Soil samples were also collected from these sample plots monthly. Species identifications were carried out in accordance with the Flora of Turkey and East Aegean Islands (Davis 1965; Davis 1967; Davis 1970; Davis 1972; Davis 1978; Davis 1982; Davis 1984a; Davis 1984b; Davis 1986).

2.2.2 Soil Analyses

From each community, soil samples were collected monthly at a depth of 40 cm, with three replicates. These soil samples were subsequently air-dried at room temperature and prepared for analysis by grinding and sieving through 2 mm and 0.5 mm mesh sieves. Soil samples underwent various analyses, including determination of average moisture content at the time of sampling, soil texture using the method of Demiralay (Demiralay 1993), soil reaction (pH at a 1:2.5 soil-to-water ratio), electrical conductivity (EC in µS/cm), and analysis of exchangeable ions (Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}, SO_4^{-2} and Cl^{-}) following the procedure by Kacar (Kacar 1994). Additionally, determination of HCO_3^{-} was carried out using titrimetric methods according to Sağlam (Sağlam and Dengiz 2013).

2.2.3. Statistical Methods

To evaluate the annual mean soil analysis values across various communities and assess the differences between these communities, we performed a statistical analysis using the One-Way Analysis of Variance (ANOVA) method, following the guidelines outlined in Hollander's methods (IBM 2013; Hollander et al. 2015)

2.2.4. Multivariate Numerical Analyses

We analysed a matrix comprising 74 species across 50 sample plots, with each species characterized by its cover-abundance values based on van der Maarel's scale (E. van der Maarel 1979). The analysis was conducted using the TWINSPAN (Two-way Indicator Species Analysis) method (HILL 1979; Seaby and Henderson 2007). Canonical Correspondence Analysis (CCA) (Ter Braak 1986; Jongman et al. 1987; Seaby and Henderson 2007) was employed for the direct ordination analysis of the sample plots. Furthermore, we provided the EUNIS Habitat Classification codes for the communities in parentheses following their respective names (EUNIS 2023).

RESULTS

3.1. TWINSPAN (Two-Way Indicator Species Analysis) Classification

For the identification of communities within the research area, we employed a TWINSPAN analysis that was conducted up to the 4th level using the matrix comprising 74 species across 50 relevés. The resulting dendrogram, as illustrated in Fig. 2, shows the grouping of relevés into distinct communities, specifically *Pancratium maritimum*, *Elaeagnus rhamnoides, Tamarix smyrnensis-Juncus acutus, Salicornia perennans* and *Juncus acutus*.

Coastal Dune Communities (B1)

These communities inhabit the dynamic and stable dune zones formed by the coastal wind and wave effects in the research area.

Pancratium maritimum Community (B1.313)

These herbaceous formations develop in the semi-stable transition zone between the embryonic dune zone and the stable zone, which is beyond the direct reach of marine waves in the research area. They are characterized by dominant species such as *Pancratium maritimum*, along with *Cakile maritima* Scop., *Salsola tragus* subsp. *tragus* Cent. Pl., *Euphorbia peplis* L., *Polygonum maritimum* L., *Achillea maritima* subsp. *maritima* (L.) Ehrend. & Y.P.Guo, *Ammophila arenaria* (L.) Link, and various other annual or perennial halophytic coastal dune species.

Elaeagnus rhamnoides Community (B1.611)

This community is found predominantly on the summits of sand dunes within the research area, where vegetation typically attains heights ranging from 1 to 2 meters. *Elaeagnus rhamnoides* stands out as the dominant plant species in this habitat. The floristic composition is characterized by a diverse assembly of herbaceous species, including both single and perennial varieties, which are well adapted to the saline conditions of this environment. Notable species within this community include *Eryngium maritimum* L., *Salsola kali* L., and *Elymus farctus* subsp. *farctus* Cent. Pl., among others, contributing significantly to the overall biodiversity of this distinctive ecosystem.

