ASSESSING HIGH ALTITUDE ANDEAN WETLANDS USING PLANT COMMUNITY STRUCTURE: A MULTIVARIATE ANALYSIS AND REMOTE SENSING APPROACH

by

María José Ruiz-Esquide

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Abstract

High altitude wetlands of the Central Andes Cordillera in South America are unique ecosystems with valuable ecosystem functions and one of the environments most threatened by climate change. They play a significant role in sustaining endemic biota, in providing the grasslands for herd of alpacas, llamas and vicuñas and by storing water and releasing it during the year to one of the driest regions on the earth, the Atacama Desert. This ecosystem is dependent on groundwater sources, and vegetation regulates the amount of water available during the dry periods. In Chile, the increasing demand for water requires more technical knowledge and research in order to prevent further degradation. The objective of this research is the description of Tarapacá and Atacama regions' wetlands plant communities, the abiotic factors and human impacts that are more strongly associated with them by multivariate analysis and a remote sensing approach. Chapter 1 is a review of high altitude Andean wetlands and their importance. In Chapter 2, I identified differences in plant communities' structure. Each region was distinguished by 5 different plant communities according to the vegetation wetland types. Abiotic factors and physical attributes that were more strongly associated with plant communities were the number and width of principal streams found on the wetland and amount of rocks, bare land and percent of organic matter along the vegetation transects. Using field work and remote sensing, in Chapter 3, I performed a spectral discrimination among plant communities using IKONOS-2 and Geoeye-1 high resolution satellites images. They were used to identify which bands and vegetation indices were the most effective for discriminating vegetation classes. Vegetation classes did express different spectral behaviors. The classes with more reflectance variation were mixed grasses with *Oxychloe andina*, mixed grasses with salt patches and mixed grasses with

Zameioscirpus atacamensis, while classes dominated by *O. andina*, *Z. atacamensis* and *Festuca chrysophylla* expressed less variation on the spectral range. General Discriminant Analysis showed that the most important spectral bands and vegetation indices for distinguishing differences between vegetation classes were Band 1-blue, band 4-NIR and the Wide Dynamic Range Vegetation Index.

Preface

This thesis is made as a completion of the Master of Applied Science in Forestry at UBC. This work is original intellectual, unpublished, independent work by the author, MJ. Ruiz-Esquide Enriquez. In this project, the research was not subject to ethics review, produced no publications by the time of graduation, and was designed, carried out, and analyzed by the author.

The thesis was conducted under the main supervision of Dr John Richardson, head of Department, Forest and Conservation sciences and director of Stream and Riparian Research Laboratory, Faculty of Forestry, UBC.

Analysis of the research data on Chapter 2 is based on work co-supervised by Dr Gary, Bradfield, Department of Botany, Faculty of Science, UBC.

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Dedication

This Thesis is dedicated to my parents, Nancy Enríquez and Fernando Ruiz-Esquide that with their example, experience and deeply dedication taught me that by using perseverance, excellence, honesty and passion in what I love, I could achieve everything in my life and be everywhere in the world.

Gracias Mamá y Papá.

Chapter 1: HIGH ALTITUDE WETLANDS: REVIEW

1.1. High altitude wetlands in the world

A wetland is “an ecosystem that arises when inundation by water produces soils dominated by anaerobic processes, which, in turn, forces the biota, particularly rooted plants, to adapt to flooding” (Keddy, 2010). Wetlands are found in a wide range of ecological conditions from coastal deltas to high altitude swamps (FAO, 1998). Globally they cover a total surface over 6.8 million km^2, mostly located in Polar/Boreal climates, followed by subtropical/tropical, rice paddies and temperate regions (Matthews, 1989).

According to Wetlands International NGO dataset, wetlands are designated as internationally important under The Convention on Wetlands (Ramsar, Iran, 1971), called Ramsar sites. They can be classified as rivers and deltas, mangrove forests, Arctic wetlands, peatlands, high altitude wetlands and arid region wetlands. In arid regions of the world, climatic factors, ocean conditions and land features, produce either conditions warm enough to evaporate the little amount of moisture available or prevent rainfall. They are found in parts of Asia and Australia, southwestern and northern Africa, the Middle East and the western parts of North and South America. Instead of a complete lack of water, arid and semi-arid areas are often characterized by seasonal rainfall and wetlands can retain water long after the rest of the landscape has dried out.

Wetlands provide more than 15 ecosystem services, including water supply and regulation, disturbance and climate regulation through carbon storage and methane production, waste treatment, recreation, nutrient recycling, habitat/refugee, erosion control, food production, soil formation, pollination and genetic resources (Seidl and Steffens, 2000; Millennium

Assessment Project, 2005; Keddy, 2010). High altitude wetlands in particular, support unique ecosystems and services that sustain the livelihoods of people. They store water from rain and glacial melt, feed aquifers, trap sediments and recycle nutrients, enhancing both the quantity and quality of water (Wetland International, 2014). When humans manipulate wetlands, whether by draining or flooding, many services are simultaneously changed, often with unknown consequences (Keddy, 2010).

1.2. High altitude wetlands of the Andes Cordillera

Wetlands in arid environments are very rare globally and little known about wetlands in the high Andean arid zone of the central Andes (Squeo et al., 2006). High altitude Andean wetlands are minerotrophic biotopes containing dense cushion plants interrupted by pools and superficial rivulets. They contain over 60 vascular plant species with short grasses and dwarf reeds from a few millimeters to a few centimeters tall (Otto et al.,1993; Ruthsatz, 1993). The main water sources of the Altiplano wetlands are fresh and mildly saline fossil groundwater reserves, generated during the Holocene 13,000 to 8,500 yr BP (Messerli et al., 1997) and modern recharge originates from glacier streams, snowmelt and summer rains on the Andes Cordillera (Squeo et al., 2006).

These wetlands belong to the broad ecosystem, known as Puna, which encompasses diverse ecosystems of the high central Andes higher than 3400 m asl, from southern Peru to Northern Argentina and Chile. They span over 10 degrees latitude, and up to 300 km wide, and include a large diversity of subtypes including prairies, scrublands, forest, salt lakes and wetlands. Puna can be subdivided into three distinct eco-regions, based primarily on precipitation and moisture trends and they are called: Moist Puna, Wet Puna and Dry Puna. The highest elevation of Puna, and most distinctive geological feature in the region, is a phytogeographically distinct unit called the High-Andean plateau or Altiplano**,** which is dominated by grasses (genera *Deyeuxia*, *Festuca*, *Poa*, and *Stipa*). In local freshwater conditions, along the steep valley bottoms or in basin hollows, the Andean grasses become sparser and vegetation is replaced by cushion-peat bogs, which are dominated by a few grasses and a large number of cushions, plaque, rosette and dwarf shrubs (Families Juncaceae, Cyperaceae and Asteraceae).

The central Andean "Wet Puna" extends from south-central Peru to central and western part of Bolivia, between 3,800 and 4,200 m of altitude, on the east side of the Andes. Much of the precipitation falls in summer from easterlies associated with the Bolivian high pressure system over the Amazon basin. A "Moist puna" zone is present in southern Perú and extends from western Bolivia to northwest Argentina over a wide altitudinal range of up to 6,600 m of altitude and receives between 250 and 500 mm of precipitation per year, mostly in the summer.

The "Dry Puna" is characterized by the harshest conditions in terms of aridity and is located on the western side of the Andes on the Altiplano. Precipitation is scarce, normally less than 100 mm per year or totally absent on the Atacama Desert. Most of the basins in the Altiplano are endorheic and are characterized by the occurrence of salt lakes referred to as "Salares". Mechanical weathering is intense, but the cold climate, aridity and lack of leaching, high relief and the continual downward movement of mineral matter, detritus and water prevent the development of mature soils and well-established plant communities (Wilcox, 1986; Abraham et al., 2000).

Wetlands in the Dry Puna Eco-region appear as green oases in valley bottoms, shallow basins and other low areas of relief in this otherwise poorly vegetated and arid landscape. This vegetation contrasts sharply with surrounding terrestrial communities by having plant cover usually higher than 70% and high plant productivity (Kalin et al., 2012). These ecosystems are unique, extremely fragile water features sensitive to climate changes and human disturbances (Squeo et al., 2006). In addition to this, climate change coupled with land-use change is predicted to result in dramatic alterations to the gradients that drive structure and composition of riparian wetlands. The Ramsar Convention considers high Andean wetlands to be highly fragile ecosystems as a result of both natural causes (such as climate or prolonged drought on the Puna) as well as human impacts, such as non-sustainable agriculture, excessive grazing and mining (WWF, 2014).

1.3. Altiplano wetlands in Chile

Chilean high altitude Altiplano wetlands are located on the Dry Puna. The northern part of it is in the summer rain region, where precipitation is determined by the South American Summer Monsoon and South American Low Level Jets coming from the east and carrying moisture from the Amazon basin (Piovano et al., 2009). On the other hand, in the southern part of the Dry Puna (at the south of the Arid Diagonal at 24-25º S, located in Chile), the winter rain region occurs, which is influenced by the Southeast Pacific anticyclone carrying moisture off the Pacific Ocean to the west side of the Andes in winter. In this region, average annual precipitation rarely exceeds 250 mm, almost exclusively received as snow (Squeo et al., 2006). The weather conditions during the Austral summer correspond to a convection precipitation period on the Central Andes high plateau called the “Altiplano winter”, which is characterized by heavy rainfall and is responsible for 70% of the annual precipitation over the Altiplano (Aceituno & Montecinos, 1993; Garreaud, 1999). The climatic characteristics where Chilean high altitude wetlands occur are different from the rest of the neighbor countries. In the Chilean Altiplano, the Dry Puna is found, while neighboring Perú and Bolivia have the Moist and Wet Puna (Ahumada & Faúndez, 2009).

In Chile, Altiplano wetlands are located in between 18 and 27 degrees south latitude, and over 4,000 meters above the sea. The Chilean Altiplano eco-region has a total surface of 8.8 million hectares, of which only 0.56% (50,000 ha) belongs to high altitude wetlands (Biota, 2007). Most of the area (48%) is located in the Arica-Parinacota region. The remaining area is distributed between Tarapacá region (21%); Antofagasta region (22%) and Atacama region (8.7%) (Ahumada & Faúndez, 2009). These wetlands can be classified depending on its vegetation and have been referred to as Bofedales (high altitude peatlands or cushion bogs), tall grasslands and wet meadows (Wilcox, 1986).

Considering the dependence of the species on humidity and their tolerance to salt, the Chilean agricultural and cattle service (SAG) classified the high altitude wetlands into three types: **Bofedales or Peatlands**: dominated by cushion species that can accumulate peat; **Tall grassland**: dominated by plants with cespitose form, with height greater than 40 cm; and **Wet meadows**: Dominated by species with rhizome growth form and very small grasses (less than 40 cm in height). In general, vegetation on the Altiplano eco-region, outside the oasis, is dominated by shrubs and grasses. This type of vegetation is called zonal (local) vegetation according to Ahumada & Faúndez (2009) and it is determined by factors like precipitation, altitude and slope. Nevertheless, the existence of the atypical wetland presence on the area is determined by factors, generally associated with soil properties and humidity. Considering the fact that saline patches can be considered as a degradation factor where plant communities change (Ahumada & Faúndez, 2009), each of the previous vegetation types can be saline or non-saline (Table 1.1; Figure 1.1).

Table 1.1. Description of high altitude wetland types according to the classification of the Chilean Altiplano wetlands from Squeo et al. (2006) and Ahumada & Faúndez (2009)

System	Hydrological input	Soils and Salinity	Main Plant Species
Bofedales - High altitude peatlands	Bofedales occur with permanent humidity and water saturation conditions of the ground permanently through the year. Water table is always at the surface level.	Soils have a high content of organic matter. Saline areas are characteristic of transitional stages and ecotones with other wetland types. When the saline patches are >5% on the wetland, the Bofedal is considered a "Saline wetland".	Species have a cushion type of growth, very compact. The main species from this system are *Oxychloe andina* and *Zameioscirpus atacamensis*. According to the function Bofedales provide, they can be classified into: 1) *Deyeuxia chrysantha*: species that indicates a very good condition of the prairie 2) *Oxychloe andina - Distichia muscoides*: with a very intense grazing intervention. 3) *Carex incurve – Werneria pygmaeae*: Mostly located on the borders of the bodefales.
Tall grasslands	Tall wet grasslands exist with water-saturated soils during the summer.	Soils have medium values of organic matter. Sectors with saline patches have lower organic matter content and a higher water table. A 30% of saline patches it is enough to classify some of this wetlands into a "Saline tall wet grassland".	Vegetation system dominated by hard and tall grasses (>40 cm) with cespitose growth. Dominant species on this system are *Festuca deserticola* and *Deyeuxia eminens*.
Wet meadows	Water saturation levels on wet meadows soils is very diverse and the system has a wide range of tolerance, from completely water-saturated soils to very low moisture.	Soil organic matter content is variable but mostly low. Salty patches are normally present and 20% of it is at the limit to be classified as a Saline wet meadow.	Plants have a rhizomatous growth, short and dense (< 40 cm). Dominant plant species are from the genera *Carex* and *Scirpus*.

a) b) c) d) e) f)

Figure 1.1. High altitude Altiplano vegetation types. Figures a) and b) High altitude peatland or Bofedales- cushion dwarf plants vegetation with pools. Figures c) and d) Tall grassland with cespitose turf grasses and one or several channels and pools. Figures e) and f) Wet meadows with rhizomatous short grasses with a main principal channel.

Because of hyper-aridity, intense solar radiation, high-velocity winds, atmospheric hypoxia because of the high elevation, daily frost, and a short growing season, Bofedales have slow regeneration rates and are near the hydrological and altitudinal limits for plant life (Squeo et al., 2006). The distribution is naturally fragmented by topography and climate (Halloy et al., 2008). These peatlands are like none other in the world, however they are not dominated by *Sphagnum* mosses, as is typical of true bogs in the Northern Hemisphere. The most common species are members of the Juncaceae family, being *Oxychloe andina* and *Patosia clandestina*, the community dominants and primary peat-formers (Squeo et al., 2006). The records of the first plant establishment are from 6,600 years, however, the *Oxychloe* communities began to spread out only about 1,200 year ago (Squeo et al., 2006).

Fresh and mildly saline groundwater originating from glacier streams, snowmelt and rain are the water sources of these peatlands. They play a critical role in sustaining a unique diversity of rare and endemic biota in the Andes Cordillera. According to the conservation priorities in the World Temperate Grasslands Conservation Initiative Workshop, these are critical areas, for their inordinately large diversity of endemic species, concentration of bird fauna and water regulation in lower regions (Halloy et al., 2008).

Communities of native “Aymara” and “Atacameños” peoples are directly dependent upon the wetlands in this region. The peatlands are used for grazing the domestic herds of llamas (*Lama glama*) and alpacas (*Vicugna pacos*), which are the basis of the local indigenous economy (Alegría and Lillo, 1996).

These ecosystems are important for ecological restoration as they can serve as a baseline of original vegetation to guide restoration of a degraded site and also serve as a source of propagules (Poulin et al., 1999). Particularly for the restoration of complex vegetation systems like wetlands, plants are organized along environmental gradients, combining vascular plants, bryophytes and aquatic macrophytes.

Bryophytes from different genera are an important component of peatlands and a bog´s ground layer. Physiological adaptations permit bryophytes to retain water or recover from loss of water after dry periods. They are drought tolerants with the ability to survive and maintain activity despite a lack of water in the environment, maintain normal metabolism at lowered cell volume (Proctor, 2000) and have different desiccation avoidance methods than tracheophytes. Species like *Bryum bicolor* forms subterranean rhizoidal tubers and stem tubers, which aid dormancy (El-Sadaawi & Zanaty, 1990). In addition to desiccation tolerance, Bryophytes can also tolerate extremely low temperatures and recover their active state (Oliver et al., 2000). Based on this desiccation resistance, mosses have a high ability to fix carbon efficiently at low water contents. Further bryophytes from xeric habitats have been shown to recover from desiccation better than those from moist habitats, like Sphagnum (Andrus, 1986).

Vegetation structure and composition of Altiplano wetlands varies along the length of the riparian ecosystem, in response to gradients in water availability and species' requirements. HAAW vegetation is controlled by four main interacting ecological factors: (a) water quantity and seasonal availability, especially during dry periods, (b) favorable ambient temperatures and occurrence of frost events that control the duration of the growing season, (c) water pH, availability of nutrients (mainly, N, P, K, Ca and Mg), and exposure to toxic elements such as As, B, Fe, and Al in the water, and (d) biotic factors such as seed dispersion by animals, grazing and human impacts (Villagran & Castro, 1997). The porous nature and extremely compact growth of the vegetation on Bofedales, as well as impeded drainage and evaporation, probably contributes to retention of large volumes of water, mostly during spring runoff (Squeo et al., 2006). The type of vegetation established will depend on the depth of the groundwater level available. Where groundwater sources are shallow, vegetation will be more hydrophilic (Cyperaceae, Juncaceae) and as groundwater levels get deeper, more saline species appear. The vegetation composition will also depend on the amount of organic matter, as the cushion plants will accumulate slowly decomposing organic matter below them (Ahumada & Faúndez, 2009).

Bofedales' plant species for the Antofagasta region – situated between the Tarapacá and Atacama regions – are mainly dominated by hard cushions of *Oxychloe andina*, often as high as 75% coverage (CIREN-INNOVA CHILE, 2010). Grasses in the genera *Deyeuxi*a and *Festuca* are present in low percentages (< 5%) and the most common type of intervention is grazing of the llama herds. As the Bofedales have higher salinity, the species *Zameioscirpus atacamensis* and *Puccinellia frigida* appear. Tall grasslands are mainly dominated by species from the family Poaceae, particularly the genera *Deyeuxia* and *Festuca*. In the ecotone Tall grasslands-Bofedales it is possible to find *Parestrephia lucida* and at very low proportion (25%), *Oxychloe andina*, *Eleocharis pseudoalbibacteata* and *Phylloscirpus deserticola*. Dominant species of wet meadows are *Juncus balticus* and *Bolboschoenus maritimus* with coverage ~50%. In some cases, when the flooding is intermittent, *Tessaria absintioides* and species of the genus *Distichlis* appear.

Among the aquatic plants, the species *Azolla filiculoides* and *Lemna minor* are described to occur in the freshwater (non-saline) Bofedales. *Myriophyllum quitense* and *Potamogeton strictus* are found in the saline version of Bofedales, tall grasslands and wet meadows and have a high feeding value for domestic herds (Ahumada & Faúndez, 2009). Peatlands located in the southern limit of the dry Puna were unexpectedly young, dynamic and sensitive to environmental changes. According to Earle at al. (2003), Chilean high altitude peatlands do not represent the old ecosystems formed during the early Holocene as is usually assumed for peatlands with thick accumulations of peat such as the *Sphagnum*-dominated systems in the south of Chile or elsewhere in the northern hemisphere.

The national bioclimatic vegetation classification system for Chile describes wetland vegetation on this area as an "atypical zone communities" dominated by hydrophilic plants (Luebert & Pliscoff, 2006). The same authors describe the transition from arid environment on the hill slopes to humid environments on the valley bottom, as a clear transition from an arid shrub matrix dominated by *Parastrephia lucida, Senecio adenophyllus* and *Azorella compacta* to a wetland community of *Oxychloe andina, Distichia muscoides, Azolla filiculoides, Lemna gibba*, and *Myriophyllum aquaticum*.

These ecosystems have been historically under a high human influence, by grazing and firewood extraction. Apparently degraded zones tend to show an increase of *Pycnophyllum bryoides*, *A. compacta* and *Festuca ortophylla*, which are colonizing species in the first phases of plant establishment. *P. lucida*, *Festuca ortophylla, Pycnophyllum bryoides*, and *Deyeuxia breviaristata* are part of the community described by Luebert & Pliscoff (2006), which can take up the niche of the arid matrix vegetation and occupy wetland niches if environmental conditions permit.

1.3.1. Tarapacá region

The Tarapacá region, situated in the north of Chile, is along with Antofagasta and Atacama, among the most arid regions in the country and in the world. The driest range of this area, receives between 0 and 200 mm of annual precipitation (Arroyo et al., 1988). Despite the aridity of this region, the large difference in altitude, from the Pacific Ocean to elevations over 4,000 m a.s.l., makes the Tarapacá region a particularly diverse place in terms of ecosystems. From coastal scrublands with Cactaceae, to flat interior prairies in the highlands and the high elevation Andean vegetation, the Tarapacá region has the tree species which is the highest elevation naturally occurring tree species in the world, *Polylepis tarapacana* (Simpson, 1979) and the highest woody cushion plant in the world *Azorella compacta* grown up to 5,200 m a.s.l. (Halloy, 2002). According to the bioclimatic classification of vegetation in Chile proposed by Luebert & Pliscoff (2006), Tarapacá high altitude wetlands are located as part of the hydrophilic vegetation dominated by the species *Parastrephia lucida-Festuca ortophylla* and *Parastrephia lucida – Azorella compacta*. Tarapacá region study sites were located mostly where rural-indigenous people are the landowners, and who are responsible for administering their wetlands and directly use them for consumption of plants and water and for cattle grazing. The remaining study sites of Tarapacá region were located in the Isluga National Park, administered by the Chilean National Forest Service, who permits the usage of the wetland under management standards (Figure 1.2).