Wetland Communities (A2/F9)

The communities are situated in specific areas within the research site where seasonal inundation occurs because of flooding in both lakes and drainage channels. These locations undergo periodic changes in water levels, leading to temporary waterlogging. As a result, these habitats exhibit distinct ecological characteristics and support unique plant communities that have adapted to distribute in such saline dynamic and hydrologically variable environments.

Salicornia perennans Community (A2.5515)

Within the research area, there exists a halophytic herbaceous community that distributed in wetlands sensitive to seasonal inundation, primarily between November and June, near the mouth of the Yeşilırmak River. This community is characterized by its floristic composition, with the dominant presence of the perennial species *Salicornia perennans*. Additionally, numerous other both annual and perennial halophyte species, including *Suaeda prostrata* Pall., *Salsola kali*, *Spergularia marina* (L.) Besser, and *Tripolium pannonicum* (Jacq.) Dobrocz., are found as constant species within this community.

Juncus acutus subsp. acutus Community (A2.522)

Within the research area, there exists a halophytic tall herbaceous community that is subject to seasonal inundation, primarily occurring between the months of November and May. This community is situated near the confluence of the Yeşilırmak River with the sea. The floristic composition of this community is notably characterized by the predominance of *Juncus acutus* subsp. *acutus*. Furthermore, this habitat contains a multitude of other halophytic species, among which notable constant species include *Carex extensa*, *Tripolium pannonicum* (Jacq.) Dobrocz, and *Atriplex hastata* L., etc.

Tamarix smyrnensis-Juncus acutus subsp. acutus Community (F9.31343)

Emerging immediately beyond the coastal dune habitats, there exists a shrub community that is seasonal flooded, predominantly occurring between the months of November and June. This community represents the climax stage of halophytic habitats within wetland ecosystems. The floristic composition of this community is characterized by the dominance of *Tamarix smyrnensis* and co-dominant species such as *Juncus acutus* subsp. *acutus*. Moreover, several constant species, including *Samolus valerandi* L., *Crypsis aculeata* (L.) Aiton, *Atriplex hastata* L., and *Juncus maritimus* Lam. among others, are prevalent within this halophytic habitat.

3.2. Statistical Analysis of Soil Analysis Data for the Communities

The outcomes of the One-Way Analysis of Variance (ANOVA) assessing disparities in soil parameters across the various communities within the research locale are as follows: Statistically significant distinctions were discerned among the communities concerning soil texture (F (4, 175) = 7673.872, p = 0.000), pH levels (F (4, 175) = 49.170, p = 0.000), and electrical conductivity (EC) (F (4, 175) = 72.763, p = 0.000). Furthermore, notable variations manifested in the concentrations of cations, including Ca^{+2}, (F (4, 175) = 286.600, p = 0,000), Mg^{+2}, (F (4, 175) = 230.483, p = 0,000), Na^{+},(F (4, 175) = 55.279, p = 0,000), K^{+} (F (4, 175) = 363.862, p = 0,000), along with anions such as Cl^{-},(F (4, 175) = 76.795, p = 0,000), HCO_3^{-},(F (4, 175) = 3.976, p = 0,000), SO_4^{-2}, (F (4, 175) = 132.628, p = 0,000), and the mean soil moisture content at the time of sampling (F (4, 175) = 363.037, p = 0.000). These findings indicate significant differences among the communities in terms of these soil parameters (Table 1).