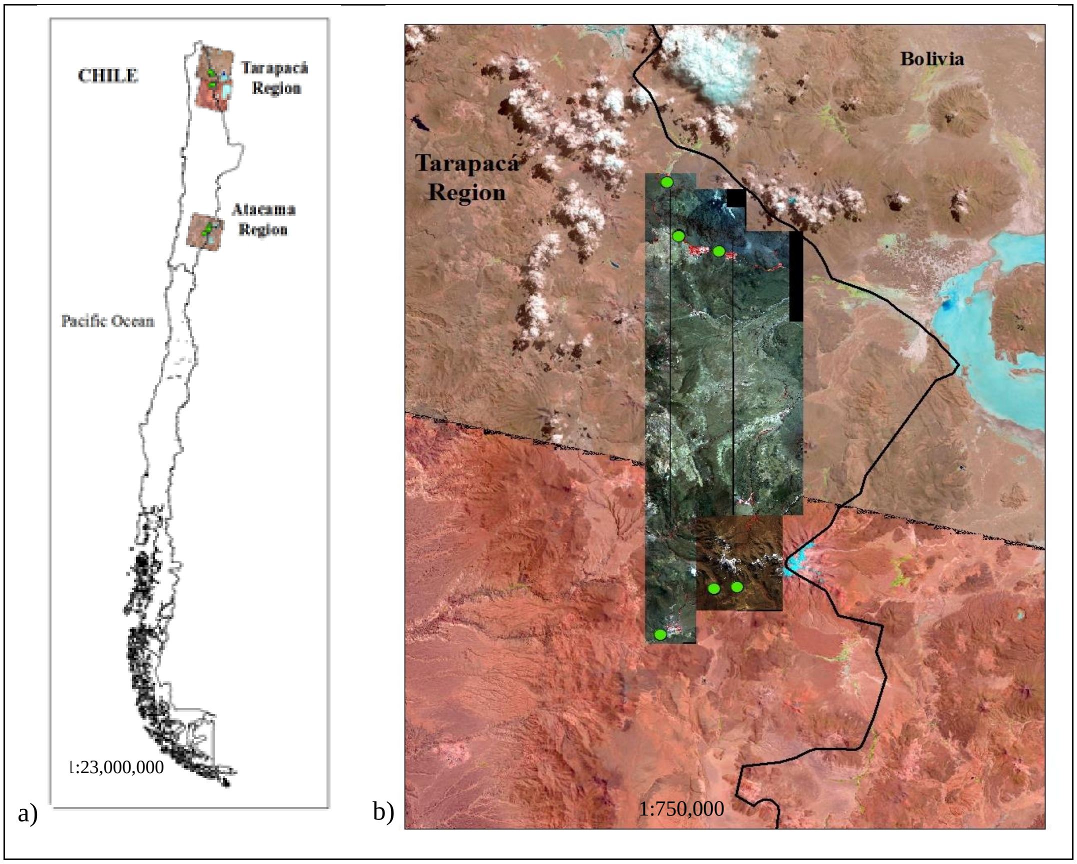


Figure 1.2. Study site locations in Tarapacá region, Chile. Figure 1.2 a) General location map showing Tarapacá and Atacama region distribution in Chile. Figure 1.2 b) Detailed location map showing the study sites (green dots) on Tarapacá region. Northern sites are inside Isluga National Park. Sites are on top of Geoeye-1 and IKONOS high resolution satellite images. Landsat satellite images are used as a background layer.

1.3.2. Atacama region

According to Novoa et al. (2008), 80% of the region is classified as a desert-type climate. The Atacama region has a high geographic variability, which determines 4 main climate groups: Coastal desert, high altitude Andean tundra, transitional desert and cold high altitude desert which determines vegetation types. According to Gajardo (1994), Atacama high altitude wetlands are located in the Andean desert of "Ojos del Salado" volcano area, in which dominant vegetation is high altitude and desert steppes vegetation types. Atacama study sites were located in Nevado Tres Cruces National Park (Figure 1.3). The National Park is located 150 km east of Copiapó city in between the Atacama Desert and the Argentine border, in the southernmost margin of the Andean Altiplano. The climate is characterized as "subtropical semi-arid desert" (Miller, 1979) and precipitation does not exceed 150-200 mm annually (Aravena, 1995).

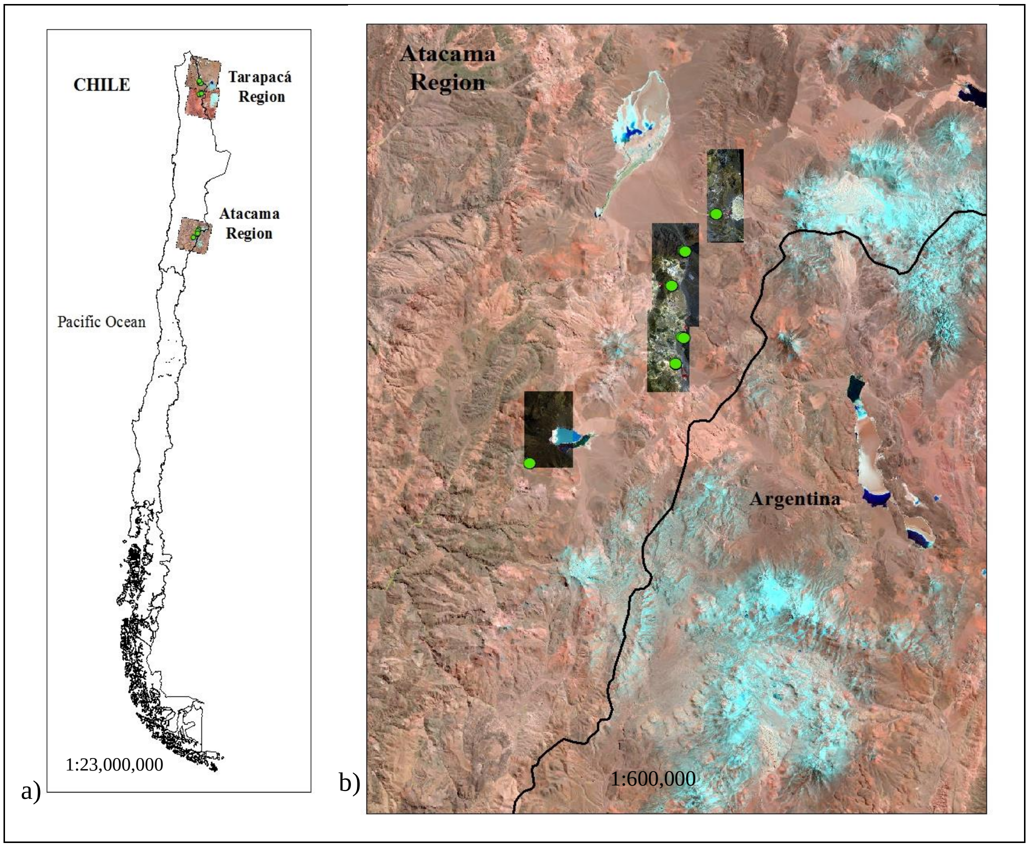


Figure 1.3. Study site locations in the Atacama region, Chile. Figure 1.3 a) General location map showing Tarapacá and Atacama region distribution in Chile. Figure 1.2 b) Detailed location map showing the study sites (green dots) on Atacama region. All the sites are located inside Nevado Tres Cruces National Park. Sites are on top of Geoeye-1 and IKONOS high resolution satellites images. Landsat satellite images are used as a background layer.

This Park, which is managed by the National Forest Service, is also protected by the International Ramsar Convention since 1996. The Ramsar site includes the area surrounding two brackish water lagoons united by the “Pantanillo-Cienaga Redonda” biological corridor. The site acts as an important regulator of the biotic and abiotic elements forming the ecological web of this Andean ecosystem. Unfortunately, the same area has several pressures on the exploitation of water and land by the mining industry.

1.4. Altiplano wetlands dynamics

In terms of vegetation abundance, Altiplano wetlands are in the middle of a desert tundra habitat and have relatively dense vegetation and high productivity. Because the water supply for wetlands is summer precipitation and aquifers, water table is a primary determinant of the plant composition, and hydrophilic plants from Juncaceae and Cyperaceae are possible to find where the water table is at a surface level. When the level of the aquifer is deeper, grass species start to appear and share the niche with hydrophilic plants until the point they are displaced (Ahumada & Faúndez, 2009). A second characteristic that determines vegetation patterns is salinity patches, which are formed in response to evaporation and low availability of water in the ground. In this case species like *Disticlis humilis* can appear as a very salt tolerant species. A third factor is the amount of organic matter content, which depends on the water content in the ground (Ahumada & Faúndez, 2009).

On Altiplano wetlands, vegetation dependence on aquifers is higher where salinity patches appear occasionally or only during the dry periods. Thus, Bofedales are more dependent on the aquifer levels and its variations than tall wet grasslands and wet meadows, where the amount of salty patches is higher and salt tolerant plants are present. The successional changes of vegetation happen because of different water tables as a result of water extractions from the aquifers and has been recorded as a transition of species, from hydrophilic species to species from the genera *Stipa* and *Festuca*, both plants characteristic of tall wet grasslands. Based on the experiments made on Altiplano wetlands re-colonization dynamics over 4 years, it is possible to infer the following diagram of succession stages (Ahumada & Faúndez, 2009). From the experiments it was possible to notice, after 2 years of water restriction, the transition from hydrophilic plants to halophyte plants and in some cases to the saline crust (dry barren land).

According to dynamic processes in Altiplano wetlands, Ahumada & Faúndez (2009) propose that deterioration depends on the availability of water. Vegetation types then, will change from the non-saline systems to a saline ones, and highly water-dependent systems like Bofedales are oriented to shift into less water-dependent ones. Vegetation types will be gradually transformed from **Bofedales** to **Tall grassland** and finally to **Wet meadows** (Figure 1.4).

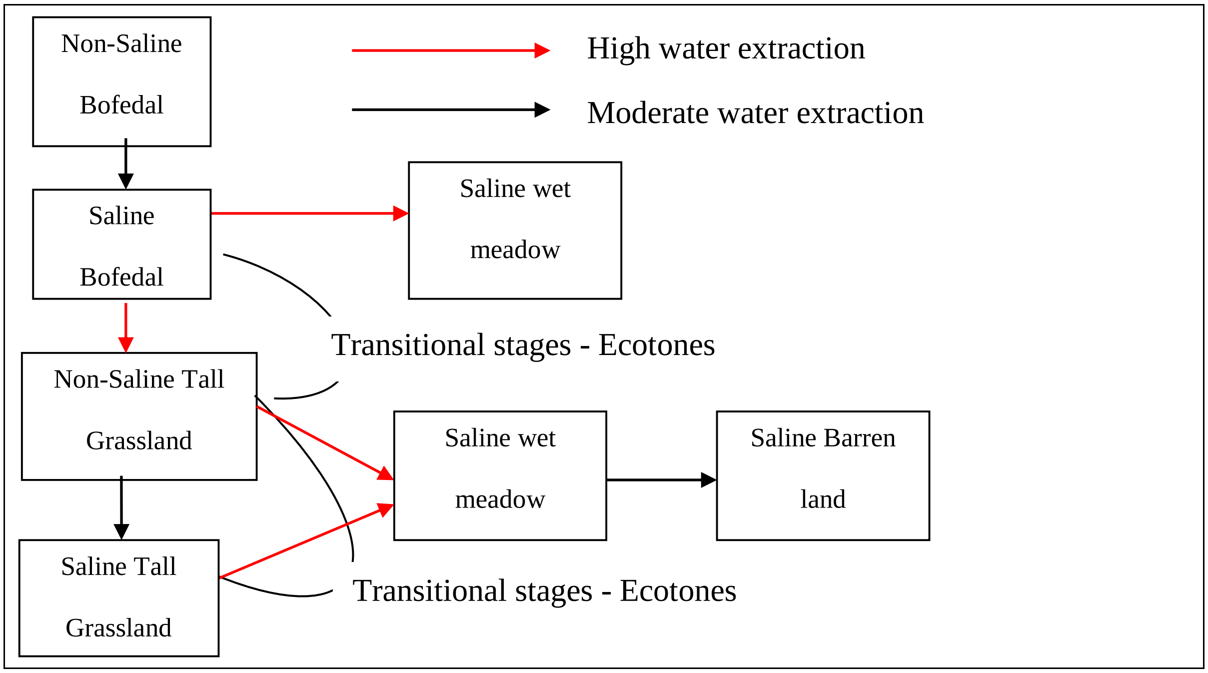


Figure 1.4. Vegetation dynamics on Altiplano wetlands. Adaptation from Ahumada & Faúndez (2009).

1.5. Environmental effects on wetland plant assemblages

The existence of biotic and non-biotic factors determines the existence of the different types of wetlands described above. They could appear as pure stages or as a combination of them. Those factors can be expressed like physical attributes, for example, presence of superficial water, shape of vegetation (cushion, grass, etc.), or presence of superficial salt and/or organic matter (Ahumada & Faúndez, 2009). The interaction between soil moisture, organic matter and salinity make up a matrix where vegetation is distributed across heterogeneous areas where different habitats can be associated with a specific plant community.

The structure of plant communities has been shown to have a high degree of spatial variability that that depends on both, abiotic and biotic factors (Fu et al., 2004). This has been demonstrated for Altiplano communities where the magnitudes and balance of biotic and abiotic factors determined the kinds of wetlands present (Ahumada & Faúndez, 2009). Vegetation structure and composition of Altiplano wetlands varies along the riparian ecosystem, in response to gradients in water availability and the dependence species have to the water table. Therefore, changes in the depth of water will consequently produce changes in plant assemblages and in the configuration of the communities across the wetlands. Knowing plant assemblages and their distribution between wetlands is important for wetland conservation and the restoration of their original ecological functions. Depending on the abiotic factors, plant assemblages will follow environmental gradients in the wetland. For example plant assemblages in mined bogs in North America differ from those near the margins of natural bogs, and certain species are associated with the center, due to the presence of pools (Poulin et al., 1999). In this case, both environmental gradients and the wetland microtopography are considered for restoration purposes.

According to the Millenium Assesssment Project (2005), environmental drivers are any natural or human factor that directly or indirectly causes changes in an ecosystem. Without understanding the factors driving environmental changes, it is difficult to design effective strategies for environmental management. Although these drivers can operate on different temporal and physical scales, understanding their dynamic relationships can improve the direction of the intervention.

Understanding plant distribution across environmental gradients is not only a major goal in plant ecology and stand dynamics, but also by addressing this gap in our knowledge, we will be able to predict more precisely how wetland plant communities will respond to anthropogenic intervention. Two human disturbances that can explain vegetation variation between wetlands are grazing and water extraction. Intensive grazing results in soil compression that can alter hydrology, lowering infiltration, affect sediment production and increase seed loss (Adler and Morales, 1999). On the other hand, many studies have found vegetation associated with hydrologic gradients from margins to the center in natural bogs and there is enough evidence that water table depths and peat moisture content are significantly correlated with plant species composition (Damman & Dowhan 1981; Poulin et al 1999; Weltzin et al., 2000; Haapalehto, 2011; Palanisami & May Chui, 2013).

In the case of salt marshes, biotic interactions play an important role in driving plant distribution patterns across horizontal salinity gradients (Crain et al., 2004). Studies revealed that plants from a certain salt marsh (*Juncus*, *Distichlis* and *Scirpus*) grow better in fresh water than in full strength salt water and therefore, the spatial segregation across the gradient is driven by competitively superior freshwater marsh plants displacing salt-tolerant plants to physically harsh salt habitats (Crain et al., 2004). In this context, plants develop strategies to adapt to those changes but sometimes changes on the environment occurs so quickly that species are not able to respond and a new community of plants occupies the niche (Grinnell, 1924; Vandermeer, 1972). For example, species significantly associated with grazing are able to grow very low to the ground to avoid grazing or have superior physiological responses to grazing compared to taller plants (Adler & Morales, 1999).

Changes of vegetation can be triggered by two reasons according to variations in water supply. Gradual changes in water supply because of changes in climatic cycles on precipitation produce slight changes in vegetation and salinity that can be assessed. Drastic changes on water supply, because of water extraction from the aquifers, produce fast changes of vegetation that cannot be perceived and it is possible only to observe the stubble of dead vegetation and the colonization of new plants from a different wetland type (Ahumada & Faúndez, 2009).

The increasing demand for water, mostly because of mining activity, requires improving the knowledge about the ecosystems that share the same landscape with the economic development. There are examples of severely degraded and vanishing peatlands in northern Chile (Villagran & Castro, 1997). Consequently, a better understanding of the processes that determine spatial patterning in vegetation and ecosystem function is needed in order to properly assess both the impacts of shorter duration disturbances as well as longer-term consequences in a changing climate.

1.6. Multivariate analysis of plant communities

Natural plant communities are distributed along environmental gradients, where transitions can be found and where plants respond differently to environmental factors leading to different compositions (Chahouki, 2013). Plant communities in high-altitude ecosystems are extremely sensitive and fluctuate with small changes in environmental factors. This close relationship between plants and environmental factors is observed in different high-altitude plant communities in the world, for example, in the Tibetan Plateau in the Himalayas and in the Altiplano basin of the Andes. Chang & Gauch (1986) in their study on the Tibetan Plateau, described how plant communities have a strong variation to the environmental factors because they are often near the limits for survival of plants.

Studying vegetation distribution is a basic aspect of the design and management of vegetation systems like wetlands (Biota, 2007; Zhang et al., 2008). The goal of most studies in plant ecology is to find and explain spatial and temporal interactions in the complex vegetation system along environmental gradients. Therefore community ecologists try to understand the occurrence and abundance of taxa in space and time considering interactions with biotic and abiotic factors. By dealing with so many complex relations (each sampling unit is characterized by many attributes, data show redundancy and internal relations and some information is only indirectly interpretable), the use of multivariate analysis make data easier to handle and has been widely used in community ecology. Multivariate analysis in ecology can be divided into three groups: regression analysis; ordination analysis and classification (cluster) analysis (Jongman et al., 1995). In this thesis I use ordination techniques to study the relation between plant communities and environmental factors because they are the best methods to analyze species composition by constructing gradients, where the goal of which is to find the dependence of the response variables (plants) on explanatory variables (environmental variables). Ordination techniques were developed in the 1930s but were more widely recognized after the 1950s (Goodall, 1954; Whittaker, 1967), and are mainly used to identify similarities between species and samples. Results are projected in such a way that species and samples most similar will be displayed closer and the most dissimilar will appear further apart (Leps & Šmilauer, 2003; Chahouki, 2013).

1.7. Remotely sensing wetlands

Up-to-date information on the upland and surrounding areas of the wetlands is extremely important as land use practices on those areas can cause loss of wetland functions, goods, services and values (Ozesmi & Bauer, 2002). Because wetlands are connected with their adjacent areas through groundwater or surface flows from the uplands, wetland management needs to be addressed under a broad landscape perspective.

Species discrimination for floristic mapping requires intensive fieldwork, including taxonomical information, data analysis and visual estimation of percentage cover for each species, which can be very time-consuming, and extremely costly if we wish to assess wetlands on a landscape scale. Sometimes it can be unfeasible due the lack of access to the systems, as most high altitude wetlands are located in remote areas (Adam et al., 2010). Remotely sensed data from satellites are an alternative for large geographic areas or direct field work (Ozesmi & Bauer, 2002, Adam et al., 2010).

Currently, a variety of Earth observation datasets are available for mapping wetland vegetation. Remote-sensing data are available from airborne to space-borne sensors, from multispectral to hyperspectral sensors, with different temporal and spatial resolutions, ranging from sub-meter to kilometer scales (Adam et al., 2010). There is gradually more free access to some of the new satellites and sensors at different scales that have come on-stream (Davidson & Finlayson, 2007; Kerr & Ostrovsky, 2003). However, freely available satellite imagery has some limitations, and although Landsat-TM and SPOT satellites instruments have proven to be a potential source for defining vegetation density and vigor, they have been insufficient for discriminating vegetation at a species level.

LANDSAT and SPOT satellites images are constrained in their ability to identify vegetation due to their limited spectral and spatial resolutions. Using spatial resolutions of 30 m (Landsat) or 1000 m (SPOT), identification of small individual wetland plants is not possible. Most of the species are herbaceous or shrub types of plants, distributed in small patches along a highly dynamic hydraulic gradient. Except for grass-vegetated wetland types, most Andean wetlands vegetation patches would rarely exceed two meters in extent and are embedded in a complex mosaic of plants associations, within a matrix of shallow water. This complex, heterogeneous pattern of wetlands plants also implies that spectral identification could be a challenge too. For example, with the broad spectral bands, Landsat provides, it could be too difficult to discriminate vegetation types because the overlap of their spectral signatures (Davidson & Finlayson, 2007; Johnston & Barson, 1993).

Wetland plants are not as easily detectable as other terrestrial plants, not only because of the difficulty in identifying boundaries between vegetation community types but also because of the confusion between vegetation reflectance spectra and the underlying soil, water and atmospheric vapor spectral noise (Adam et al., 2010). The most important factors affecting the spectral reflectance among wetlands' vegetation are the biochemical and physical parameters of the plants, such as the pigments chlorophyll *a* and *b*, carotenes and xanthophylls, and wetland species appear to have considerable variation in these pigments as a function of plant species and hydrologic regimes (Anderson, 1995).