Table 1
Results of the Duncan Test for the Variation of Parameters (EC, pH, Average Soil Moisture at Sampling, Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-} and SO_4^{-2}) among the Communities

Communities	pH (1:2.5)	EC (µS/cm)	Moisture (%)	Ca^{+2} (me/100g)	Mg^{+2} (me/100g)	Na^{+} (me/100g)	K^{+} (me/100g)	Cl^{-} (me/100g)	HCO_3^{-} (me/100g)	SO_4^{-2} (me/100g)
Pancratium maritimum	8.06 a	399.81 d	6.16 d	10.14 d	8.65 d	0.85 b	1.51 d	8.23 c	0.47 b	0.03 c
Elaeagnus rhamnoides	7.37 c	354.69 d	6.73 d	11.98 c	7.88 d	0.16 d	0.32 e	6.19 c	0.45 b	0.03608 c
Tamarix smyrnensis	7.94 a	2085.57 b	44.47 a	18.06 b	17.17 c	1.40 a	4.54 b	37.85 b	0.51 ab	0.08 a
Juncus acutus subsp. acutus	7.56 b	1544.88 c	31.09 c	21.89 a	21.26 b	0.60 c	4.01 c	30.44 b	0.56 a	0.045 b
Salicornia perennans	7.50 b	3753.64 a	34.31 b	21.86 a	24.88 a	0.71 bc	5.07 a	88.28 a	0.43 b	0.047 b
Total standard error	0,027	118,61	22,14	0.39	0.55	0.04	0.14	2.78	0.012	0.001

**The differences between means denoted by separate letters are statistically significant at the 1% confidence level.

3.4. 3.4.2. Canonical correspondence analysis (CCA)

According to the Monte-Carlo permutation test results, the first four axes were found to be significant ($p < 0.001$) and were used in the interpretation of ordination. Axis 1 had an eigenvalue of 17.23, explaining 46.89% of the total variance, while Axis 2 had an eigenvalue of 9.71, explaining 29.51% of the total variance. Axis 3 had an eigenvalue of 6.43, explaining 3.80% of the total variance, and Axis 4 had an eigenvalue of 6.31, explaining 3.73% of the total variance. Ordination results were interpreted based on intra-set correlation coefficients (Table 2).

The edaphic factors that primarily contribute to the separation of relevés associated with coastal dune and wetland groups can be discerned along the horizontal axes of Axis 1 and Axis 4. Specifically, relevés of wetland communities are situated on the negative side of Axis 1 and Axis 4, whereas relevés of coastal dune communities are located on the positive side of the horizontal axes. According to the CCA ordination, the edaphic factors that facilitate the division of relevés into two main groups, coastal dune and wetland, are Ca^{+2} and Mg^{+2} on Axis 1, as well as instantaneous soil moisture (%) on Axis 4 (Fig. 3, Table 2). Moreover, when evaluated in conjunction with the Duncan table, it has been determined that the effective parameters in Axis 1 and Axis 4, respectively Ca^{+2}, Mg^{+2}, instantaneous soil moisture (%), and Cl^{-} in Axis 4, exhibit variations between coastal dune and wetland communities (Table 1).

Table 2
Eigenvalue and intraset correlation coefficients of edaphic parameters of communities in the Yeşilırmak Delta. (Significant values are shown in bold)

Soil parameters	Axis 1	Axis 2	Axis 3	Axis 4
pH	0.07	**-0.53**	0.40	0.09
EC	0.07	-0.04	**-0.60**	0.14
Ca^{+2}	**0.61**	**-0.51**	-0.11	-0.16
Mg^{+2}	**0.73**	0.25	0.13	0.15
Na^{+}	-0.01	-0.46	-0.29	0.27
K^{+}	-0.22	-0.14	-0.09	-0.06
Cl^{-}	0.34	0.35	-0.04	**0.59**
HCO_3^{-}	-0.09	-0.04	-0.15	**-0.72**
$SO4^{-2}$	-0.08	0.15	0.02	0.03
Soil moisture (%)	**0.66**	-0.13	0.29	0.07
Canonical Eigen value	17.2349	9.70649	6.43924	3.80478
% variance explained	46.8989	29.51722	6.31368	3.73059
Multiple correlation species/environment scores	0.862468	0.62735	0.605539	0.500988
Kendal rank correlation of species/environment scores	0.628779	0.415017	0.450265	0.34111

The effective parameters contributing to the segregation of relevés within wetland and coastal dune communities exhibit distinctions based on the specific habitats of these communities (wetland vs. sand dunes). Analysing the CCA diagram in conjunction with Duncan's results, it becomes apparent that various edaphic factors drive the internal grouping of relevels within wetland halophytic communities. Notably, these factors include Mg^{+2} and instantaneous soil moisture (%) concerning Axis 1, concerning Axis 3 EC and concerning Axis 4 Cl^{-}. Conversely, for coastal dune communities, the parameters influencing the internal grouping of relevels include Ca^{+2} concerning Axis 1, pH, and Ca^{+2} concerning Axis 2 (refer to Fig. 2, Table 1, and Table 2 for detailed results).

According to our results, the edaphic factors effective in the zonation of communities in different saline ecosystems (wetlands vs. coastal dunes) also vary. This is essential for understanding the unique ecological dynamics at play in wetland and coastal dune ecosystems. Thus, aside from shared halophytic traits, these ecosystems are further delineated by distinct edaphic parameters that contribute to their differentiation.

DISCUSSION

According to the findings obtained from this study, the horizontal zonation of halophytic communities in the Yeşilırmak Delta Plain is primarily influenced by soil salinity gradients and the parameters affecting these gradients. Additionally, the salinity dynamics in wetland habitats and coastal dunes within the study area differ due to variations in hydrological regimes and soil texture (Moreno et al. 2018). This disparity arises from factors such as organic matter content, $CaCO_3$ levels, clay (%), silt (%), and sand (%) in the soil, which play crucial roles in shaping the micro-nutrient composition of the soil (Sağlam and Dengiz 2013).

Furthermore, the wetland halophytic communities, which distributed in soils with silty-clay textures, are exposed to seasonal inundations originating from channels and lakes. In contrast, the halophytic psammophilic communities, which develop in sandy-textured habitats, are subjected to marine-derived deposition and direct wave action (van Puijenbroek et al. 2017). As a result, the salinity parameter's values (EC, Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}; Cl^{-}, $HCO_3^{-}$and SO_4^{-2}) in the sandy dune habitats where psammophilic (coastal dune) communities are distributed are lower compared to the habitats where wetland communities are found (Table 1). This is attributed to the porous texture of coastal dunes, which facilitates the leaching of salts through rainfall-induced washing processes (Apaydin et al., 2009; Du & Hesp, 2020; Rogel et al., 2000). Consequently, soil salinity levels in habitats with higher sand content are lower compared to flooded habitats due to the enhanced removal of salts through rainwater leaching (Contreras-Cruzado et al. 2017). Additionally, it is noteworthy that the dominance of calcium carbonate in the sand composition, indicated by the presence of lime tiles and concretions, contributes to the basic nature of the soil (pH = 7.30 – 8.50). The humus content and moisture levels in the substrate further influence the vegetation types in various sections of the sands (Ćuk et al. 2023). This comprehensive understanding of the ecological dynamics underscores the intricate relationship between edaphic parameters and the zonation of halophytic communities in the Yeşilırmak Delta Plain.

In contrast, the Ellenberg salinity indicator values of species in the psammophilous halophytic communities in the research area are relatively higher compared to species in the halophytic communities developing in the salt marsh habitats. However, it is crucial to note that the salinity indicator values of halophytic species can vary regionally, and the mechanisms of salinity formation in the rhizosphere, as well as species' adaptation mechanisms, can differ (Hill et al. 1999; Grigore et al. 2014). Despite the higher salinity values in the soils of wetland habitats compared to coastal dune habitats (Table 2), halophytic species in wetland areas are exposed only to physiological drought due to the high groundwater level in these habitats. In contrast, halophytic species in coastal dune habitats are subjected to both salinity-induced physiological drought and physical drought due to the sandy texture, resulting in the lack of groundwater. Consequently, halophytic species in coastal dune habitats have developed adaptations to maintain high intracellular osmotic values (Grigore et al. 2014; R. Liu et al. 2018; F. X. Wang et al. 2018). These adaptations enable them to distribute in the challenging environmental conditions of this type habitats.