The new generation of high spatial resolution satellites, has become available and offers an opportunity to map vegetation in fine spatial detail. This high spatial resolution information can benefit biodiversity conservation, particularly in arid ecosystems, where the difficulty arises from mapping small patches of vegetation immersed in extensive bare lands. High spatial resolution images enable identification of small features in desert landscapes such as shrubs, small patches of grasslands or little ponds (Chávez & Clevers, 2010). The IKONOS system from space imaging, launched in 1999, offers multispectral and panchromatic imagery at resolutions of 4 m and 1 m, respectively. At these resolutions, direct identification of certain species and species assemblages becomes feasible (Turner et al., 2003). IKONOS-2 provides high spatial resolution data in the visible and near-infrared portion of the electromagnetic spectrum that, coupled with a higher spatial detail, can address in a better way wetland habitat determination (Dechka et al., 2002). Despite the high variability in wetland vegetation communities, IKONOS-2 images have been successfully used to classify, map and monitor water-dependent environments and vegetation like wetlands, tundra and riparian marshes (Adam et al., 2009; Dechka et al., 2002; Zhang et al., 2008).

Geoeye-1, a high-resolution earth observation satellite owned by GeoEye, was launched in 2008. It simultaneously collects panchromatic imagery at 0.41 m and multispectral imagery at 1.65 m. It has several applications for detailed classification of earth surfaces. Because of its extraordinary panchromatic spatial resolution, studies based on Geoeye data are mostly focused on the identification of objects in urban environments, single tree or animal identification with the Object-based analysis (OBA) technique (Chávez & Clevers, 2010; Korom & Phua, 2011; Dribault et al., 2012; Aguilar et al., 2014). However, a variety of vegetation studies have been done to classify water-dependent environments with OBA. Examples include: delineating internal structure in peatlands (Dribault et al., 2012), identification of riparian vegetation based on textural information and chlorophyll indices using near infrared band. Wetland transitions have been detected by identifying trees gradient on the image (Gutierrez et al., 2012 ; Suzuki & Iiyama, 2012).

1.8. Conservation and management

The concern about the future of the Altiplano wetlands in this water-stressed region is particularly enhanced in the light of a decreasing precipitation context, to nearly 50% of what it was 100 years ago in north-central Chile (Alegría & Lillo, 1996).

Chile has gone farther than any other country in the world in creating a market economy based on private water rights. Since 1981, although water was defined as a “national public good” in the water code, it was also defined as a “market assets” allowing the privatization of water. This process has had negative consequences for the people of Chile and for the ecosystems.

The degradation of the most important watersheds has brought the subsequent shortage of drinking water to many rural villages and indigenous communities (Larrain & Schaeffer, 2010). Firstly, initial allocation of water rights was granted for any firm or person interested, allowing in some cases huge levels of market concentration and secondly the minimum amount of environmental flow was not granted (Bitrán et al., 2011). Current changes of vegetation, as a result of groundwater extraction, have been so fast that they have not allowed proper management and conservation programs to ensure the future of the indigenous peoples who depend on them (Ahumada & Faúndez, 2009). Consequently, a better understanding of the processes that determine spatial patterning in vegetation and ecosystem function is needed in order to properly assess both the impacts of shorter duration disturbances, as well as longer-term consequences of a changing climate.

1.9. Study objectives

The development of accurate assessments techniques that can give us information about the health condition of the system will help us to assess the actual state of the high altitude wetlands in Chile, and allow stakeholders to develop management approaches to control or reverse to degradation processes. The analysis of environmental variables interacting with plants communities using multivariate methods and assessment of high spatial-resolution images from Geoeye-1 and IKONOS-2, specifically for the Chilean Altiplano wetlands, has never been done.

The general objectives of this thesis are first to outline particular relationships between abiotic factors and plant communities on high-altitude Altiplano wetlands, and second to assess if high spatial resolution images can provide is accurate data for vegetation identification on the wetlands. In Chapter 2, by using multivariate analysis methods I study the relation between plant community assemblages and the abiotic factors that could be acting as environmental drivers. The methods selected are oriented to detect species-environment relationships and the response of species to environmental variables. In Chapter 3, I assess the capacity of high spatial resolution imagery to differentiate Alpine wetland plants communities by identifying which bands and / or vegetation indices are the most accurate at discriminating among vegetation classes.

This application of satellite imagery will definitely help conservation and management initiatives, because high altitude wetlands are dispersed over a large territory and most frequently in remote and inaccessible places. So the discovery of satellite indices that can express a good relation with the species composition and structure of wetlands could be a powerful tool in the assessment and management approaches by remote sensing.

Finally, I hope this research will be useful to improve knowledge of Altiplano wetlands and their degradation, in order to provide tools for government agencies and facilitate decisions related to industry and environment.

Chapter 2: ASSESSING PLANT COMMUNITY STRUCTURE OF HIGH ALTITUDE ANDEAN WETLANDS BY MULTIVARIATE ANALYSIS.

2.1. Introduction

The composition of Altiplano wetland depends mainly on water table levels, salinity patches and amount of organic matter (Ahumada & Faúndez, 2009), therefore plant assemblages occur along such environmental gradients. Different ordination models can be used to describe the species' response to a continuous environmental variable. Linear and unimodal models are frequently used in multivariate analysis (Leps, J., & Šmilauer, P., 2003). The linear approximation is simplest whereas the unimodal assumes that the species has an optimum along the gradient. If there are no predictors available, and we look at a single response, then we can only summarize the distributional properties of that variable. In the case of multivariate data this can be done by a hierarchical classification or clustering, or by the ordination approach of "indirect gradient analysis" represented by Principal Component Analysis (PCA), Correspondence Analysis (CA), Detrended Correspondence Analysis (DCA) and Non-metric Multidimensional Scaling (NMDS) (Jongman et al., 1995).

If we have predictors (environmental variables) for a set of response variables (species or samples), we can summarize relations between multiple response variables and the predictors using the "direct gradient analysis", represented by Redundancy Analysis-RDA, Canonical Correspondence Analysis-CCA and Detrended Canonical Correspondence Analysis-DCCA. This second group of methods, aim to describe relationships between species composition and the underlying environmental gradients, which supposedly influence those patterns.

Ordination methods have been broadly used to understand community patterns and to establish a monitoring system that may serve to identify and predict future vegetation changes and assess impacts of conservation and management practices (Chahouki, 2013).

Despite the utility of ordination methods for organizing large datasets, especially when underlying relations occur that are difficult to observe, classification methods can be very effective for giving additional information about direct linkages between species. Classification methods are techniques used to group objects (samples or species) that have internal similarities and that can differ from other groups. When the variables that are grouped together are species, the homogeneity can be interpreted as a similar ecological behavior (Leps & Šmilauer, 2003). There are several types of classifications, based on how do they agglomerate the data. Hierarchical clustering is a classification method, where things are put together in groups, based on their similarities and "nested" within other groups. Two-way clustering (or bicluster), refers to doing a cluster analysis on both the rows (samples) and columns of the matrix (species), followed by two dendrograms. The purpose of this type of cluster is to graphically present the relationship between sites and the data. Another classification technique is the TWINSPAN method, a divisive hierarchical method, popular among community ecologists (Hill et al., 1975; Hill, 1979), inspired by classical phytosociology classificatory methods (Leps & Šmilauer, 2003). TWINSPAN is very useful to understand how species are distributed among the samples by visualizing those on a dual-entry table, which helps the user to complement clustering classifications.

The objective of this chapter is to better understand the behavior of some of the variables that interact on Altiplano wetlands ecology and are associated with plant community structure under different abiotic conditions. In order to address that, it is necessary to study the relationship between plant community assemblages in wetlands and the abiotic factors that could be acting as environmental drivers. The methods selected aim to answer the questions that can detect species-environment relationships and the response of species to environmental variables, which are: a) How are the plant communities structured in Altiplano wetlands? b) Which plant communities can be found and which abiotic factors are more strongly associated with them? and c) Do wetlands affected by different human activities have different plant communities?

2.2. Materials and methods

2.2.1. Study sites

The geographical position of the study sites are between 19°07’- 27°30’S latitude and 68°54’ - 69°17’ W longitude. The locations correspond to the northern and southern distribution of the Bofedales ecosystem in Chile, and are in the administrative regions of Tarapacá and Atacama. Fieldwork was conducted between January and February of 2013, during summer time, where eight wetlands per region were assessed in the field. The sites belong to the geomorphologic-ecological region of the Altiplano plateau that includes Andean steppe above 4,000 m a.s.l. The climate of this region has a tropical influence (Gajardo, 1994), with summer precipitation coming from the Peruvian and Bolivian Amazonian forest, and it is classified as “subtropical semi-arid desert” by (Miller, 1975) in the northern sites (Tarapacá region) and both, summer and winter precipitation on the southern sites (Atacama region). Sampled sites ranged from 3,935 and 4,659 m a.s.l. for the Tarapacá region and in between 4,010 and 4,300 m a.s.l. for the Atacama region. Sites fall into three land-use categories: inside a National Park with local community management (“Volcán Isluga” National Park), outside a National Park (Proximity of Lirima and Cancosa towns) both in Tarapacá region and inside a National Park with water extraction (“Nevados Tres Cruces” National Park) in the Atacama region.

As stated in Chapter 1, plant communities for the study area belong to the ecological unit called “High altitude wetlands” (Squeo et al., 2006; Biota, 2007; Ahumada & Faúndez, 2009), and are classified in three vegetation classes known as high altitude peatlands or Bofedales, tall grasslands and wet meadows.

2.2.2. Field data collection

The measurement considered the collection of data from environmental variables and plants, following five methods: Abiotic factors and wetland physical attributes description, vegetation transects, dominant species description per vegetation unit and flora plots. A total of 16 wetlands were sampled in the study area, 8 of them in the Tarapacá region and 8 in the Atacama region. Each method is fully described in the next sections.

Abiotic factors and physical attributes

A total of 20 abiotic factors and physical attributes from each wetland were measured (Table 2.1). Water quality data of the principal channels in each wetland were measured using a YSI instrument. Geographic data were collected using a Garmin Explorer GPS, with precision around 1 meter. The rest of the variables were categorical data, measured by visual observation and were based on several documents for high altitude Altiplano wetland environmental assessment (CIREN-INNOVA CHILE, 2010; MMA, 2011; Ahumada & Faúndez, 2009; CEA, 2006).

Table 2.1. Abiotic Factors and physical attributes measured in the field.

Feature	Attribute	Description
Wetland	Shape of wetland (SHW)	Visual estimation of the shape of the wetland: a) basin (water flows in the wetland) b) sloping (water runs down) c) flat (water flows out the wetland)
	Salty patches (SAL)	Visual estimation of % of salt crust patches found on wetland surface
	Shallow water in wetland (SHA)	Visual estimation of % of shallow water patches/pools found on wetland surface
	Wetland slope (WETSL)	Interval of wetland slope; 0-10%; 11-30%; >30%
	Wetland aspect (WA)	Dominant wetland aspect: North, East, South, West; NE; ES; SW; NW
	Wetland perimeter definition (BORD)	a) defined: clear separation of plants and desert b) undefined: fuzzy definition of vegetation
	Heterogeneity of peatland/marsh/grassland composition (HE)	Homogeneous: one dominant vegetation system Heterogeneous: several vegetation systems
	Altitude (ALTITUDE)	Wetland location on meters above sea level (m a.s.l)
	Hill slope (HILLSL)	Interval of the slope of the hills adjacent to the wetland. 0-10%; 11-30%; >30%
	Vegetation (VEG)	Type of dominant(s) vegetation type: Bofedal-Tall grassland-Wet meadows
	Aquatic macrophytes (MACRO)	Presence of aquatic vegetation
	Shape of plant growth (SHGR)	plant dominant growth type: cespitose, grass, rhizomatous
Stream	Principal channel depth (cm) on the transect (DEP)	Principal channel depth (cm) on the transect
	Channel width (WID)	Principal channel width (cm) on the transect
	Water temperature (TEMP)	(Celsius degrees)
	Principal channels (PCH)	Number of principal channels along the transect
	Secondary channels (STR)	Number of secondary channels along the transect
Human Intervention Level	Human presence/trace (ANTR)	Any finding of human signal ex. garbage, wheel or foot prints etc., proximity to roads and/or industrial areas.
	Cattle presence (CATT)	Cattle sighting
	Wildlife presence/trace (WILD)	Bird sightings or any finding of its presence ex. Footprints, feathers, feces, etc.

Wetland vegetation transects

Wetland transects are useful for recognizing vegetation distribution patterns or possible gradients in the hydrophilic condition. The side to side transects registered all vegetation changes from the outside border of the wetland through the central channel. Transects were located in designated areas that expressed most of the variation of the wetland regarding vegetation types and non-plant features. Each wetland was looked and walked around in order to decide the most suitable place. Transect started at the beginning of plant communities, all across the wetland until the other edge. One transect per wetland was recorded. In each transect the length of each species (woody) or patches (for grasses) were measured. For grassy patches 3 samples of a 1 m-line-points intercept was done, in both sides of the transects, inside each grassy patch. Vegetation was recorded every 10 cm (Goodall, 1954). Non-plant components recorded on the transects were barren land, rocks, organic matter, dried dead plants, shallow water, streams, streams with macrophytes and principal channel. These variables are included in the multivariate analysis as environmental variables with the abiotic variables and physical attributes described in the previous section.

Flora plots

According to the methodology used by Biota (2007) for Altiplano wetlands, flora coverage was recorded using circular plots (100 m^2) in a Braun-Blanquet cover estimated scale. Botanical nomenclature for vascular plants follows Zuloaga et al. (2009) and unknown plant species were collected for subsequent identification by the Chilean botanists and forest engineer Patricio Medina and double checked by the specialist Prof. Luis Faúndez from Botany Laboratory, Faculty of Agronomy, Universidad de Chile. Bryophytes were identified by the specialized biologist Mr. Victor Ardiles from the Natural and Historical National Museum of Chile.

Plant coverage plots

Structural characteristics (vegetation types, coverage and dominant species) and the percentage of coverage per vertical strata of vegetation were measured. Each wetland had between 4 and 8 plant cover plot, depending on the number of changes in vegetation along transects. Plot points used the method for the study of the structure of tropical grasslands, developed by CEPE/CNRS - Centre d’Etudes Phytosociologiques et Ecologiques Louis Emberger/Centre National de la Recherche Scientifique., France - adapted to Chile by Etienne & Contreras (1981) and validated for Chilean Alpine wetlands by Biota (2007). This methodology describes growth form of dominant plants (Tall woody species or trees, small woody species or shrubs and grasses), and their percentage of cover. The points do not have any defined size as it is a visual description and they are located in the central part of a defined homogenous polygon.

2.2.3. Statistical analysis

Several multivariate techniques were used in the analysis of the community data and the environmental variables measured for the wetlands. They considered the following: Selection of environmental variables by PCA; Biodiversity parameters of richness (S), evenness (E), Shannon diversity (H), Simpson diversity (D) skewness and kurtosis description for plant community data; Clustering of community data; Unimodal/Linear model selection to plants community data, Indirect Gradient analysis and Direct gradient analysis.

Different statistical techniques were used to select the 14 environmental variables that explained the most of the variation. The selected variables explained 95.94% of the variation within a subset of 28 explanatory variables (abiotic variables + non plant components from transects). The methods included a PCA pre selection of correlated environmental variables by using weights of Axis 1 and 2 and automatic and manual forward selection.

For the classification of plant communities and final environmental variales selection, several ordination methods were analyzed. After the preliminary analysis, PCA for linear model and DCA – CCA for unimodal models (indirect – direct) provided the most effective results. Effectiveness was measured in terms of ecological interpretability and effectiveness at spreading out the points. In order to choose the most appropriate ordination method based on a model of linear or unimodal response, I used “length of gradient” according to the Leps & Šmilauer (2003) methodology, performing a Detrended Correspondance Analysis (DCA), detrended by segments using Hill´s scaling without log transformation of the plant community data. After the ordination and as a complementary technique, the data matrix was analyzed under three types of classifications: Hierarchical cluster analysis, Two-way Hierarchical cluster analysis (TWHC) and Two-way indicator species analysis (TWINSPAN). Cluster analyses were performed in order to identify any classification that could group wetlands (sites) into vegetation types. The two-way cluster used Ward´s linkage method and Sorensen’s distance measure. To check if the wetland classification was significantly different from a random grouping, a Multi-response Permutation Procedure (MRPP) test was performed. The software CANOCO version 3.12 (ter Braak & Šmilauer, 1998) and PC-ORD 6.0 (McCune & Mefford, 2005), were used to perform the ordinations, clustering classifications and statistical tests.

Data matrix

The data (dependent variables) consisted of the abundance (% cover) of individual plants on transects. Independent variables were the environmental factors described in section 2.2.1 (abiotic factors). Relative plant abundance on transects was calculated considering the proportion of each plant on transects per wetland relative to the total cover of plants. Abiotic components of transects (rocks, water, bare ground and dead plants) were not considered as part of the data matrix for the ordination analysis. Wetlands were named with a code A for the Atacama region and T for the Tarapacá region plus the number of the site.

2.3. Results

2.3.1. How is the plant community structured in Altiplano wetlands?

A total of 71 plant species were identified in the study area, representing 25 families, distributed across 45 genera. The most diverse plant families were Poaceae (19 species) and Cyperaceae (6 species), followed by Juncaceae, Juncaginaceae, Ranunculaceae and Rosaceae, each with 3 species. Of the 71 species identified in this study, only 40 species were found on the transects. The remaining 31 species on the list (representing 44% of the total) were collected by informal surveys, flora plots or vegetation descriptions. Endemism of the species at a regional level was very high; 84% of the species were found either in Tarapacá or Atacama region and only 16% (11 species) of the species listed were found common to both regions. The regions were 28.2% similar (Sorensen Index) in terms of species composition.

Tarapacá Wetlands

Tarapacá has 53 species recorded, 28 of them registered by the transect method. The distribution of the plants in Tarapacá region was very heterogeneous (Figure 2.1.a). There were at least 10 dominant species and the wetlands have in between 7 and 16 species registered on transects (Figure 2.1.b). The species that had the highest cover on transects per wetland were *Distichia muscoides* (45% on wetland T4), *Deyeuxia curvula* (31% on wetland T6), *Werneria pygmaea* (42% on wetland T5), *Festuca chrysophylla* (23% on wetland T3), *Oxychloe andina* (35% on wetland T8) and *Zameioscirpus atacamensis* (23% on wetland T4). Bryophytes (between 3 and 10%) are present in small proportions in half of the wetlands.

The highest plant diversity within the wetlands was found in 3 wetlands (between 12 and 16 taxa) while the rest of the wetlands were less diverse with between 6 and 10 different plant species along transects. There was no trend found between the wetlands plant diversity and any of the non-plant variables measured on the field.

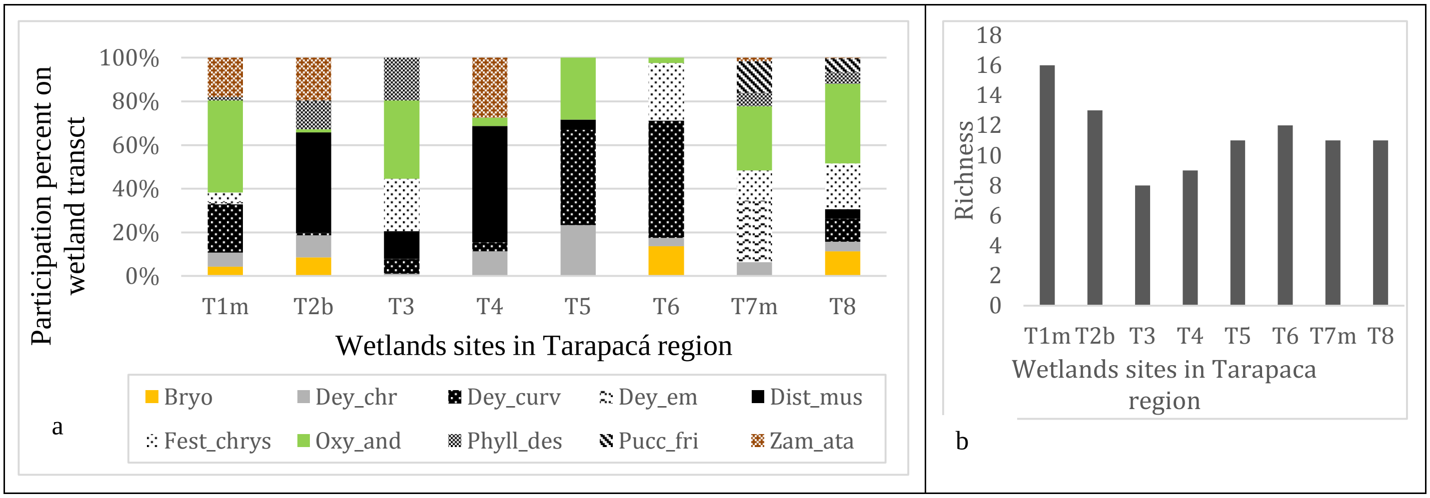


Figure 2.1.a) Characterization of dominant plants species cover per wetland transects in Tarapacá region. Plants codification: Bryo- Bryophytes; Dey_chr-*Deyeuxia chrysophylla*; Dey_curv-*Deyeuxia curvula*; Dey_em-*Deyeuxia eminens*; Dist_musc-*Distichia muscoides*; Fest_chrys-*Festuca chrysophylla*; Oxy_and-*Oxychloe andina*; Phyll_des-*Phylloscirpus deserticola*; Pucc_fri-*Puccinellia frigida* and Zam_ata-*Zameioscirpus atacamensis*. Figure 2.1.b) Wetlands richness in Tarapacá region.

The most frequent species were *Deyeuxia chrysophylla* and *Oxychloe andina*, present in the 8 wetlands studied in the region, followed by the species *Deyeuxia curvula* which was present in 7 wetlands of the region. Most of the species (64%) were not frequent and were found in 3 or fewer wetlands. Bryophytes were present in 4 of the 8 wetlands in proportions that went from 2 up to 10% cover of the wetland transects.

Tarapacá region wetlands had an average of 30% (range 13 to 52) of transects covered by the non-plant variables (barren land, secondary channels, stream with and without macrophytes, rocks, organic matter, shallow water and dead plants). The most abundant were barren land

(10.8% average), shallow water (7.25% average) and stream with macrophytes (3% average)

Atacama Wetlands

Atacama had 25 species recorded and 19 noted along transects. The distribution of the plants in the Atacama region wetlands was simpler in the Tarapaca region. The sites were more similar to each other, with 4 species dominating most of the wetlands: *Deschampsia caespitosa, Oxychloe andina, Zameioscirpus atacamensis* and *Zameioscirpus gaimardioides* (Figure 2.2). The species that were more abundant and more frequent at the same time were: *Deschampsia caespitosa*, present in 7 of the 8 wetlands sampled in the region and *Oxychloe andina*, present in 6 of the 8 wetlands sampled in the region. Most of the species on the transect (56%) had between 4 to 20% cover and about 30% of them had less than 3% of cover in each transect. Atacama region wetlands had on average 27% (range 2 to 42%) of transects covered by the non-plant variables. The most abundant were shallow water and stream with macrophytes. The Atacama region wetlands showed no apparent relation between plant diversity and the proportion of non-plant components on transects, similarly to the Tarapacá region.

Different from Tarapacá region wetlands, most of the species in Atacama region wetlands were present in only one or two wetlands (10 species). There was no species common to all 8 wetlands. *Deschampsia caespitosa* was the most frequent, present in 7 wetlands, followed by *Oxychloe andina* and *Zameioscirpus atacamensis,* present in 6 and 5 wetlands, respectively. Considering the parameters extracted from the ordination´s summary on plant data from transects, Tarapacá wetlands have higher richness with a regional average of 11.4 species compared with 7.2 for Atacama wetlands (Appendix, Table 1). Evenness is higher in Tarapacá transects than in Atacama ones, so in terms of species, wetlands in Tarapacá region have less variation in plant communities between wetlands. There was greater diversity of plants in the Tarapacá region transects and those communities were more homogeneous in its percent of cover among the wetlands. On the other hand, the wetlands in the Atacama region were less diverse, with fewer species, and a higher variation of the distribution of plants cover among sites. The four most abundant species for the Tarapacá region wetlands (*O. andina*, *D. muscoides*, *D. curvula* and *F. chrysophylla*) represented 51.4% of plant cover while for Atacama the 4 most abundant (*O. andina*, *Z. atacamensis*, *D. caespitosa* and *Z. gaimardioides*) represented 71.5% of the plant cover on all the transects.

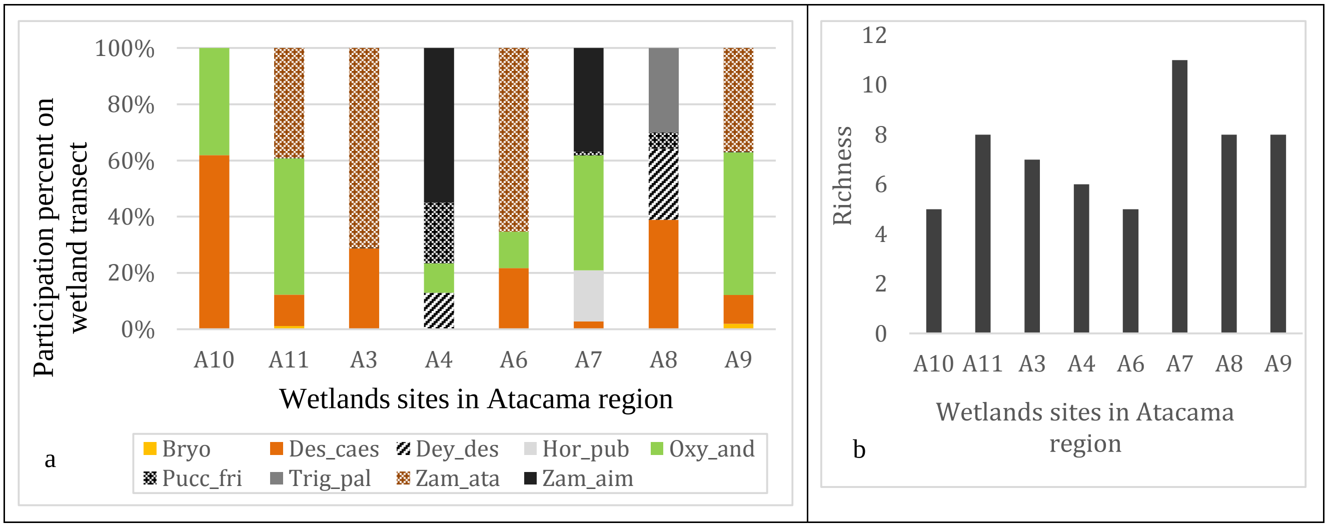


Figure 2.2.a) Characterization of dominant plants species cover per wetland transects in Atacama region. Plants codification: Bryo- Bryophytes; Des_caes-*Deschampsia caespitosa*; Dey_des-*Deyeuxia deserticola*;Dey_em-*Deyeuxia eminens*; Dist_musc-*Distichia muscoides*; Hor_pub-*Hordeum pubiflorum*; Oxy_and-*Oxychloe andina*; Pucc_fri-*Puccinellia frigida*; Trig_pal-*Triglochin palustris*; Zam_ata-*Zameioscirpus atacamensis* and Zam_aim-*Zameioscirpus gaimardioides*. Figure 2.2.b) Wetlands richness in Atacama region.

Shannon and Simpson diversity indices showed that all plants were more equally abundant in Tarapacá than in Atacama (1.88 versus 1.32, respectively) and a higher Simpson's diversity is found in Tarapacá's data set (0.79 versus 0.67, respectively). Lower values on the skewness in Tarapacá region reflected that the distribution of the plants had more dominant species and then lower skewness represents more evenness in the relative abundances of species than in Atacama, where the higher skewness reflects a few and different dominant species. The higher kurtosis in Atacama wetlands also showed that most of the variance in plants was a result of the uneven representation across species (Appendix – Table 1).

Considering abiotic variables most wetlands, in both regions were located between 3,900 and 4,300 m a.s.l. However in the Tarapacá region wetlands T3 and T4 were found up to 4,400 and 4,600 m a.s.l. Atacama wetlands were mostly located facing N-NE aspects (the morning-warm face), while only two of them were SW (the afternoon-cool face). Tarapacá visited sites were much better distributed on different aspects, present in most of them. Running water channels inside the wetlands on Atacama region were more homogeneous, with widths around 40 cm (20 - 60 cm) and 20 cm depths, while Tarapacá region wetland channels had much more variation. They had widths and depths varying from a few centimeters up to 80 cm width and 20 cm depth.

Tarapacá region study sites had more aquatic species in their streams (88% of the wetlands had aquatic plants) and more diversity (*Azolla filiculoides, Lemna minor, Myriophyllum quitense,* and *Ranunculus aff. uniflorus*), while *Myriophyllum quitense* was the only species present in the Atacama region's study sites (present on 63% of the wetlands). The bryophytes identified for the study were *Bryum argenteum* and *Bryum* cf *pallescens*, located in both regions. This species are widely distributed in Chile and already registered from Atacama region in the north of the country to Magallanes y Última Esperanza region in Patagonia (3,000 km south of the Atacama region), including Easter and Juan Fernández islands in case of *Bryum argenteum*.

2.3.2. Which plant communities can be found and which abiotic factors are more strongly associated with them?

Environmental Variable Selection

In order to select a subset of environmental variables that explain most of the variation of the data, a PCA was performed with 28 explanatory variables (Figure 2.3). The explanatory variables were the 20 abiotic factors and physical attributes (Section 2.2.2) plus the 8 non-plant components contributing to the percent cover of transects (barren land, rocks, organic matter, dead plants, shallow water, streams, streams with macrophytes and principal channel). Considering the Pythagorean distance by looking at the longest arrows on the graph it is possible to observe the explanatory variables that have a higher weight on the distribution of the plots, explaining indirectly the plants' distribution along the gradients or axes (see Appendix Table 2). Variables that are more strongly associated with wetland sites and that are positively correlated are shallow water, shape of wetland, and the amount of salty patches. A second group of variables are barren land, depth of the channel and hill slope were also associated with plant distribution. Finally, third group of variables were width of the channel and temperature. The environmental variables with the longest arrows were shape of wetland (SHW), shallow water (SHA), salty patches proportion (SAL), width of the principal channel (WID) and water temperature (TEMP) (Figure 2.4).

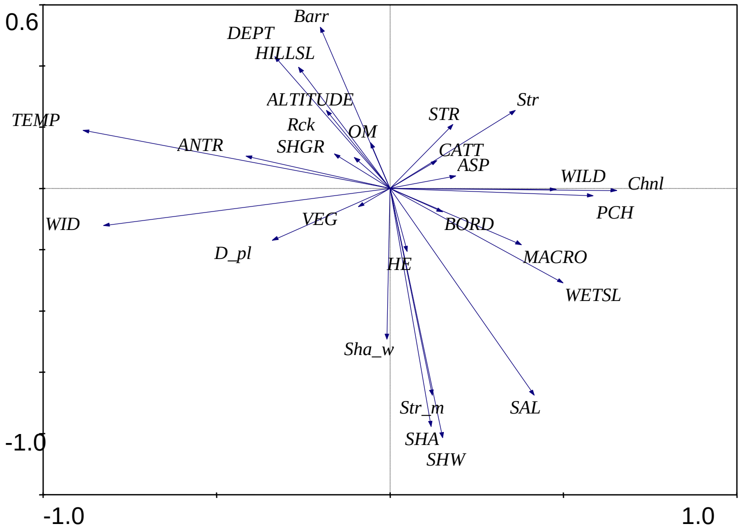


Figure 2.3. Environmental variables plot diagram from Principal Component Analysis (PCA) of 28 original explanatory variables. Arrows that are pointing in the same direction correspond to variables that are more strongly correlated with the wetlands sampled. Abreviations from the environmental variables can be found in Table 2.1

As the numbers of wetland sampled sites were 16 and it is possible to perform ordination only with fewer explanatory variables than the number of sites, the 14 environmental variables that had the strongest correlation patterns (plus a grouping variable) were selected from the original 28 variables (Table 2.2).

To check the consistency of PCA selection, the automatic and manual forward selection were applied. This method reduces variables by adding environmental variables one at a time, including the variable that is most significant in the analysis, until none of remaining variables are "significant" when added to the model. The automatic option recognizes the most important ones and lists the eigenvalues (λ) in decreasing order of importance (Appendix Table 3). The manual forward option additionally lists all the variables with the weights and the user selects where to stop (Appendix Table 4). The three variables selection methods (PCA and forward selections) show slight differences in the environmental variables they selected as more important ones. By comparing all the methods, there were 14 variables that were common in at least two of the methods. Those variables are listed in Table 2.2 and were the environmental variables selected for the multivariate analysis.

Table 2.2. Explanatory environmental variables used for constrained ordination methods. PCA environmental variables axis score (AX1 and AX2) values of the 15 strongest variables contained in at least two selection methods. Type of variable quantitative (Q) or categorical (C).

N	Code	AX1	AX2	Environmental Variable	Description	Type of Variable
1	Barr	-0.1999	0.5269	Barren Land	Percentage of Transect	Q
2	Chnl	0.6533	-0.0066	Channel	Percentage of Transect	Q
3	Sha_ w	-0.009	-0.492	Shallow water	Percentage of Transect	Q
4	Str_ m	0.1221	-0.675	Stream with macrophytes	Percentage of Transect	Q
5	SHA	0.1185	-0.7775	Shape of wetland	3 shape form types	C
6	PCH	0.5853	-0.0237	Principal channels	Number	Q
7	WID	-0.8249	-0.1212	Principal channel width	Width of Channel	Q
8	TEMP	-0.8833	0.1895	Temperature	Temperature	Q
9	ANTR	-0.4156	0.1052	Anthropogenic intervention	Anthropogenic intervention	C
10	WILD	0.4788	-0.0036	Wildlife footprints	Wildlife	C
11	OM	-0.0551	0.1492	Organic matter	Percentage of Transect	Q
12	Rck	-0.1604	0.1126	Presence of rocks	Percentage of Transect	Q
13	HE	0.0494	-0.2052	Heterogeneity	Heterogeneity of the wetland	C
14	MACRO	0.3792	-0.1838	Presence of macrophytes	Presence / Absence	C

Ordination Method

The lengths of the gradients on DCA for the plant distribution entire data set were 4.491 for Axis 1 and 2.842 for Axis 2. Therefore, the appropriate model for these data is unimodal. The data were too heterogeneous to use a linear model. The indirect method – Detrended Canonical Analysis (DCA) was selected from between several ordination methods after an exploration analysis.

The result from DCA identified the two regions distinctively. In the sample distribution biplot (Figure 2.4.), it is possible to observe that the Tarapacá region sites (green triangles) are placed on the left side of the horizontal axis and the Atacama region sites (red triangles) on the right side.

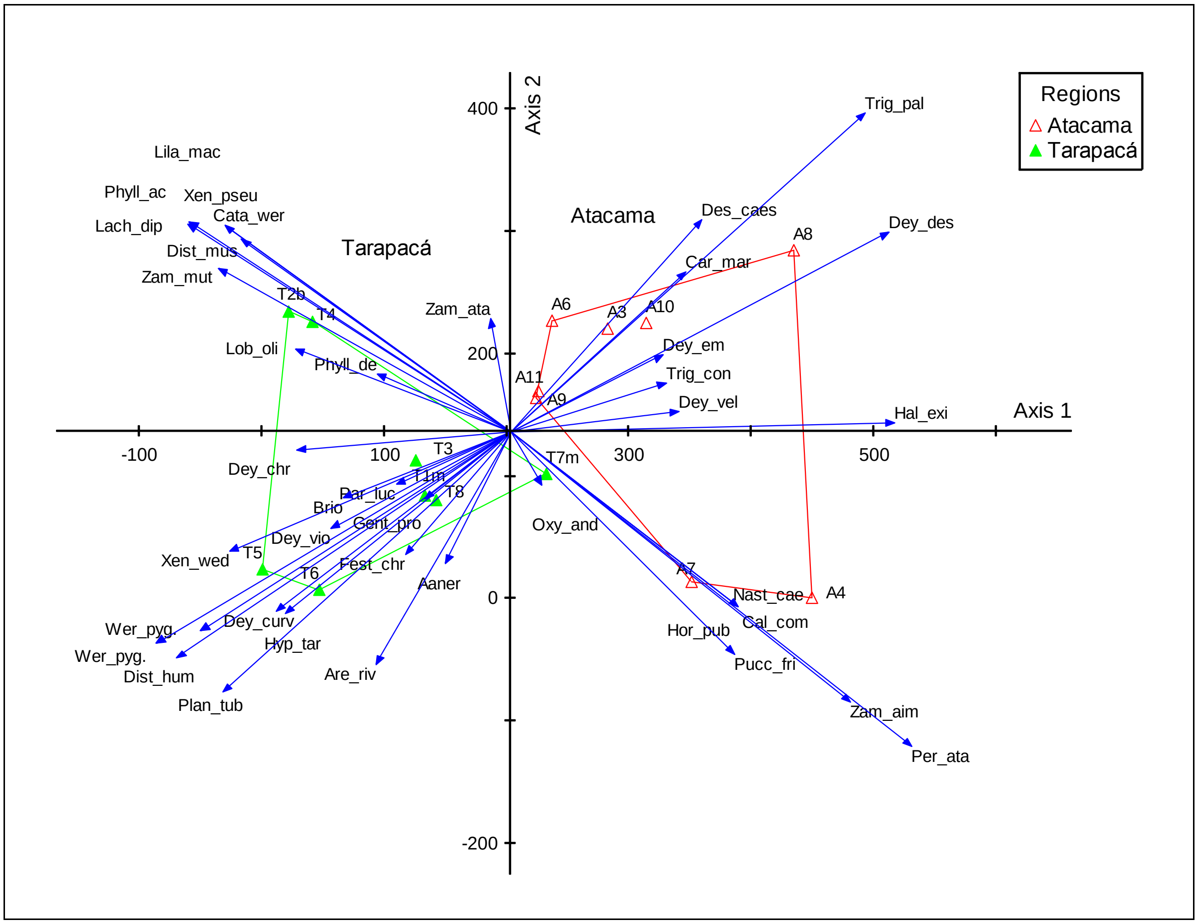


Figure 2.4. Species-wetlands variables biplot diagram from Detrended Correspondence Analysis (DCA). The diagram shows the scores of the first two axes with scaling focused on inter-species correlation. Species are represented by blue arrows, wetland sites by triangles, and convex hulls denote the range of variation among sites for the two regions (red color for Atacama sites and green for Tarapacá sites). Species are labelled by their abbreviated Latin names. For full species names see Table A- 6 of Appendix section.

Considering that wetlands samples that are far apart (> 4 SDs) have a very low probability of sharing species, and according to the distribution of the species on the Cartesian plane (Figure 2.5), five different plant assemblages for each region, were defined (Tables 2.3 and 2.4). The following tables describe plant assemblages and the wetland vegetation type in which they were mostly found.

Table 2.3. Tarapacá region plant group species according to DCA. Wetland type refers to the main classification of plants habit growth type, measured in the field. Plant assemblages come from DCA.

Description	**Wetland Type**	**Plant assemblages**
These species are strongly related in between them and occur in a high relative abundance on wetlands T2b – T4	Peatland/wet meadows	*Lilaeopsis macloviana- Lachemilla diplophylla– Xenophyllum pseudodigitatum– Catabrosa werdermannii– Distichia muscoides– Phylloscirpus acaulis - Zameioscirpus muticus.*
These species are also related with wetlands T2b –T4 but share less similarities in abundance than the previous group.	Peatland/wet meadows	*Lobelia oligophylla– Phylloscirpus desertícola – Zameioscirpus atacamensis.*
These species are similar in relative abundance and are strongly associated with wetlands T3-T8-T1m	Peatland / Tall grassland	*Parastrephia lucida – Bryophyte sp. – Gentiana prostrata– Festuca chrysophylla– Aa nervosa– Deyeuxia aff. Violácea.*
This group of species is very similar in relative abundance and can be found associated with wetlands T5-T6.	Peatland/Tall grassland / wet meadows	*Xenophyllum weddellii– Deyeuxia curvula– Hypochaeris taraxacoide– Arenaria rivularis– Werneria pygmaea– Distichlis humilis – Plantago tubulosa.*
This species is not related to any other in particular. It is a frequent species, present in almost all wetlands and strongly related to wetland T7m, which is located on the ordination diagram, closest to wetlands in Atacama region.	Peatland	*Oxychloe andina.*

In the Tarapacá region, peatand wetland type is present in all the classes (Table 2.3), while for Atacama region, Tall grasslands is the most common one (Table 2.4).

Table 2.4. Atacama region plant group species according to DCA. Wetland type refers to the main classification of plants habit growth type, measured on the field. Plant assemblages come from DCA.

Description	**Wetland Type**	**Plant assemblages**
This pair of species was more related to wetland A8 than any other, but far apart from all the rest of the wetlands.	Tall grassland – wet meadows	*Triglochin palustris- Deyeuxia desertícola.*
This pair of species were closely related to wetland A8 and A10.	Tall Grassland	*Deschampsia caespitosa- Carex marítima.*
This group of species was mainly related to wetlands A10 and then to wetlands A11-A9-A3-A6.	Peatland- Tall Grassland	*Deyeuxia eminen- Triglochin concinna- Deyeuxia velutina.*
This group of plants was more related to wetlands A4-A7 than to any other.	Peatland- Tall Grassland	*Nastanthus caespitosus- Calandrinia compacta- Hordeum pubiflorum- Puccinellia frígida-Zameioscirpus gaimardioide- Perezia atacamensis.*
This species stand apart on the ordination diagram and were related to wetlands A4 and A8.	Tall grassland – wet meadows	*Halerpestes exilis.*

Cluster analysis (Appendix, Figure 1) and MRPP confirmed the differences in between Tarapacá and Atacama regions wetlands plant communities. I used a Multi-response permutation procedure (MRPP) to check if the classification of the wetland sites was significantly different between regions. According to the MRPP results and considering an effect size of 0.21, the differences between wetlands are strong enough to support the classification ($p < 0.0001$). The two-way hierarchical cluster (Appendix, Figure 2 and Table 5 respectively) became the most useful clustering tool compared to Hierarchical Cluster and TWINSPAN, visualizing the species clustered in relation to the regions. TWINSPAN and hierarchical cluster supported DCA by making very similar wetlands groupings. If we look at plant similarities the main species that influence the clustering on Peatlands-Tall grasslands wetlands type of the Tarapacá region were *Oxychloe andina-Festuca chrysophylla*, followed by *Deyeuxia chrysantha-Deyeuxia curvula-Distichia muscoides* with less importance.