In the zonation of communities within the research area, the soil pH gradient is a highly significant environmental factor that plays a crucial role in the floristic differentiation of vegetation (Costa et al. 2003; B. S. Cui et al. 2011; Contreras-Cruzado et al. 2017). This is because there exists a close relationship between soil reaction and soil fertility; soil pH directly and indirectly affects the availability of nutrient elements in the soil, the activities of fungi, bacteria, and actinomycetes that contribute to soil productivity and fertility, and the formation of soil structure (BİLEN and SEZEN 2011; Naz et al. 2022). Indeed, the toxicity of hydrogen ions in highly acidic soils leads to various changes in many chemical properties of the soil, strongly inhibiting plant growth as the acidity increases. Consequently, pH variations in older marshes, particularly in terms of organic content accumulation and salt accumulation/percolation in sediments, indirectly impact factors, influencing vegetation zonation (Costa et al. 2003). Therefore, soil pH values are a crucial edaphic parameter influencing the distribution of both psammoseral and hydroseral communities in the research area (B. S. Cui et al. 2011).

Studies aiming to determine the effects of biotic and abiotic environmental factors on the development of vegetation in flooded saline habitats (wetland) and how these factors manage the upper and lower limits of species have been conducted (Lee and Kim 2018). Waterlogged soils can occur due to floods, heavy precipitation, or irrigation practices, and are exacerbated by poor drainage, compacted soils, or flat topography. Excess moisture in the soil restricts (hypoxia) or entirely depletes (anoxia) oxygen availability, leading to oxygen deficiency in plants (Karunarathne et al. 2023). Therefore, the zonation of communities in generally flat and waterlogged areas like delta plains is determined by sediment accumulation processes (Sarika and Zikos 2021) and the "local microtopography" and resulting "hydrological regime" that vary over short distances. Moreover, plant zonation and community development in the area are strongly influenced by changing physical factors. For instance, salinity values and periodicity of inundation periods in salt marshes function as primary stress factors. Therefore, the morphological, physical, and chemical properties of the soil are closely related to both the hydrological regime in the area and the distribution of plant species (Yin et al. 2020). Additionally, in delta plains, the duration of inundations and consequently the amount of ions, minerals, and particles accumulated in the soil also vary due to microtopographic gradients resulting from slight differences in elevation (Contreras-Cruzado et al. 2017; Tug et al. 2019). Therefore, the hydrological regime gradient arising from local microtopographic gradients regulates the seasonal and habitat-dependent effects on many physical and chemical properties of the soil, organizing the distribution of plant communities in the area (Contreras-Cruzado et al. 2017). This is because the flood regime also creates conditions that hinder the growth of most plants by affecting root respiration, germination, seedling growth, and soil chemical processes (Silvestri et al. 2005).

Wetland halophytes respond differently to chloride ions (Cl−): some are stimulated by Cl^- (e.g., *Sueada* sp., *Atriplex* sp.), some are minimally affected by 200 mM Cl^- (e.g., *Atriplex* sp, *Spartina* sp., *Beta* sp.), and others are substantially affected by 100 mM Cl^-. Toxic levels of Cl^- are around 4–7 mg g^{-1} for sensitive plants and 15–50 mg g^{-1} for tolerant plants. Plants manage Cl^- toxicity by limiting Cl^- transport to the shoot. Halophytes accumulate high Cl^- content in tissues (340–475 mM) to maintain turgor, whereas other plants have lower concentrations (7–70 mM). Cl^- concentrations vary across plant parts; leaves have similar Cl^- levels, while floral tissues, fruits, and seeds contain lower concentrations. Cl^- concentration also depends on the halophyte species, and minor seasonal changes occur in some plants. In summary, halophytes adapt to salinity by regulating Cl^- transport and accumulating varying Cl^- concentrations, with differences observed across plant parts and species. Magnesium ions (Mg^{2+}) are essential cofactors for various enzymes and are part of the chlorophyll molecule. However, Mg^{2+} competes with calcium ions (Ca^{2+}) for binding sites on root plasma membranes, and excessive Mg^{2+} can be toxic to halophytes. For instance, higher Mg^{2+} concentrations were detrimental to the germination and radicle survival of the halophytes. Mg^{2+} accumulation mainly occurred in specific cells of certain halophytes. Interestingly, Mg^{2+} has been suggested to protect cells from NaCl toxicity similar to Ca^{2+}. Studies showed that increasing salinity led to higher Ca^{2+} and Mg^{2+} levels, which helped wetland plants like *Juncus acutus* cope with salt stress. Dicotyledonous halophytes had higher Mg^{2+} concentrations than monocotyledonous ones. Overall, Mg^{2+} plays crucial roles in plant metabolism but must be balanced, as excess amounts can be harmful, affecting various physiological processes and potentially leading to ion imbalances in halophytes.(Hasanuzzaman et al. 2019)

Therefore, gradients in physicochemical factors such as salinity and flooding, which arise from the combined influence of numerous environmental parameters, are determining factors in the distribution of species and the zonation of vegetation in wetland habitats (Lee et al. 2016). For instance, in well-developed wetland habitats in terms of succession, a plant zonation parallel to the shoreline is observed (Costa et al. 2003). This is because in wetlands near a lake, salt minerals transported to the terrestrial environment during seasonal flooding are deposited during periods of water recession, leading to the formation of a soil salinity gradient. Additionally, winds blowing from the lake towards the land contribute to the transfer of salty spray landward, thereby increasing soil salinity (Du and Hesp 2020b).

Soil salinity level (EC, soil anion and cation levels) and the redox potential of soil water play a key role in the horizontal zonation of vegetation (Q. Cui et al. 2021). Indeed, both the soil salinity values of the coastal dune and wetland communities in the research area exhibit significant differences (Table 1), acting as a significant factor in the zonation of halophytic communities (Table 2, Fig. 3) (Chenchouni 2017; Moreno et al. 2018). For instance, the communities in the research area exhibit a decrease in the average EC values; psammoseral ones ranging from *Pancratium maritimum* to *Elaeagnus rhamnoides*, and hydroseral ones ranging from *Salicornia perennans*, *Tamarix smyrnensis* to *Juncus acutus* subsp. *acutus*. This zonation of plant communities is organized into characteristic communities following successional processes (Ivajnšič et al. 2016).

In summary, the complex dynamics within wetland communities are influenced by parameters such as Mg^{+2}, instantaneous soil moisture (%), EC, and Cl^{-}. Meanwhile, the unique features of coastal dune communities are shaped by factors like pH and Ca^{+2} at the study area. These findings highlight the distinct ecological complexities of these environments, providing valuable insights into the complicated dynamics controlling wetland and coastal dune ecosystems.

CONCLUSION

Soil salinization serves as a crucial edaphic factor affecting plant life in both natural and agricultural settings, particularly functioning as a regulatory factor in the zonation of halophytic communities. In certain locations within the delta plain, it has been observed that indigenous halophytic plant communities develop due to localized soil salinization gradients. This study, unprecedented in the delta plain, aimed to determine the degree of influence of soil salinization factors on the distribution of natural wetland and coastal dune halophytic communities. Additionally, given the deltaic nature of the research area, we believe that this research will contribute valuable insights into the causes and dimensions of salinization, along with its agricultural implications. Consequently, this study is anticipated to provide recommendations for mitigating salinization in the delta, addressing the factors leading to significant agricultural productivity losses. Moreover, it is crucial to conduct a comparative analysis of areas hosting salt marshes and coastal dunes, each harbouring halophytic communities with distinct characteristics. Examining these areas as integral parts of the overall study area, rather than considering salinization processes separately, is fundamental for understanding the dynamics of salinization processes and halophytic habitat dynamics. This holistic approach is essential for gaining comprehensive insights into the intricate processes shaping these unique ecosystems.