According to the literature reviewed in Chapter 1, this classification is correct as *Oxychloe* and *Distichia* are both described as dominant for fresh-water (non-saline) Bofedales system while, *Festuca* and *Deyeuxia* are both cespitose grass plants from the Poaceae family, described for Tall grasslands in a transition to saline systems. According to DCA, among the 14 environmental variables used in the analysis, those that were more strongly associated with the wetland communities of the Atacama region are: presence of rocks and water depth on the principal channel in the wetland. In contrast, Tarapacá region plant communities were much more influenced by the amount of organic matter, number of principal channels and amount of bare land (Figure 2.5).

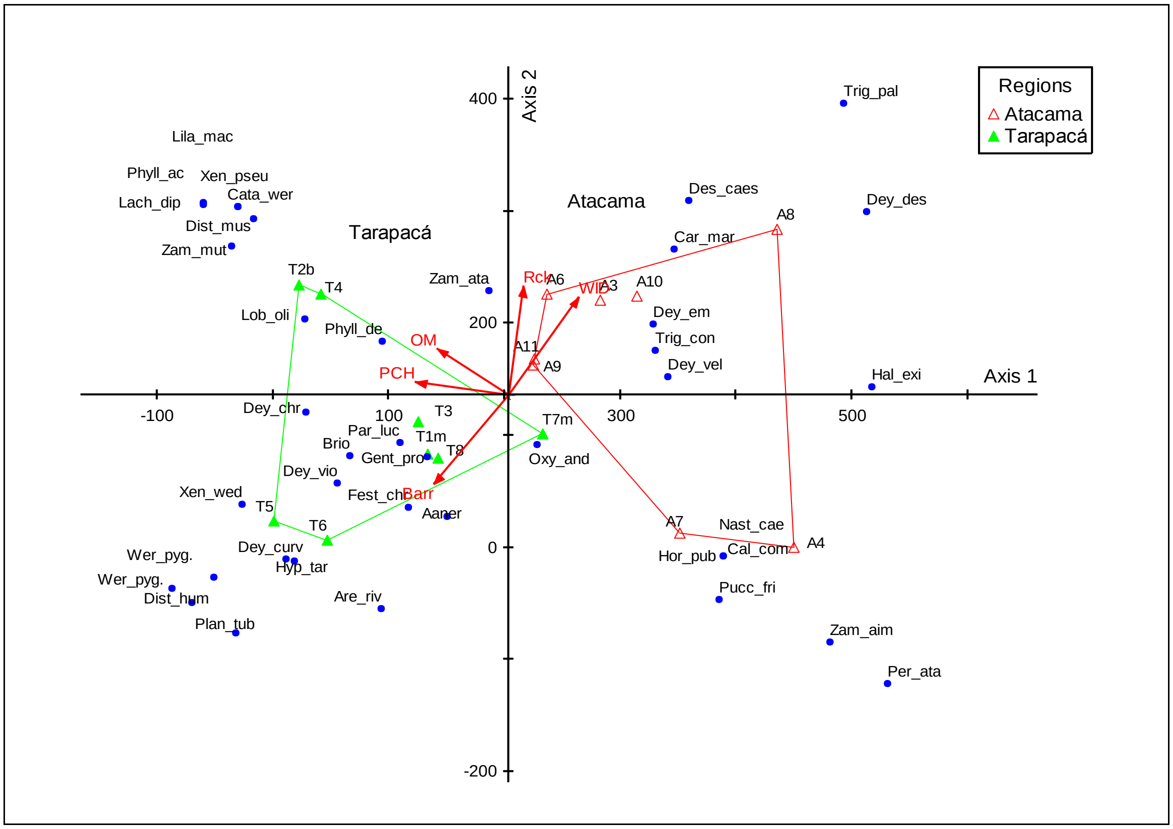


Figure 2.5. Species-wetlands sites-environmental variables diagram from Detrended Correspondence Analysis (DCA). The diagram shows the environmental variables (arrows) pointing in the direction of their maximum correlation with the species distribution as determined by DCA. Species are represented by blue dots, wetland sites by

triangles, and environmental variables by red arrows. Species are labeled by the first three letters of their Latin names. For full species names see Table 7 of Appendix section.

Abiotic and physical attributes can also be analyzed by vegetation type (Table 2.5), where certain groups of plants can be more or less associated with them. Therefore, for Tarapacá region sites, most of the abiotic factors selected by DCA are related to the three vegetation types (peatland, tall grasslands and wet meadows), while for Atacama region only expressed one environmental variable associated with tall grasslands. Also, the variables bare land and organic matter are associated with a larger number of species, while the amount of rocks and width of the channel are associated with much less (Figure 2.5 and Table 2.5).

Table 2.5. Abiotic factors associated with plant group species according to DCA. Wetland type refers to the main classification of plants habit growth type, measured on the field. Plant assemblages come from DCA.

Description	**Wetland Type**	**Plant assemblages**	**Abiotic factors**
Tarapacá region	Peatland / Tall grassland	*Parastrephia lucida – Bryophyte* sp. – *Gentiana prostrata– Festuca chrysophylla– Aa nervosa– Deyeuxia aff. Violácea.*	The presence of *Festuca chrysophylla* and *Aa nervosa* are strongly influenced by the patches of bare land. The rest of the species of the group are partially influenced by the variable
	Peatland/ Wet meadows	*Lilaeopsis macloviana- Lachemilla diplophylla– Xenophyllum pseudodigitatum– Catabrosa werdermannii– Distichia muscoides– Phylloscirpus acaulis - Zameioscirpus muticus.*	Organic matter strongly affect the community of plants
		Lobelia oligophylla– Phylloscirpus desertícola – Zameioscirpus atacamensis.	They are partially affected by organic matter and the number of channels on the wetland.
	Peatland/Tall grassland / wet meadows	*Xenophyllum weddellii– Deyeuxia curvula– Hypochaeris taraxacoide– Arenaria rivularis– Werneria pygmaea– Distichlis humilis – Plantago tubulosa.*	*Deyeuxia curvula– Hypochaeris taraxacoid*e and *Plantago tubulosa.*are are strongly influenced by the patches of bare land. The rest of the species of the group are partially influenced by the variable.

Table 2.5. Abiotic factors associated with plant group species according to DCA. Wetland type refers to the main classification of plants habit growth type, measured on the field. Plant assemblages come from DCA.

Description	**Wetland Type**	**Plant assemblages**	**Abiotic factors**
Atacama region	Tall Grassland	*Deschampsia caespitosa-Carex marítima.*	They are equally influenced by the width of the channel.

2.3.3. Do wetlands affected by different human and cattle activities have different plant communities?

Finally, if we consider information about the level of human and cattle intervention, we can get a table which shows which plant associations can be found in different types of wetlands and can tolerate different levels of intervention (Table 2.6). Tarapacá region wetlands most common human intervention levels were low to medium while in Atacama region most of the sites showed high levels of the same variable. The same thing occurred when comparing grazing levels, where high levels are found in Atacama region wetland sites while in Tarapacá region wetlands sites medium to high levels were found. One difference regarding grazing between the regions, measured on the field, is that on Tarapacá region most of the intervention was produced by the domesticated ungulates llamas (*Lama glama*) and alpacas (*Vicugna pacos*), while in Atacama region wetlands sites most of the grazing was produced by the wild ungulates Guanacos (*Lama guanicoe*) and Vicuñas (*Vicugna vicugna*).

Table 2.6. Table of intervention level by wetland type per region. Wetland type refers to the main classification of plants habit growth type, measured on the field. Plant groups come from DCA. Intervention level refers to human, grazing by cattle or wildlife presence.

REGION	WETLAND TYPE	LIST OF PLANTS	HUMAN INTERVENTION LEVEL
Tarapacá	Peatland/wet meadows	*Lilaeopsis macloviana- Lachemilla diplophylla– Xenophyllum pseudodigitatum– Catabrosa werdermannii– Distichia muscoides– Phylloscirpus acaulis - Zameioscirpus muticus.*	Human: Low Grazing: medium to high
	Peatland/wet meadows	*Lobelia oligophylla– Phylloscirpus desertícola – Zameioscirpus atacamensis.*	Human: Low Grazing: medium to high
	Peatland /Tall grassland	*Parastrephia lucida – Bryophyte sp. – Gentiana prostrata– Festuca chrysophylla– Aa nervosa– Deyeuxia aff. Violácea.*	Human: Medium to high Grazing: Medium to high
	Peatland-Tall grassland – wet meadows	*Xenophyllum weddellii– Deyeuxia curvula– Hypochaeris taraxacoide– Arenaria rivularis– Werneria pygmaea– Distichlis humilis – Plantago tubulosa.*	Human: Medium Grazing: High
	Peatland, Tall grassland, Wet meadows	*Oxychloe andina.*	This species is present in most of the wetlands and cover all the range of intervention
Atacama	Tall grassland – wet meadows	*Triglochin palustris- Deyeuxia desertícola*	Human: High Grazing: High
	Tall Grassland	*Deschampsia caespitosa- Carex marítima*	Human: High Grazing: High
	Peatland- Tall Grassland	*Deyeuxia eminens- Triglochin concinna- Deyeuxia velutina.*	Human: High Grazing: High
	Peatland- Tall Grassland	*Nastanthus caespitosus- Calandrinia compacta- Hordeum pubiflorum- Puccinellia frígida-Zameioscirpus gaimardioide- Perezia atacamensis.*	Human: High Grazing: medium to low
	Tall grassland – wet meadows	*Halerpestes exilis.*	Human: High Grazing: Medium to high

2.4. Discussion

2.4.1 How is the plant community structured in Altiplano wetlands?

Wetlands of the Tarapacá region are more diverse in plant species than in Atacama region, with 53 species instead of 25 species, and 20 plant families versus 13, respectively. From the plants found on transects, in both regions there were a few dominant species, while most of the other species were scarce. This composition is typical in North American wetlands, where half of the species occur in < 10% of the wetlands (Poulin et al., 1999). This pattern has also been described for high altitude wetlands around the world in Tibet and the Central Andes (Adler & Morales, 1999¸ Chang and Gauch, 1986). The dominance of *Oxychloe andina*, followed by smaller proportions of *Deyeuxia* and *Festuca* is described for Altiplano wetlands by the National Office of Natural Resources in Chile (CIREN-INNOVA CHILE, 2010), for the region that is located in between the two areas of this study, supporting the continuity of plant communities found for this study. This institute also points out the appearance of *Zameioscirpus* in the communities as an indicator of salinization of the systems. For this study *Zameioscirpus atacamensis* and *Zameioscirpus gaimardioides* appeared as dominant species in the Atacama region wetlands, suggesting that wetlands in Atacama region expressed more salinity and therefore drier conditions than Tarapacá region wetlands. This condition is also supported by the fact that Atacama, in contrast to the Tarapacá region, is located in the dry portion of the Puna ecosystem. This area has drier and harsher environmental conditions than Tarapacá region, which receives more influence form the Amazonian tropical summer rains.

Richness and diversity parameters reflect that wetlands of the Tarapacá region have higher plant diversity and evenness than the Atacama region. The results match with the information of the total number of species on the region (all field methods). The higher plant diversity on Tarapacá region sites can be explained by the heterogeneity of the sites in Tarapacá versus Atacama regions, were most of the sites were located on the morning-warm aspects of the Andes Cordillera, while Tarapacá region wetlands are well distributed along all aspects. Also, the number of streams within the wetland, and channel widths and depths reflects much more variation in Tarapacá region wetlands than in Atacama regions ones, suggesting a broader spatial configuration that could drive micro-environmental and topographic conditions that will result in more differences of plants communities. This could suggest that plant communities on Atacama region wetlands are found in a shorter environmental gradient, more specific and restricted to a smaller variety of abiotic factors.

Skewness and kurtosis also reflected the complexity of the systems, where in both regions, a group of a few species were dominant and most of the species, appeared with a very low frequency. The highly uneven distribution of plant abundance in both regions, although stronger in Atacama region, might indicate the potential vulnerability of the ecosystems and little resilience and capacity to adapt to changes. Considering that each plant occupies a very particular niche and they are found in small proportions, small changes on the environment could trigger shifts in the species originally found on the wetlands as they would not have suitable conditions to live and would be rapidly replaced by other species.

2.4.2 Which plant communities can be found and which abiotic factors are more strongly associated with them?

Detrended Correspondence analysis (DCA) demonstrated that it was possible to identify different plant communities on high altitude Andean wetlands and that certain abiotic factors were more strongly associated with them.

Although both regions belong to the same wetland types, plant communities are very different; not only in species composition but also in the assemblages they form on the wetlands. With a Sorensen Index of similarity of 28.2%, wetlands on Tarapacá and Atacama regions have only 11 species in common reflecting high levels of endemism. This is expected considering that the sites are located 1,000 km away from each other and high altitude wetlands are an oasis inside a desert matrix, where the options of dispersal processes are minimal. The Atacama region has one of the floras with the highest levels of endemism in Chile (Letelier et al., 2008), representing 19% of the total flora of continental Chile (Squeo et al., 2006).

The species *Oxychloe andina* is the most abundant and frequent in both regions, which indicates a predominance of high altitude peatland (Bofedales) among the other high altitude wetland vegetation types. Considering the other dominant species of each region, wetlands from Tarapacá region have plants from the families Poaceae and Juncaeae, which can be found in more saline systems (Tall and wet grasslands, instead of Bofedales) or in ecotonal areas, associated with water dependent environments. On the other hand, the main Atacama species belong to Poaceae and Cyperaceae families, which are described to be associated with water dependent-non-saline environments like Bofedales.

The species *O. andina* and *D. muscoides*, both selected as main indicators for peatland-wet meadows on Tarapacá region, are cushion caespitose species described as key species in peatland (Bofedales) systems and *Z. atacamensis* is a cushion-rhizomatous plant also described for fresh-water bofedales in a transition to wet meadows. *Phylloscirpus deserticola* and *D. crhysophylla*, selected for wet meadows, are rhizomatous grasses commonly found on non-saline wet meadows and *D. curvula* is described to be found on the ecotones between Bofedales and wet meadows.

There is less information available in the literature for Atacama wetlands. Nevertheless, it was possible to identify some species that were selected by DCA as main indicators for the wetland communities that are described in the literature for more saline high altitude systems, for example, *P. frigida, C. maritima* and *A. rivulari* are described to be found in wet meadows or with low water table levels.

2.4.3 Do wetlands affected by different human and cattle activities have different plant communities?

Atacama wetlands are more homogeneous in configuration (considering the non-plant components of transects) than those of Tarapacá ones. Tarapacá wetlands have much more variation regarding channel depths and widths. This variation could be a result of historical grazing intervention described in Chapter 1 and usage of Tarapacá wetlands, where cattle modify wetland configuration by changing physical and chemical properties of the channels and the soils, like channel depths, widths, amount of water available per wetland, soil compression, barren land patches, among others and therefore change plant communities.

The heterogeneity of Tarapacá region wetlands could reflects the resilient capacity and tolerance of plants to survive in it. On the other hand, the homogeneity of Atacama region wetlands, implies a much more vulnerable system, as they have been historically less affected to human intervention and therefore local plants assemblages reflects the exceptional uniqueness of these systems. Therefore, Atacama high altitude wetlands would probably have fewer possibilities to tolerate changes from the environment and a less capacity to preserve plant assemblages as original ecosystem units. The fragility of Altiplano wetlands and the reason that motivates governmental agencies to take care of them, has been described before (e.g., Squeo et al., 2006; Ahumada & Faúndez, 2009; MMA, 2011) and is consistent with the worldwide statement of Chang and Gauch (1986) that plant communities in high-altitude ecosystems are extremely sensitive and fluctuate with small changes in environmental factors.

The species *Distichlis humilis* is an indicator of saline sites (Ahumada & Faúndez, 2009) and in this work it was found in Tarapacá, especially in wetlands T5 and T6 where high level of grazing intervention and medium level of wild animal presence were found. Ahumada & Faúndez (2009) suggest that *Deyeuxia chrysantha*, found in all Tarapacá wetlands and in high proportions, is a species that reflects good condition of the prairie. The species *Distichia muscoides* is also recognized as an indicator of a very high grazing intervention and it was only found in Tarapacá wetlands. On the other hand *Oxychloe andina*, present in both regions, is also an indicator of intense grazing intervention, which is supported by the fact that the sites studied on Tarapacá region are located in an area that has been historically inhabited by local communities of shepherds. Field data reflect much more cattle intervention on Tarapacá sites by the number of grazing indicators species. *Oxychloe andina* and *Zameisocirpus atacamensis* are the main species that define high altitude peatland communities (Squeo et al., 2006; Luebert & Gajardo, 2000) and on the study area are identified by having a low to medium level of human influence and medium to high level of grazing intervention by cattle.

According to Luebert & Gajardo (2000) the species *Parastrephia lucida* is part of the arid shrub matrix that surrounds the wetlands and it is only found in wetland T7m, which has more similarities with Atacama sites in all the analyses. The presence of this species on the wetland could reflect the introduction of external arid vegetation elements into the wetland structure and the beginning of degradation process.

Regarding aquatic macrophytes presence, seven of the eight wetland in Tarapacá region had species registered in their streams, while only 63% of Atacama wetlands had them. The aquatic species identified for the wetlands (*A. filiculoides*, *L. minor*, *M. quitense*, and *R. uniflorus*) are described to be indicators of good condition of the wetlands in non-saline systems. According to the information collected in the field, human influence is higher in Tarapacá wetlands via grazing, while Atacama region wetlands are mostly affected by humans through proximity to mining roads and water drills, which pump water for mining companies located nearby. The higher presence of aquatic macrophytes on Tarapacá region may indicates that despite the high levels of grazing, wetlands ecosystem still maintain a good condition and cattle are not a factor that is deteriorating the system as much as water extraction is in Atacama wetlands.

Also, a higher proportion of Bryophytes was found in the Tarapacá region sites, which can indicate a better condition of those wetlands, or at least that Tarapacá wetlands preserve moisture conditions that are suitable to sustain the bryophytes wetland community. A higher presence of bryophytes on Tarapacá region wetlands also implies that despite the high grazing pressure those wetlands receive, the ecosystem still retains the wettest part of it, and presumably can maintaining suitable moist soil conditions to permit the development of the most sensitive part of the wetland community.

In general, wetlands on Tarapacá and Atacama regions showed differences in their plant communities. Tarapacá region wetlands are much more influenced by the long history of grazing animals, reflecting that on the configuration of the physical attributes of the wetland and consequently plants community composition. On the other hand, wetlands of the Atacama region exhibit a shorter environmental gradient, with harsher conditions where most of the factors associated with plant communities depend on the availability of water on the wetland.

Chapter 3: EVALUATING THE SUCCESS OF HIGH-RESOLUTION DIGITAL IMAGERY FOR ASSESSMENTS OF HIGH ALTITUDE WETLAND PLANT COMMUNITIES

3.1. Introduction

The current status of the Altiplano wetlands of the Chilean Andes is that they are affected by industrial activities that have modified their original condition and therefore affected their ecological functions (Ahumada & Faúndez, 2009). A change in plant species composition and structure can influence the hydrology and principal functions that wetlands typically provide. Therefore, local governments, international policy makers and private institutions in Chile are justifiably interested in investing in technologies and resources for sustainable management of wetlands located in the driest desert in the world, the Atacama Desert.

3.1.1. Vegetation indices

Remote sensing technologies have been shown to be a valuable ecological tool, and many spectrum-based vegetation indices have been developed (Turner et al., 2003). Vegetation indices are usually composed of red and near-infrared radiances or reflectances and are one of the most widely used remote sensing measurements Their objectives are to differentiate vegetation features and evaluate functional properties. Normalized Difference Vegetation Index (NDVI), the most common and well documented vegetation index, is widely used for describing, analyzing and monitoring vegetation characteristics (Dechka et al., 2002; Kerr & Ostrovsky, 2003; Gitelson, 2004). Based on the ability of some spectral bands to recognize vegetation spectral behavior, several vegetation indices were selected for this study (Table 3.1).

Table 3. 1. Satellite images spectral bands and vegetation indices (VI) description used to discriminate vegetation types.

Index / Band	Formula	Description
Band1 – Blue 450 – 520 nm	Waveband	Provides the greatest water penetration but is very affected by atmospheric scattering. It is used for analysis of water depth, land/water boundaries mapping and soil/vegetation discrimination (Aronoff, 2005).
Band2 – Green 520 – 600 nm	Waveband	Useful for assessment of vigor vegetation and urban features. This band provides moderate water penetration and less atmospheric scattering, so it is useful for water quality and sediments studies (Aronoff, 2005).
Band3- Red 630 – 690 nm	Waveband	Includes chlorophyll absorption and it is used for discrimination of vegetation types and assesses plant condition. It is the visible band least affected by atmospheric scattering so can express great image contrast (Aronoff, 2005).
Band4 – NIR 760 – 900 nm, near infrared	Waveband	It has proven to be particularly useful to distinguish vegetation types and conditions. Differences in reflectances in this band are useful in distinguishing species. It can detect plant water stress (Aronoff, 2005; Govender, et al., 2009).
Simple Ratio (SR)	SR = NIR / R	SR is described as the ratio of light that is scattered in the NIR range to that which is absorbed in the red range and it was developed to minimize the light scattering at the forest floor (Jordan, 2014). SR has been applied as a good indicator of crop growth and has been demonstrated to be closely related with grain yield even more than aboveground biomass. Also, provides reliable information for yield forecasting (Serrano et al., 2000).
Normalized Difference Vegetation Index (NDVI)	NDVI = (R – NIR) / (R+NIR)	The NDVI is perhaps the most recognized and often used vegetation index (VI). It is a simple, but effective VI for quantifying green vegetation. It normalizes green leaf scattering in the near-infrared wavelength and chlorophyll absorption in the red wavelength. NDVI values range is from -1 to 1 where healthy vegetation generally falls between values of 0.20 to 0.80 (Aronoff, 2005)
Enhanced Vegetation Index (EVI)	EVI = 2.5 *((NIR - RED) / ((NIR + 6*RED - 7.5*BLUE) + 1))	The enhanced vegetation index (EVI) was developed to optimize the vegetation signal by better sensitivity in high biomass regions. In areas of dense canopy, the NDVI values can be improved by using information in the blue wavelength. Information in this portion of the spectrum can help to correct soil background signals and atmospheric influences (Huete et al., 2002).
Chlorophyll Index Green (CIG)	CIG = (NIR/GREEN - 1)	CIG was proposed to estimate LAI and green leaf biomass remotely using reflectances in the green around 550 nm. Specific absorption coefficients of chlorophylls in the green spectral regions is much smaller than in the red region. Thus, in these spectral ranges absorption does not saturate at moderate to high chlorophyll contents (Gitelson, 2003).
Wide Dynamic Range Vegetation Index (WDRVI)	WDRVI = (0.1 * NIR1 - Red) / (0.1 * NIR1 + Red)	WDRVI has been shown to have a good correlation with vegetation fraction why it seems to work better and enables a more robust classification of crops' physiological characteristics (Gitelson, 2004).
Chlorophyll vegetation index (CVI)	NIR*RED/GREEN ^2	The CVI is obtained from the Green SR by introducing the red/green ratio to minimize the sensitivity to differences in the canopy LAI, before canopy closure (Vincini et al., 2008) and has been found to have a high sensitivity of the green band to photosynthetic pigment content (Blackmer et al. 1994).
Normalized Difference (Green NDVI)	GNDVI = (NIR-GREEN)/(NIR+GREEN	Green NDVI was developed as an alternative to NDVI because Chl saturates at very low concentration. GNDVI is an index that could be slightly sensitive to atmospheric effects, while still sensitive to a wide range of Chl-a concentrations. (Gitelson et al., 1996).

The atmosphere influences the amount of electromagnetic energy that is sensed by the detectors of an imaging system. The electromagnetic radiation signal collected by satellite sensors is modified by scattering and absorption of aerosols and gases while traveling through the atmosphere from Earth's surface to the sensor (Chavez, 1988; Song, 2001). Atmospheric aerosols increase the apparent reflectance of dark objects causing loss of information and reduce the accuracy of image analysis when not corrected. For image classification, atmospheric correction is not needed, if the training and classification data are in the same relative scale. In contrast, when the analysis involves multi-temporal images, atmospheric correction should be taken into account. Ideally a method that uses ground information is the most accurate to correct atmospheric haze effects (Chavez, 1988). Dark object subtraction (DOS) is the simplest and widely used atmospheric correction approach. This approach assumes the existence of dark objects - pixels within each band that have a very low or no reflectance on the ground - where a zero or very small number is assigned (Song, 2001; Tyagi, 2011). Clear, calm and deep water bodies, have the minimum digital number (DN) of the histogram (Ahern et al, 1977; Campbell, 1992). The correction of atmospheric scattering is very important, especially in shorter visible bands. By correcting it, the effect of path radiance is removed and the surface reflectance (that characterizes the surface properties) is recovered (Fallah, 2012).

3.1.2. Spectral classification of wetlands

Water, vegetation and bare soil have substantially different spectral reflectance in the visible part of the spectrum (0.4 – 0.7 µm). Clear and turbid water has lower reflectance spectral values than vegetation, or dry, wet or salt soils over all the range (0.4 – 1.0 µm). Vegetation reflectance is higher than soil in some parts of the spectra, between 0.4 – 0.6 and 0.8 – 1.0

μm, but is lower in between 0.6 and 0.8 μm (Aronoff, 2005). Each part of the spectra is captured by the sensors in different bands, which are used for different applications, depending on the properties each earth surface feature reflects (Table 3.1).

Wetland classification is difficult because of spectral confusion with other land-cover classes among different types of wetlands. Studies of spectral reflectance of several wetland types are needed in order to get an accurate classification because most computer-based classification methods are dependent on different spectral responses of wetland vegetation types (Ozesmi & Bauer, 2002).

Important plant components of all wetlands are bryophytes. They represent the wettest part of the wetlands and are responsible for the capacity of wetlands for retaining water during the dry periods (Andrus, 1986). They exhibit different spectral characteristics than vascular plants. In the visible portion of the spectrum, mosses exhibit typical absorption in the blue and red, but have a “green” peak reflectance. The moss reflectance in NIR is less reflective than in vascular plants and is characterized by a strong water absorption (Bubier et al., 1997). Mosses have lower reflectance than typical vascular vegetation in the short-wave infrared portion of the spectrum (1.3-2.4 μm) (Bubier et al., 1997). Most bryophyte species are physiologically adapted to low light intensities and therefore have a low chlorophyll *a*:*b* ratio compared to vascular plants (Mishler & Oliver, 1991). As absorption spectra for both pigments-chlorophyll *a* and *b* occurs between 600 and 700 nm, and bryophytes are known to have a low content of chlorophyll *a*:*b*, the Red band would express low reflectance values on the images and then it would be difficult to discriminate them in the spectral analysis. Therefore, the fact that wetlands have bryophytes as part of their communities makes its spectral identification fuzzier in the Red band.

According to Zhang et al. (2008) in their study of spectral characteristic of plant communities, different vegetation types showed varying patterns of spectral reflectance due to the differences in tone, shape or texture of their components. Spectral variations can also occur within species because of soil or water background, precipitation, topography and stresses (Adam et al., 2010). Others have demonstrated that vegetation types with the same physiognomy, but which varied in floristic composition, were often difficult to differentiate using remote sensing, resulting in a misclassification and misinterpretation (Zhang et al., 2008). Both studies suggest that the difficulties of identifying vegetation types from satellite images, from easiest to hardest are water, marshes, deciduous forested wetlands, evergreen forested wetlands and scrub-shrub wetlands.

Canopy architecture is a major determinant of reflection properties. It affects reflectance through scattering effects that are superimposed over leaf reflectance spectra and by its effects on the amount of non-vegetation background (litter, soil, water) that is exposed through the canopy. In addition to canopy many wetlands plant types, exposes substantial amount of standing water and/or soil, substrates that are highly absorbent and that strongly affect reflective properties (Spanglet, 1998).

Soil salinity has little effect on the signature of soil moisture content for dry valley soils (Levy et al., 2014). Everitt et al. (1988) found that well-developed saline efflorescence and crusts are always associated with high reflectance in the visible and near-infrared spectra, which was corroborated by (Howari et al., 2000), in their study of spectral properties of salt crusts demonstrated that soils treated with increasingly higher salinity solutions arrive at a point where the soil particles are covered with salt, and the spectra of the soil disappears and expresses a higher reflectivity.

For Andean wetlands, the challenge of classification is both spectral and spatial. The spectral identification of vegetation has to deal with the recognition of several species co-dominating one plant patch and the spatial challenge is the small size of those plant patches. Therefore, the use of free access data with medium-scale resolution (30-100 m) might not be appropriate for a correct assessment of the system. Techniques and imagery data that can provide detailed information requires not only the appropriate identification of spectral bands but also high spatial resolution imagery with a pixel level information less than a meter.

3.1.3. Remote sensing classification techniques used for wetland identification

The common image analysis methods used for identifying and mapping wetland vegetation with multispectral imagery include supervised, unsupervised or hybrid digital image classification. Unsupervised (or clustering), groups pixels with similar spectral values and the analyst gives the cluster class labels. Supervised classification methods uses pixels with known class types to train the computer to recognize classes, whereas a hybrid approach uses both.

There are several techniques reviewed for wetland classification based on vegetation like clustering, principal component analysis (PCA), maximum likelihood classification, minimum distance to means, discriminant function analysis, parallel-piped method, regression analysis, and vegetation indices (Ozesmi & Bauer, 2002; Adam et al., 2009). Most of the methods have been very effective in separating vegetation from other features, and defining vegetation density, vigor, moisture, but not efficient in defining the species composition (Adam et al., 2009). More powerful techniques have been developed to improve the accuracy of discriminating vegetation types in remotely sensed data, like knowledge-based classifications in which they combined images with environmental variables and forest maps (Domacx & Suzen, 2006). Artificial neural network (ANN) and fuzzy logic approaches were also investigated to improve the accuracy of mapping wetland vegetation (Adam et al., 2009) and although they proved to be useful in mapping vegetation types, ANN can be computationally demanding dealing with large datasets (Xie et al., 2008). Adam et al. (2010) stated that there is no single classification algorithm that can be considered optimal for improving vegetation discrimination and the use of classifier algorithms must be based on how appropriate they can be to achieve specific objectives.

3.1.4. The statistical analysis approach

One of the approaches described by Ozesmi & Bauer (2002) on wetland classification is to use PCA to reduce the number of bands, and then apply clustering to the few principal variables. Principal Components Analysis (PCA) is an analytic technique designed to reduce the dimensionality of a set of variables while retaining the maximum variability and was one of the earliest ordination techniques applied to ecological data (Chahouki, 2013). PCA is used abundantly for image analysis and classification purposes because it is a simple, method of extracting relevant information from complex data that has proven to be better than other techniques in discriminating different types of images (Bajwa & Hyder, 2005). Another method used by ecologists to discriminate group variables on vegetation classification with remote sensing imagery data is Discriminant Analysis (DA). The General Discriminant Analysis (GDA) investigates differences between groups, indicating which attributes contribute most to group separation. The stepwise DA approach is built step-by-step and at each step all variables are reviewed and evaluated to determine which one will contribute most to the discrimination. A successful discriminant function analysis will only keep those variables that contribute the most to the discrimination between groups (Switzer, 1980). Discriminant analysis functions have been used successfully for statistical classification of remotely sensed satellite imagery and plant classification. Dutcher (2009) used linear discriminant analysis functions to select the wavelengths that were determined to be useful for species classification on the characterization of wetland invasive vegetation. Other methods to analyze differences in vegetation spectral responses are one–way ANOVA and Cluster analysis. The tree diagram clustering plot or dendrogram is useful to detect and interpret the connection between groups of objects (Chahouki, 2013) and observe dissimilarities through distance linkages. It has been used as a tool for analyzing plant communities and for wetland vegetation composition with remote sensing data (Tuxen et al., 2011).

The objective of this chapter is to evaluate the ability of high-spatial resolution imagery for differentiating Altiplano wetland plant communities. To do so I assessed which bands and / or vegetation indices are the most accurate at discriminating vegetation assemblages. In order to address this, it was necessary to study the spectral response of plant community classes and species from a series of ground-based data points. The Objectives of this Chapter are a) to address if different high altitude wetland plant communities and/or species have different spectral reflectance and b) to detect which bands and vegetation indices are more suitable to identify variation between vegetation.

3.2. Materials and methods

3.2.1. Study area

As stated in Chapter 2, section 2.2.1 the study area is located in the northern part of Chile, South America, in the Tarapacá and Atacama regions, between 19°07’ and 27°30’S and

68°54’ and 69°17’ W. The wetlands are considered to be oases in the middle of the most arid desert on the world, the Atacama Desert with very dense vegetation on the valley bottoms. Depending on the species composition, there are three types of high altitude wetlands, described in Chapter 1: high altitude peatlands, (locally called Bofedales), Tall grasslands and Wet meadows. (Table 1.1, Chapter 1).

3.2.2. Data collection

Field sampling

During January and February 2013, 16 wetlands were measured and 87 field description points were collected. Data collection occurred during the summer months in Chile when plants have the highest growing rates of photosynthetic activity (CIREN-INNOVA CHILE, 2010; BIOTA, 2007; CEA, 2006). Points are placed along transects and were located in different patches of vegetation or plant community types (Figure 3.1). Field point descriptions were located where it was possible to find a patch of vegetation with similar characteristics in terms of plants composition. For each point the main plant species and percent of cover were recorded, following Braun-Blanquet methodology (Poore, 1955).

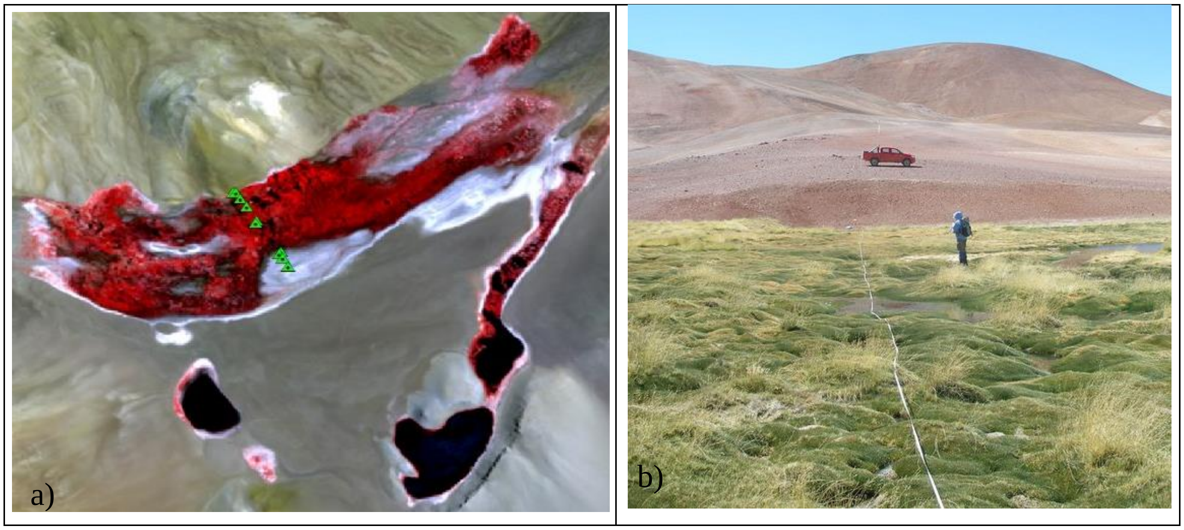


Figure 3.1. Wetland transect. Figure a) Satellite image view of a transect along one of the wetlands on the study area. Green triangles on a multispectral RGB IKONOS from the same transect. Figure b) Ground view of a wetland transect.

Spectral data acquisition

Radiance values from satellite images IKONOS-2 and Geoeye-1, for all bands, from each field point, were extracted using Arc GIS 10.2. To be consistent with field work data the images used for the analysis were acquired during the summer months of 2013 in the southern hemisphere.

Imagery data consist of 6 GEOEYE-1 satellite images, from February 2nd and March 6th, 2013, with a spatial resolution of 0.41 m on panchromatic and 1.65 meters on multispectral and 3 IKONOS-2 satellite images, from March 11th, 2013 with spatial panchromatic and multispectral sensor bands resolution of 0.82 meters and 3.2 meters respectively. All images provided spectral information for bands Blue (445 to 516 nm), Green (506 to 595 nm), Red (632 to 698 nm) and Near Infrared (767 to 853 nm). The Panchromatic band (526 to 929 nm) was not used for the analysis because it does not give any direct information regarding chlorophyll content and the spatial resolution is less than for multispectral bands, which make the images not comparable (multispectral and panchromatic). In addition to the spectral values, vegetation indices were also calculated and considered in the statistical analysis (Table 3.2).

Table 3. 2. IKONOS-2 and Geoeye-1 Wavebands and vegetation indices formula and spectrum range.

Index	**Codification**	**Range (λ or DN)***
Waveband1 – Blue	b1_B	6 - 842
Waveband2 – Green	b2_G	3 - 694
Waveband3- Red	b3_R	10 - 814
Waveband4 – NIR	b4_NIR	226 - 1530
Simple Ratio	SR	1.17 – 25.3
Normalized Difference Vegetation Index	NDVI	0.07 – 0.92
Enhanced Vegetation Index	EVI	-3.82 – 52.5
Chlorophyll Index Green	CLIG	0.30 - 360
Wide Dynamic Range Vegetation Index	WDRVI	0.01 – 0.68
Chlorophyll vegetation index	CLVI	1.03 – 9885
Normalized Difference	(Green NDVI)	0.13 – 0.99

*DN – Digital numbers after formula application to radiance unit values.

All radiance single pixel values obtained were atmospherically corrected by the subtraction of the water values on each image in each band. Therefore, the values used for statistical analysis are the expression of vegetation reflectance without the influence of atmospheric particles that contaminate the spectral data through absorption and scattering of the radiation from the earth surface.

Plant group classifications

According to the ground-based descriptions, all transect points were grouped in 14 classes based on the dominant species (Table 3.3). Classes 1 to 3 are non-plant dominated and the rest of the classes are dominated by a single species with a percent cover more than 50% or a mix of several species in similar proportions defining a mixed patch of vegetation.

Table 3. 3. Vegetation type classes grouped by dominant species according to wetland transect field descriptions.

Vegetation Type Classification	Class	Description
Bare Land	1	Barren land with no presence of plants
Water	2	Wetlands streams or pools
Rocks	3	Mineral, exposed soil
Salt +grasses	4	Patches of vegetation with Salt presence > 30%[*1]
Oxychloe andina (Oa)	5	Patches of vegetation where the named species is dominant and has >60% cover
Deyeuxia ceaspitosa (Dca)	6	
Deyeuxia curvula (Dcu)	7	
Deyeuxia deserticola (Dde)	8	
Deyeuxia velutina (Dve)	9	
Zameioscirpus atacamensis (Za)	10	
Festuca chrysophylla (Fch)	11	
mix *Oxychloe andina* (MixOa)	12	Patches of vegetation where Oa has at least a 40% cover and less than 60% cover and no other species have a higher dominance.
mix *Zameioscirpus atacamensis* (MixZa)	13	Patches of vegetation where Za has at least a 40% cover and less than 60% cover and no other species have a higher dominance.
Deyeuxia eminens (Dem)	14	Patches of vegetation where De is dominant and has >60% cover

[*1] According to Ahumada & Faúndez (2009) Classification of high altitude Altiplano wetlands

At least half of the wetlands sampled had bryophyte species underneath other vascular plants, forming patches or combined with some other plant types. Although they have important ecological roles in wetlands, bryophytes were not considered in this study as a vegetation class by themselves. Considering the low reflectance produced by bryophytes, data points with ≥ 40% bryophyte composition were not included in the study. Additionally, and differently than with bryophytes, because of salt crust reflectance properties, I expected that grasses covered by salt, will have a spectral reflection differently than pure grasses. Because the goal of this study was looking for the vegetation spectral response, only classes 4 to 14 were used in the discriminant analysis.

3.2.3. Data processing and statistical analysis

Using the 4 bands and vegetation indices' spectral values, the statistical analysis Principal Components Analysis, General Discriminant Analysis, Cluster Analysis and one-way

ANOVA were performed using STATSoft Statistica Software.

Principal components analysis

The selection of the vegetation indices or bands from a big set of variables that could better explain the differences between groups of plants classes were essential to address the first question of this chapter. I used Principal Component Analysis (PCA) to select from a group of 11 highly correlated variables (bands + indices) those that could better explain differences in vegetation class types. The PCA was implemented using the PC-ORD package (McCune et al., 2005).

General discriminant analysis

4. A General Discriminant Analysis (GDA) was conducted to determinate which spectral bands or vegetation indices are best for vegetation class identification. The model building option was forward stepwise, the dependent variable was vegetation classification and the continuous predictor variables were bands 1-4 plus the 7 indices (Table 3.2). The analyses performed by GDA and examined here are Classification Matrix, Summary of Stepwise regression, Multivariate Test of Significance (Wilks) and Class Means for Predictor Classes Plots. For this analysis the dependent variables were vegetation classes and the independent, continuous variables were the bands and/or vegetation indices selected by the PCA.

Cluster analysis

In the interest of finding a relation between image spectral bands or vegetation indices with plant classes' spectral values, a Cluster Analysis was performed. I used hierarchical clustering for all the radiance values from Bands 1 to 4 and for digital numbers of vegetation indices. The results are expressed on a tree diagram, which shows the linkage distances between variables.

One-way ANOVA

I used a one-way ANOVA for each band and vegetation index selected by the GDA model. This analysis was useful to observe the differences of each vegetation class by one selected variable (bands and vegetation indices) at a time. In addition, this analysis was also useful to show which vegetation classes are more sensitive to certain variables (bands or vegetation indices). Because I was looking for which vegetation classes are more unique and differ from others in each band, a Tukey's test from the one-way ANOVA was performed.

4.1. Results

4.1.1. Do different plant communities have different spectral reflectance?

Vegetation classes expressed different spectral behaviors. Figure 3.2. shows the mean reflectance of each vegetation class in all the spectra. Values are grouped per band: band 1 (490 nm), band 2 (560 nm), band 3 (650 nm) and band 4 (800 nm). From the graph one can observe that *Deschampsia caespitosa* (Dca) has a higher reflectance on bands 1, 2 and 3 but decreases in the NIR. Alternatively, *Deyeuxia deserticola* (Dde) rises up in band 4 NIR. The species *Festuca chrysophylla* (Fch), *Deyeuxia curvula* (Dcu) and *Oxychloe andina* (Oa) expressed the lowest reflectance values in all bands. Different from expected, grass with salt patches did not show significantly different values on bands 1, 2 and 3 and have values similar to *Zameioscirpus atacamensis* (Za) and mixed *Zameioscirpus atacamensis* (mix 13).