Due to these functions and similar ecological contributions, delta plains and their associated subarid ecosystems must be conserved, considering their ecological balance features in relation to other environmental ecosystems. We believe that the findings obtained from this study will contribute to the research and conservation efforts of similar ecosystems.

Declarations

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This article is derived from my PhD thesis, which has been presented at Ondokuz Mayıs University. The thesis, titled A Research on The Some Edaphic Factors Affecting on The Zonation in Halophytic Vegetation in Yeşilırmak Delta,' served as the basis for this work. This research is funded through a PhD program at Ondokuz Mayıs University. Additional support was granted within the scope of doctoral thesis projects under the project number PYO.FEN.1904.18.015, affiliated with Ondokuz Mayıs University's BAP (Scientific Research Projects) unit.

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Figures

Figure 1

The Google Earth sketch of the study area and the designated locations for communities

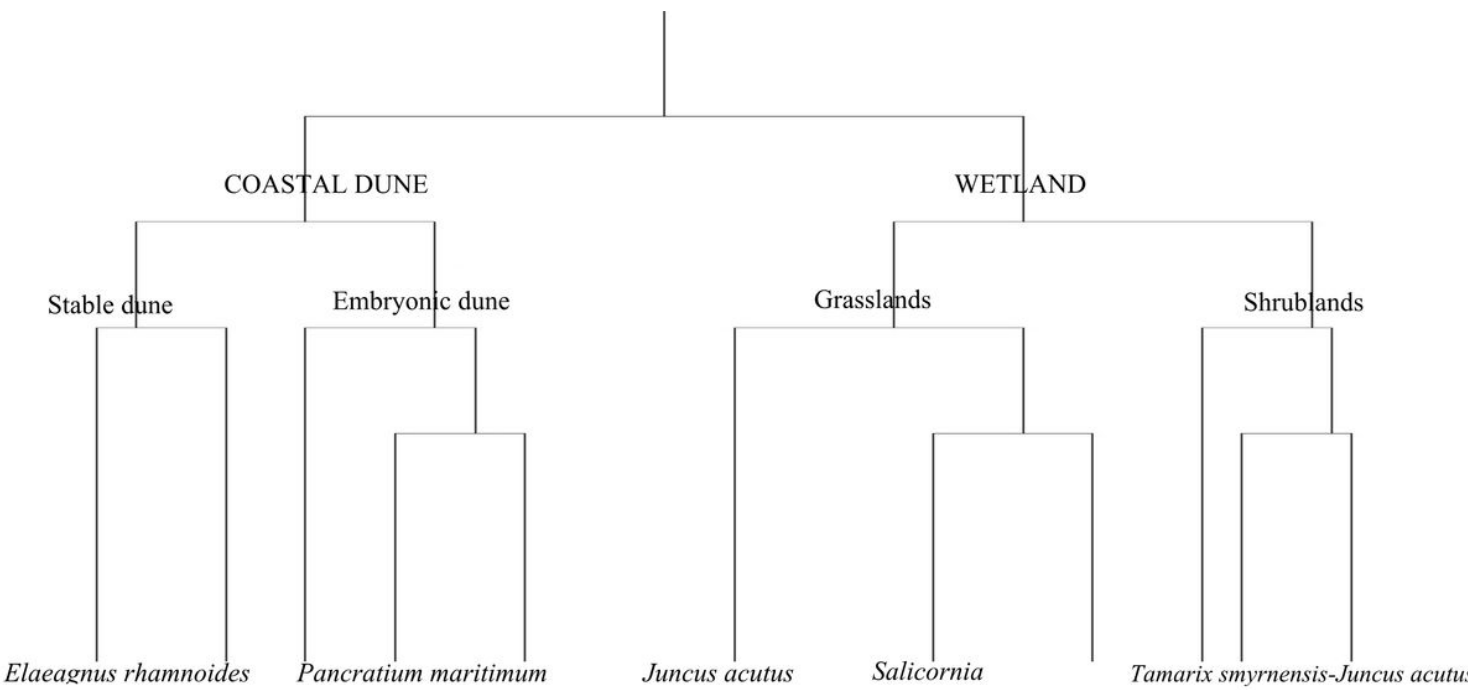

Figure 2

The TWINSPAN dendrogram of halophytic communities in the Yeşilırmak Delta.

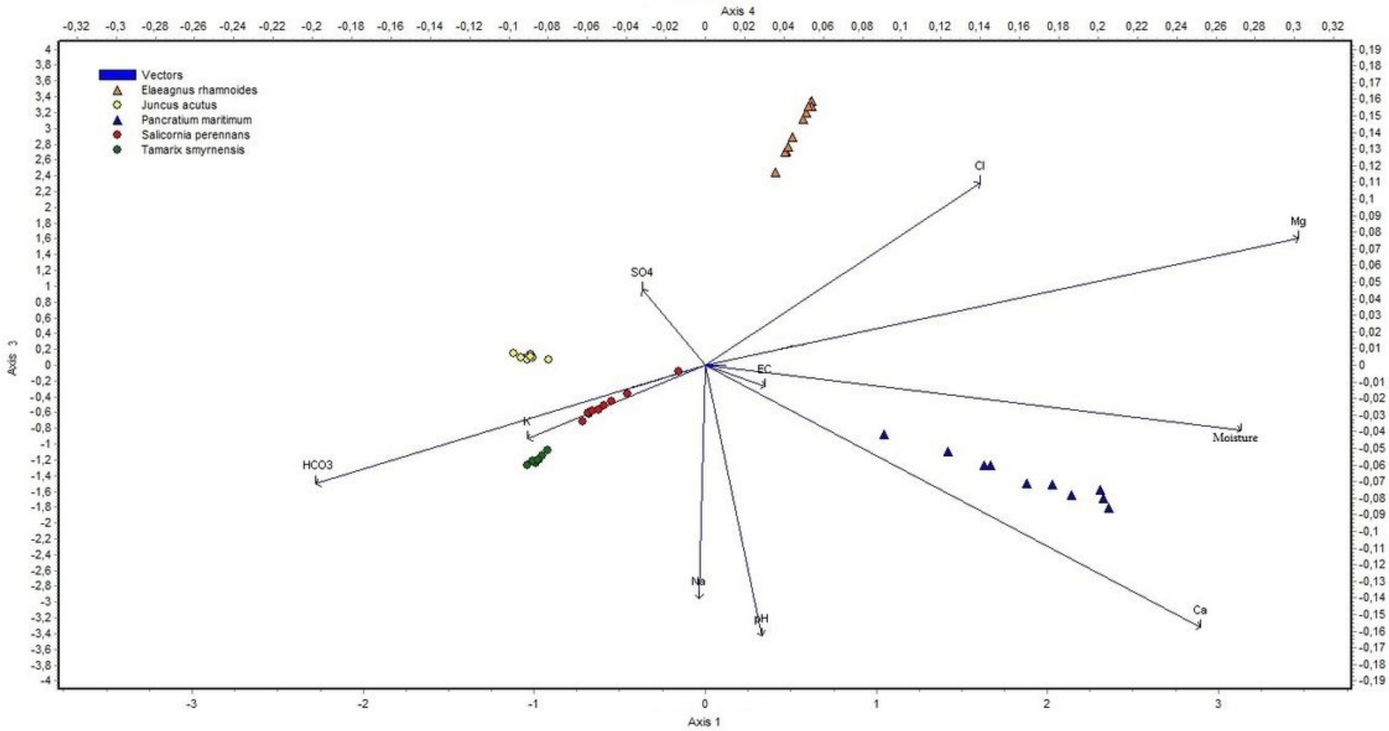

Figure 3

CCA ordination graph of halophytic communities in the Yeşilırmak Delta.