Plant class *Deyeuxia caespitosa* (Dca) reflects an outstanding spectral response on bands 1, 2 and 3, while *Deyeuxia deserticola* (Dde) remains the same and only rises up on NIR. Box plots by vegetation classes also confirm the different spectral responses by vegetation classes (Figure 3.3). The variation in the response is very clear and increased in band 4 – NIR.

Vegetation classes with more variation in the reflectance values are the three mix classes (Mix *Oxychloe andina*, Grass with Salt patches, mix *Zameioscirpus atacamensis*) plus *Deyeuxia eminens* (Dem) and *Zameioscirpus atacamensis* (Za). Vegetation classes that have less variation on spectral values are *Oxychloe andina* (Oa), *Zameiscirpus atacamensis* (Za) and *Festuca chrysophylla* (Fch).

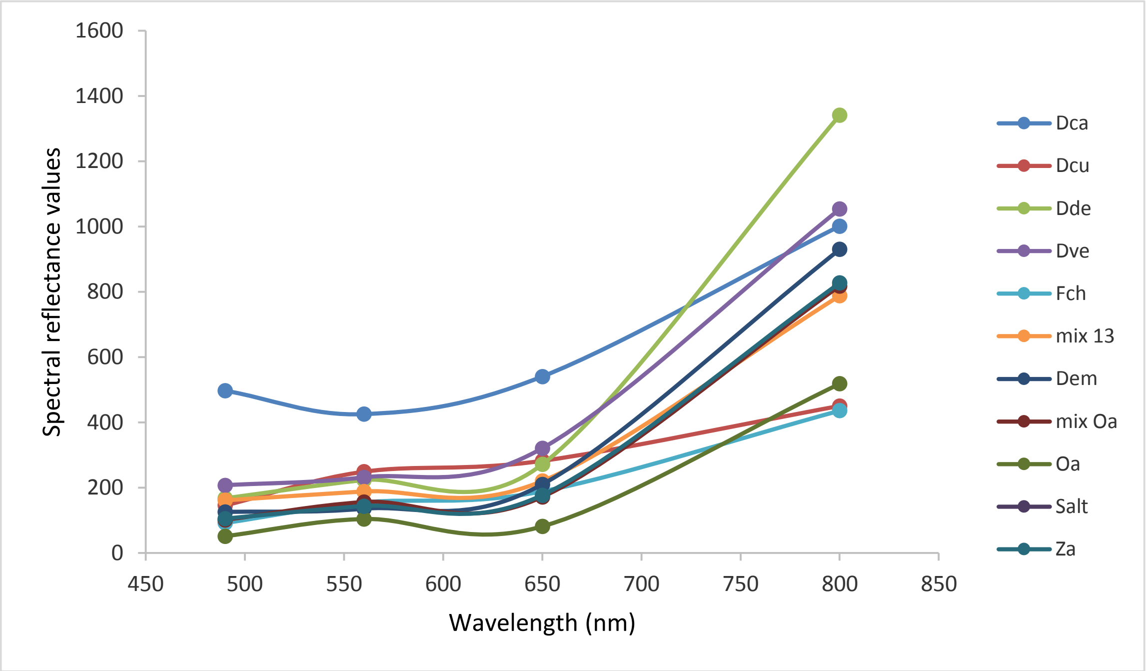


Figure 3.2. Reflectance response curve of vegetation classes per wavelength (nm). Spectral reflectance values (y-axis) from the 11 classes defined for this study are expressed per band along the x-axis (wavelength (nm)). Spectral values are gruped around band 1-Blue (490 nm), band2-Green (560 nm), band 3-Red (650 nm) and band 4-NIR (800 nm).

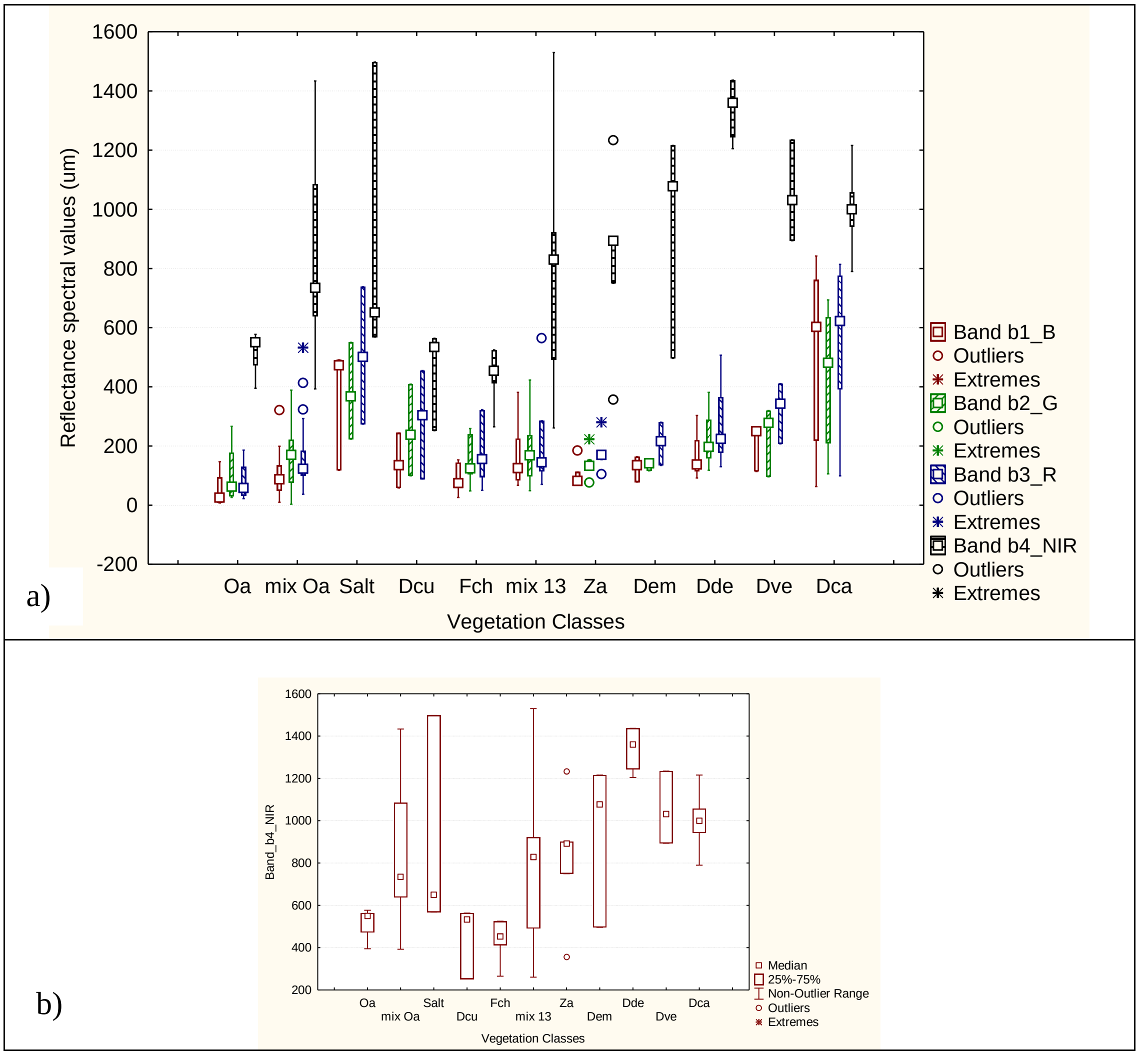


Figure 3.3.a) Box plot showing the variation of vegetation classes per all bands. b) Box plot showing the variation of vegetation classes per band 4. Plant types codification is: Oa (*Oxychloe andina*) – Mix Oa (Mix *Oxychloe andina*) – Salt (Grasses with a high content of salt) – Dcu (*Deyeuxia curvula*) – Fch (Festuca chrysophylla) – mixZa (mix *Zameioscirpus atacamensis*) – Za (*Zameioscirpus atacamensis*) – Dem (*Deyeuxia eminens*) – Dde (*Deyeuxia deserticola*) – Dve (*Deyeuxia velutina*) – Dca (*Deyeuxia ceaspitosa*).

The difference between plant classes was supported by one-way ANOVA (Figure 3.4). On bands 1, 2 and 3 vegetation-type spectral behavior variation is similar. Vegetation types Grasses with a high content of salt (Salt) and *Deschampsia caespitosa* (Dca) expressed the highest variation in all bands. A different scenario occurred on band 4-NIR, where much more spectral reflection variation can be observed in all vegetation types.

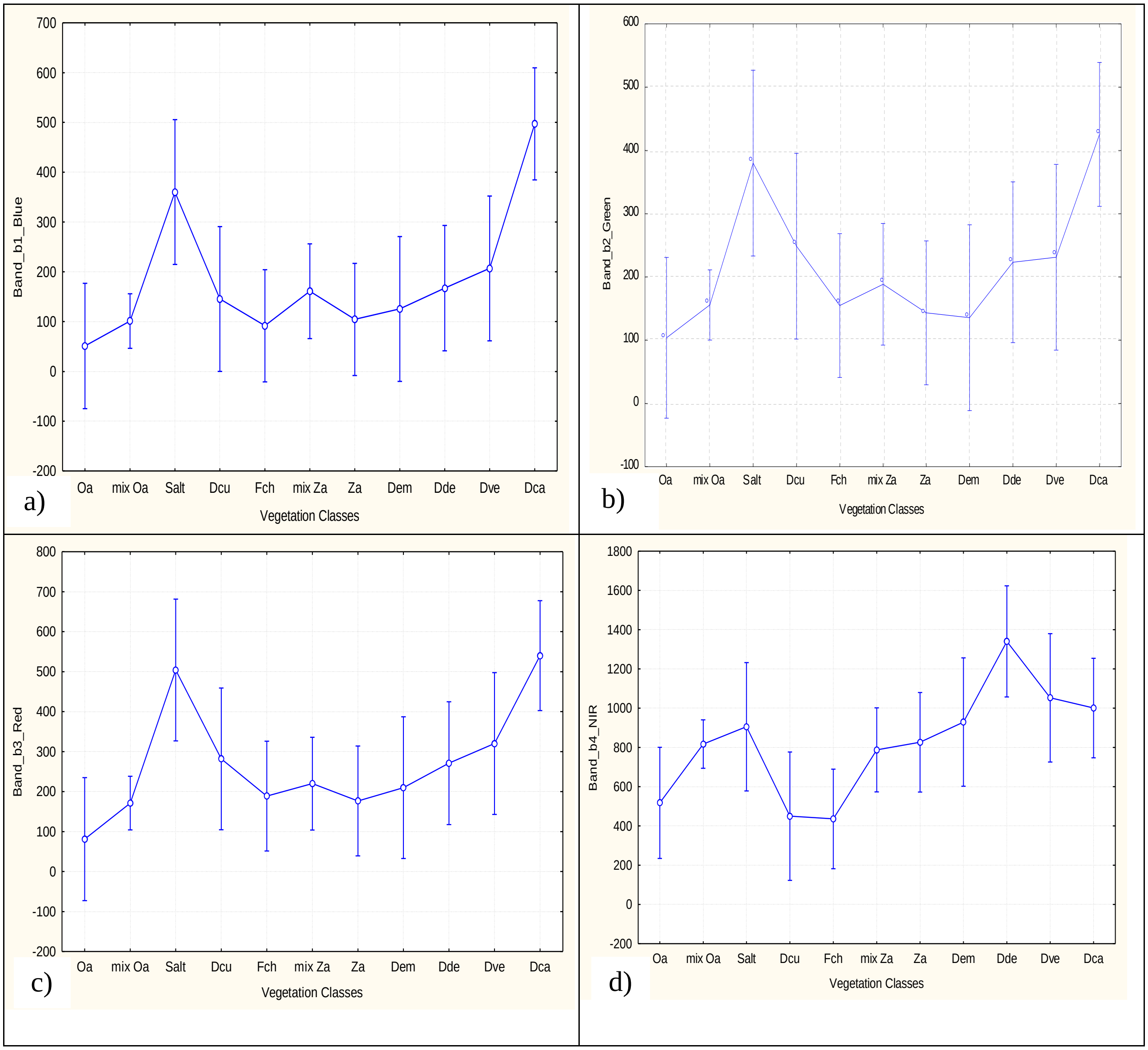
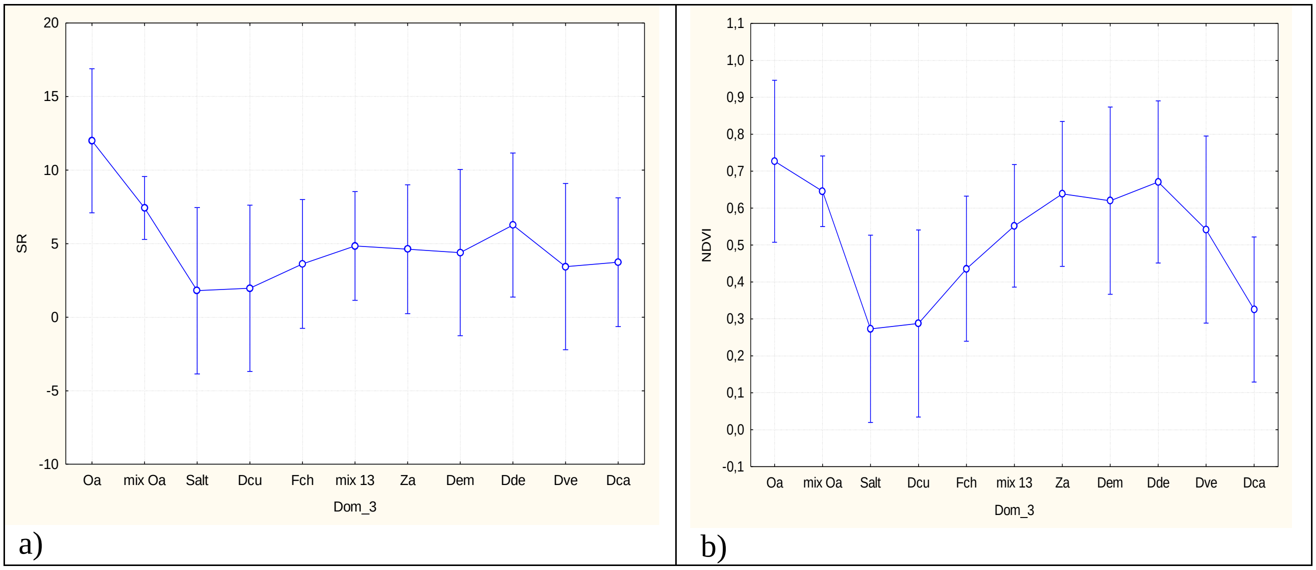


Figure 3.4. Class means of vegetation communities' classification using 4 bands spectral values. Vertical bars denote 95% confidence intervals. Figures a) Band b1 –Blue. b) Band b2 – Green. c) Band b3 – Red. d) Band b4 – NIR. Plant types codification is: Oa (*Oxychloe andina*) – Mix Oa (Mix *Oxychloe andina*) – Salt (Salt + Grasses) – Dcu (*Deyeuxia curvula)* – Fch (*Festuca chrysophylla)* – mixZa (mix *Zameioscirpus atacamensis*) – Za (*Zameioscirpus atacamensis*) – Dem (*Deyeuxia eminens*) – Dde (*Deyeuxia deserticola*) – Dve (*Deyeuxia velutina*) – Dca (*Deyeuxia ceaspitosa*).

Band 1-Blue is particularly sensitive to Grass and salt patches and *Deschampsia caespitosa* (Dca), which does not occur for the other indices or bands selected by the model (Figures 3.4

and 3.5). On the other hand band 4-NIR is more sensitive to vegetation types *Deyeuxia deserticola* (Dde), *Deyeuxia velutina* (Dve) and *Deschampsia caespitosa* (Dca). Considering vegetation classes' spectral responses on the vegetation indices SR, NDVI and WDRVI, they have similar responses, with much more reflection on vegetation types *Oxychloe andina* (Oa), mix *Oxychloe andina* (mix-Oa) and *Deyeuxia deserticola* (Dde). Grasses with salt patches had the lowest reflection values for the three indices. Chlorophyll Index Green (CLIG) and Chlorophyll vegetation index (CLVI) also had similarities in the differentiation of vegetation classes, i.e. both of them had the highest values for the grass and salt patches while the rest of the classes were almost indistinguishable or with values close to zero (Figure 3.5). Tukey's HSD test for selected variables showed that the only vegetation class identified to be unique is *Deschampsia caespitosa* (Dca) with $p < 0.05$.



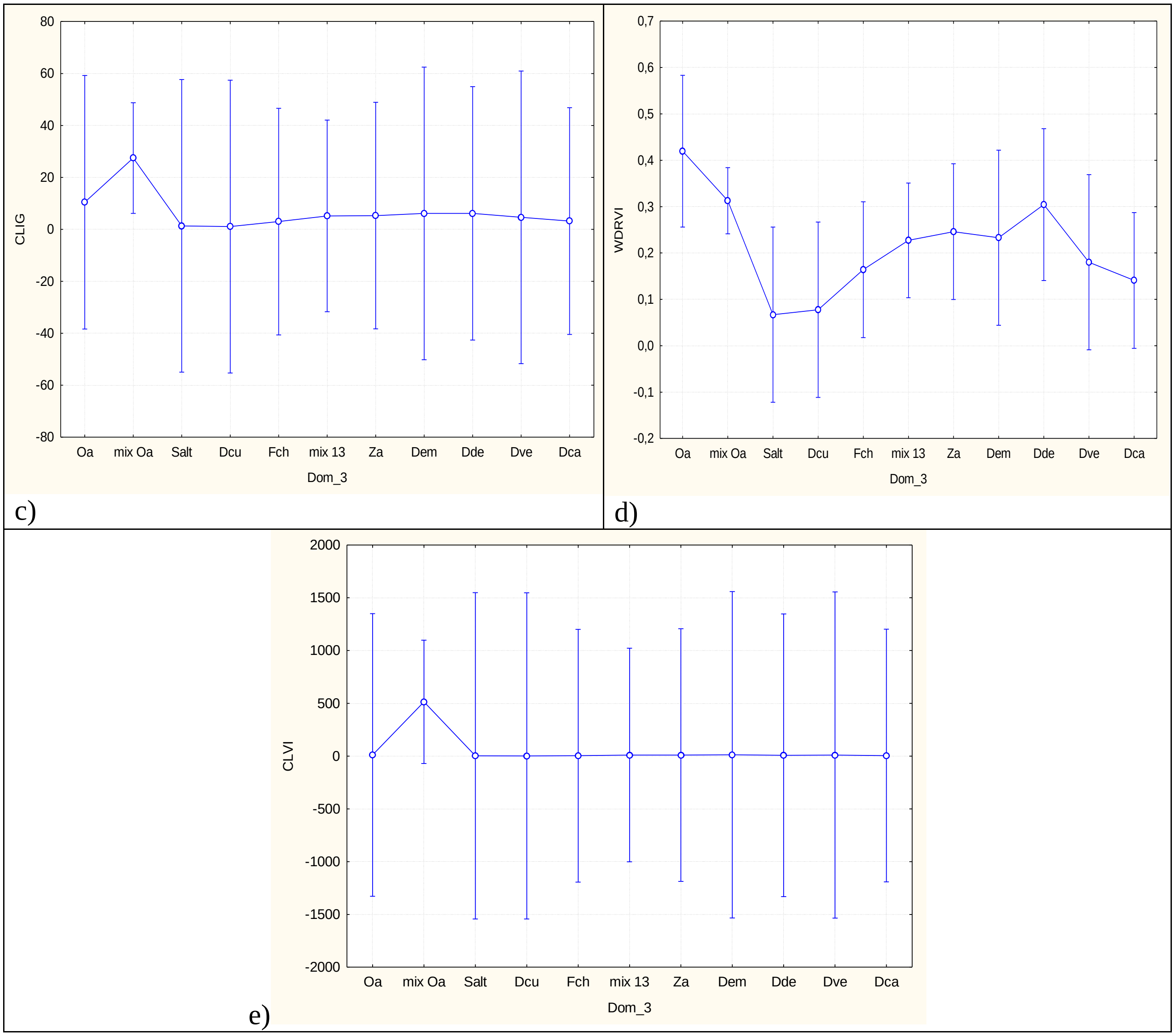


Figure 3.5. Class means for predictor variables selected by GDA model. Vertical bars denote 95% confidence intervals. Vertical axis indicates the spectral range of vegetation indices selected. Figure 3.5 a) SR. b) NDVI. c) CLIG. d) WDRVI. e) CLVI. Horizontal axis shows the 11 vegetation classes. Vertical bars denote 95% confidence intervals. Plant type codes are: Oa (*Oxychloe andina*) – Mix Oa (Mix *Oxychloe andina*) – Salt (Salt + Grasses) – Dcu (*Deyeuxia curvula*) – Fch (*Festuca chrysophylla*) – mixZa (mix *Zameioscirpus atacamensis*) – Za (*Zameioscirpus atacamensis*) – Dem (*Deyeuxia eminens*) – Dde (*Deyeuxia deserticola*) – Dve (*Deyeuxia velutina*) – Dca (*Deyeuxia caespitosa*).

4.1.2. Which bands and vegetation indices are more suitable to distinguish between vegetation classes?

Principal components analysis

Principal component analysis results group the spectral bands and indices in three locations of the coordinate axis plane. The grouping showed that some variables are correlated and explained vegetation classes in three groups (Figure 3.6. Considering the correlation and distribution of the variables on the PCA (Appendix, Table 7), the importance of some bands to reflect water and vegetation and the strength and simplicity of some vegetation indices identifying vegetation reflectance, the following variables were selected to be included in the GDA model: band 1- Blue; SR; NDVI; WDRVI; band 4 –NIR; CLVI and CLIG.

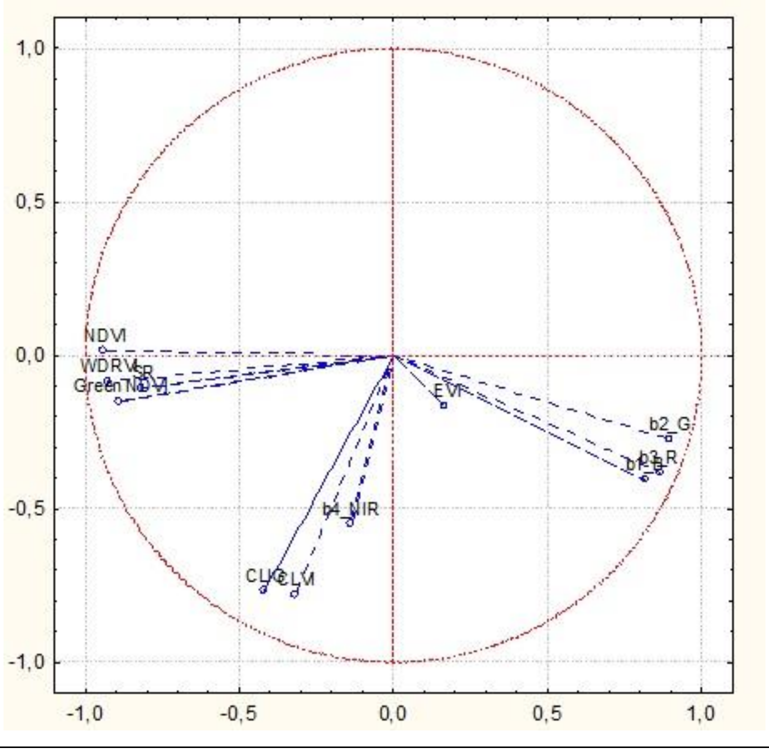


Figure 3.6. Principal Component Analysis plot of vegetation indices. Projection of the variables on the factor plane (Axis 1 x 2). Abreviations from the vegetation indices can be found in Table 3.1.

General discriminant analysis (GDA)

Forward stepwise regression results for the GDA showed that the most important variables were Band 1-blue, band 4-NIR and WDRVI (Table 3.4). Variables NDVI, CLIG, SR and CLVI were less important. Wilks multivariate test of significance confirmed the three variables selected by GDA, where band 1-Blue, band 4-NIR and WDRVI are significantly different to the rest of the bands with $p < 0.05$ (Appendix, Table 8)

Table 3. 4. Summary of forward stepwise regression steps applied to selected variables after PCA.

	Steps	Degr. of Freedom	F to remove	P to remove	F to enter	P to enter	Effect status
b1_B	Number 1	10			5.454	0.000	Entered
b4_NIR	Number 2	10			3.271	0.002	Entered
WDRVI	Number 3	10			2.308	0.026	Entered
NDVI		10			2.465	0.017	Out
CLIG		10			0.316	0.974	Out
WDRVI		10			1.932	0.061	Out
CLVI		10			0.202	0.995	Out
b1_B	Number 4	10	4.440	0.000			In
b4_NIR		10	3.505	0.001			In
WDRVI		10	2.308	0.026			In
NDVI		10			1.248	0.286	Out
CLIG		10			0.201	0.995	Out
SR		10			0.509	0.875	Out
CLVI		10			0.158	0.998	Out

The selection of bands 1 and 4 on the GDA model was also confirmed by the forward stepwise selection applied only to the bands, where the results included band 1-blue and band 4-NIR in the model at the 3rd step and variables band Green and Red were excluded (Appendix, Table 9). Class mean for Predictor Classes Plot (Figure 3.7.), shows how band 4-NIR, is distinct from the rest of the bands. NIR has higher spectral values and more variation within the spectral values than bands 1-Blue, 2-Green and 3-Red. On the other hand, Blue band has lower spectral reflectance values.

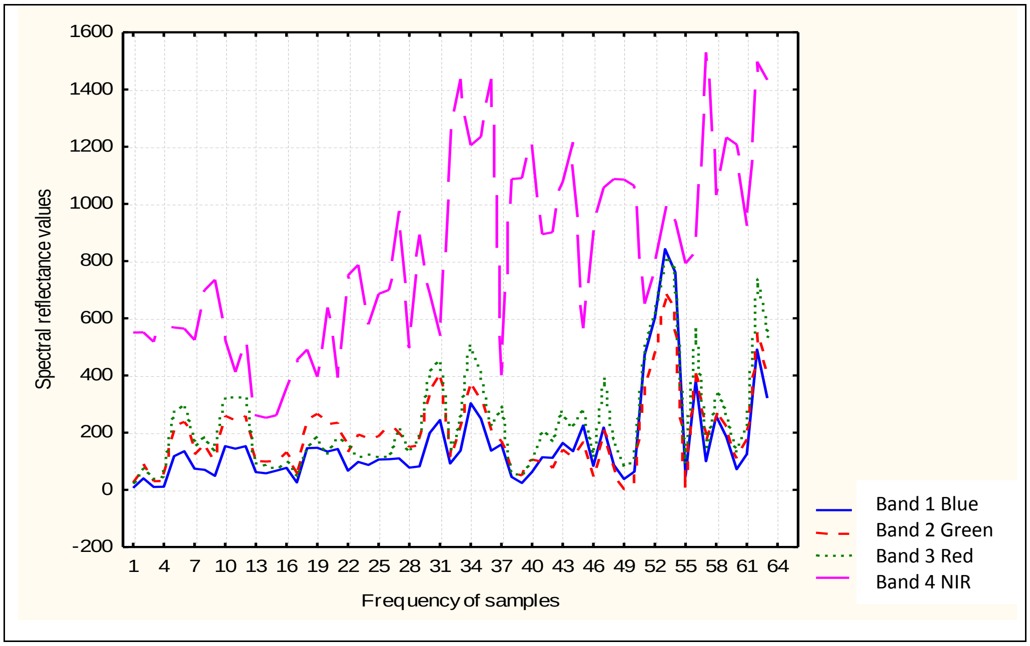


Figure 3.7. Class Means for Predictor Classes Plots. Band 4 – NIR (pinkexpress higher spectral reflectance values in all the samples of the wetlands followed by bands 3-red, 2-green and 1-blue.

Cluster analysis

The hierarchical dendrogram output for the cluster analysis (Figure 3.8) reflects similar linkages to the connections found on the PCA plot (Figure 3.6.). The first vertical dashed line indicate the pruning point in the tree, which result in three main groups. Band 1 is more closely related to the vegetation indices SR, NDVI, WDRVI and CLIG than band 4 – NIR and all of them far-off with CLVI, which establish connection at a measure of 60% dissimilarity.

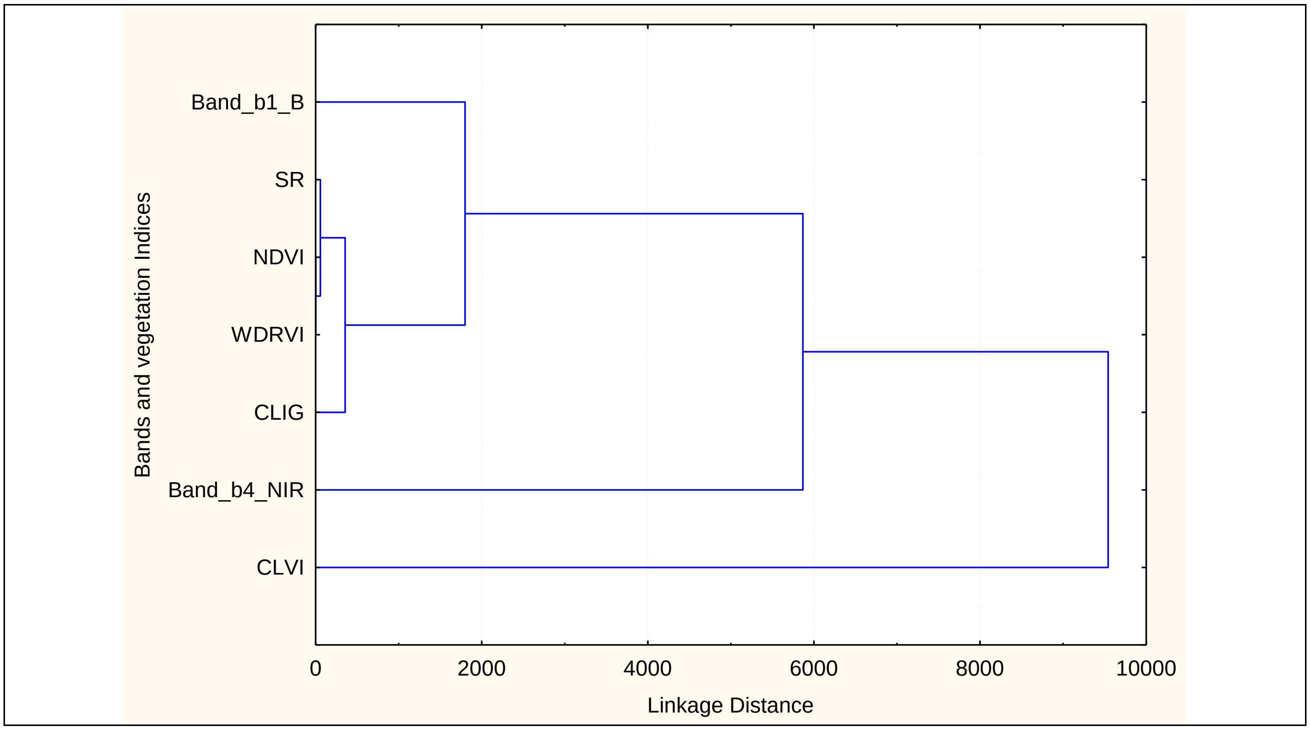


Figure 3.8. Cluster Analysis for bands and vegetation indices selected by the PCA (y-axis). Tree diagram, single linkages, Euclidean distances method. The first vertical dashed line indicates the pruning point on the tree, which resulted in three classes.

The two GDAs performed showed <45% confidence that the samples are adjusted to the discriminant function (Appendix, Tables 3.5 and 3.6). Despite this low value, if we analyze vegetation classes one at the time, they have higher assurance and at least three vegetation types have > 50% confidence by the classification. Considering only 4 bands on the GDA model, the overall accuracy of adjusting to the discriminant function to vegetation classes decreases by 2%, from 42.9 to 41.3 percent.

Vegetation types that fit the model better are similar but with around a 10% higher accuracy in each type. Vegetation types that had the highest accuracy were Mix *Oxychloe andina* (85-95%), *Deschampsia caespitosa*-Dca (60%), *Deyeuxia deserticola*-Dde (50%) and *Festuca chrysophylla*-Fch (20-40%) and *Oxychloe andina* - Oa (50%). Considering that variables with large weight are those which contribute mostly to differentiating the groups, the selection of mix *Oxychloe andina* and *Oxychloe andina* could be explained by highest participation on the samples (17 and 8 records out of 63). The other vegetation classes that had a high assurance on the model are also highly represented, with 4-5 records each.

4.2. Discussion

4.2.1. Do different plant communities have different spectral reflectance?

Plant classes are in most cases composed of more than one species, which could affect reflectance values by adding spectral noise of the non-dominant species, salt or bare land. However, it is still possible to identify differences on the responses in all bands. There is a general trend from all vegetation classes to express higher spectral values in the Near Infra Red band, which is expected considering that most of the classes are patches of dense vegetation that cover > 70% of the surface, therefore spectral responses will be detected in NIR band. Most of the classes have similar spectral values on bands blue, green and red but they stand apart on NIR. This difference points out the vigorous condition of *Deyeuxia deserticola* (Dde), *Deyeuxia velutina* (Dve) and *Oxychloe andina* (Oa), which can be clearly differentiated from all other classes on NIR band. Regarding the spectral behavior of grasses with salt patches vegetation type, it seems that the amount of salt was not significantly different in size or in concentration that could affect reflection values. In most vegetation classes small bare land patches are present, which modified the expected pure vegetation reflection.

The large variation in the reflectance values from the two mixed vegetation types can be explained because of the configuration of the vegetation patches and plant features. The variation in the spectral values can be strongly related with the proportion of exposed substrate. Both mixed classes (Mix *Oxychloe andina* and mix *Zameioscirpus atacamensis*) are a combination of different plant functional types that will probably reflect lots of different spectral values. Also, *Deyeuxia eminens* is a tufted grass, distributed along the surface in groups, which spectral reflection will express some spectral noise from soil or water. Zhang et al. (2008) in their study about spectral characteristics of salt marsh plant communities, indicated that the proportion of substrate visible was the most important factor and significantly related to variation in reflectance along the first PCA axis, while soil water content, soil salinity and oxidation reduction potential indicated no significant relationships.

The combinations of plants that are present on those vegetation classes explain the high variance on the spectral reflectance. On the other hand, the less variation in the types *Oxychloe andina* (Oa), *Zameiscirpus atacamensis* (Za) and *Festuca chrysophylla* (Fch) can be explained because, the first two, are cushion plants, forming flat and compact patches of vegetation that would have more reflective surface per surface unit. Also these species are present dominating at almost 90% coverage. *Festuca chrysophylla* (Fch) is a tufted grass that should not reflect as much as cushion plants but different from *Deyeuxia eminens*, *Festuca chrysophylla* was found in very high densities in most of the wetlands, which explains the low variance.

One-way ANOVA analysis results on the Near Infra-Red band for *Oxychloe andina,* were not expected as the species has one of the highest plant densities per m^2 in the field and therefore it was expected to have the highest reflectance values compared to the other classes on NIR. Nevertheless, the species had the highest values of NDVI and SR, suggesting that the plant class is reflecting high values on the indices based on plants with a high percentage of coverage but not on their moist condition. The four species with highest reflectance values were found closer to the streams and pools. This implies that the four species next to the streams, *Deyeuxia deserticola* (Dde), *Deyeuxia velutina* (Dve), *Deschampsia caespitosa* (Dca), and *Deyeuxia eminens* (Dem), probably have higher water content in their membranes and mesophyll cells and therefore, will express a higher reflectance on NIR. On the opposite, plant types with the lowest values, that is, *Festuca chrysophylla* (Fch) and *Deyeuxia curvula* (Dcu), were distributed along the wetlands and with a dominant presence on the wetland borders, in the ecotone with the desert ecosystem. In NIR, healthy vegetation is normally characterized by high reflectance. For Altiplano wetlands, vegetation types with more spectral reflection in NIR would have bigger and moister cells, which considering the dependence on water of these plants, can be considered as a vigorous and healthier condition (MMA, 2011). Considering the grouping of vegetation types according to the high to low spectral response on band 4-NIR, it is possible to state then, that species *Deschampsia caespitosa* - *Deyeuxia deserticola* - *Deyeuxia velutina* are the healthiest vegetated parts of the wetlands, followed by the second group, mix of the genera *Oxychloe* and *Zameioscirpus*. The least healthy would be patches dominated by *D. curvula*, *F. chrysophylla* and *Oxychloe andina.*

According to Zhang et al. (2008) the main measurement affecting the spectral characteristic of vegetation appeared to be the percentage of vegetation cover and canopy height. In alpine wetlands there is no effect of canopy height and most of the spectral responses depend on percent of cover. For the case of this research, the grouping can also be explained by other factors that can affect vegetation spectral response such as plant architecture. Canopy architecture could affect the amount of reflectance per species. Spanglet et al. (1998) suggest that the trend in NIR reflectance levels correlates with leaf characteristics of *Scirpus*, *Nuphar* and *Carex*, depending on the vertical, horizontal and curve architecture of the species and on the thickness of the leaves. Considering that, *D. curvula* (Dcu) has very curved leaves in comparison to all the other *Deyeuxia* grasses, and could have lower reflectance, which also would allow more soil reflectance and therefore lower NIR values.

Despite the differences observed among vegetation classes on spectral reflectance and the mean values, Tukey's HSD test for selected variables showed that there was only one class significantly different from the others (*Deschampsia caespitosa* (Dca)). This is interesting given the clear differences observed on the graphs, but could also imply that the spatial scale is not appropriate or that there was not enough field sampling in order to statically discriminate vegetation classes. A good improvement for this analysis, is to look for differences among the three wetland types of wetlands and then map them across all sites. By doing that, some successional sequence analysis could have shown changes from pristine to degraded sites.

4.2.2. Which bands and indices are the most suitable to distinguish between vegetation classes?

The data reported in this study suggested that the bands and vegetation indices that are most effective for discriminating between plant communities of High altitude Andean wetlands are the bands Near Infrared-NIR and Blue, and the vegetation index WDRVI.

Considering that the structure of Altiplano wetland ecosystems is a combination of high-density plants with running waters and small pools (Ruthsatz, 1993; Otto et al., 1993), the selection of bands Blue and NIR by the discriminant model is correct. Band-4 NIR is particularly sensitive to vegetation because it measures vegetative reflectance properties related to the changes into red edge and internal vegetative structure. The selection of band 4-

NIR as the most important variable to discriminate vegetation types, state that most of the alpine wetland vegetation spectral response is mainly driven by spongy parenchyma mesophyll cells, which have a significant impact on the absorption and reflectance of NIR incident energy (Aronoff, S. 2005). The efficiency of this band on vegetation recognition is well documented and supports the results of this study.

The next variable selected by the GDA model was Band 1-Blue. This band is particularly sensitive to water features and has been used to measure water depths and differentiate rock and soil surfaces from vegetated features. Considering that Andean high altitude wetlands are patches of vegetation in a matrix of small ponds and streams surrounded by bare soil and rocks, the selection of Band 1 as the second most important for the discrimination of vegetation was also appropriate. In this band, vegetation types that had a higher reflectance values are those with low dense vegetation, mostly grasses, inside a saline crust matrix. This low plants density reflects more water or ground values on the spectral values. These vegetation classes also have the highest species diversity, which can be considered as the ecotone transitional zone in between the freshwater wetland systems and the dry-alpine desert one, and therefore they are located in the intermediate sections of the wetland transects. Finally, according to transect inventories recorded in the field, *Deyeuxia caespitosa* is mostly located next to shallow waters, streams or rocks, which would explain the high reflection on band 1.

In terms of vegetation indices, NDVI is not the only index that can help to classify vegetation. In between a group of related vegetation indices, the model chose the Wide Dynamic Range Vegetation Index (WDRVI). NDVI has been used to measure photosynthetic vegetation activity in High altitude wetlands of the Andes region, taking into account the low atmospheric effect due to high altitude and the low influence of soil background due to dense vegetation cover on the Andean wetlands (Otto et al., 2011) but might not be the most efficient vegetation index to measure these ecosystems. WDRVI is a variation of NDVI, where NIR is subtracted by Red and weighted by a 0.1 factor. The selection of this index is supported by the idea that WDRVI increases correlation with the vegetation fraction. This index enables a more robust characterization of dense vegetation types by enhancing the dynamic range of NDVI, using the same bands as NDVI but linearizing the relation by including a factor of 0.1-0.2 (Table 3.1). Gitelson (2003) found that WDRVI was more efficient in the characterization of vegetation biophysical properties on crops under high biomass situations. The same can be found in alpine wetland vegetation communities, where densities occur over 70% cover in most of the cases, being common to find 100% coverage on vegetation patches that are dominated by *Oxychloe andina*, *Zameioscirpus atacamensis*, *Deyeuxia deserticola* - *Deyeuxia velutina*.

The selection of this NDVI-related index exposed that the broadly used NDVI index might not be the best choice to identify Altiplano wetland vegetation. Vegetation structure is an essential variable to identify and differentiate vegetation assessed remotely. Highly dense vegetation types found in high altitude, Andean wetland vegetation types explain the effectiveness of WDRVI index that was developed to discriminate high density crops.

The resulting images may be useful for identifying a wetland's location to precisely defined water/plants border and types of vegetation on a more detailed scale than the free satellite images available on the market (LANDSAT), but spectral and spatial resolution of Geoeye-1 and IKONOS-2 images are still not sufficient for individual species classification. According to Adam et al. (2010) the use of hyperspectral images or spectrometers would satisfy the identification of plant communities on a species level.

At the beginning of the 90s the scientific community was publishing that it was impossible to map individual plant species using remote sensing (e.g., Price, 1994). However, the combined advances of technology capturing high-level spectral information, combined with a high resolution, it became possible to differentiate dominant species and/or community types (Ustin & Gamon, 2010). Spectra are measured by ground-based spectroradiometer sensors and in the last 20 years field spectrometry has been playing vital roles in characterizing the reflectance of vegetation types in situ (Adam et al., 2009) and the existence of spectral libraries is aiding this.

Using several spectral bands for vegetation identification like hyperspectral imagery or CASI (Compact airborne spectral imager) can be useful sources to detect and map the spatial heterogeneity of wetland vegetation because it gives us more detailed information with narrow spectral channels that can offer potential (Adam et al., 2010) but they also provide some confusion at the species level in the salt marshes (Zhang et al., 2008). Despite the agreement of the effective performance of hyperspectral data in discriminating species, the reflectance of several wetland species is highly correlated because of their similar biophysical and biochemical properties.

Some alternatives combining remotely sensed technologies have been developed. Klemas (2011) suggests that the combined use of hyperspectral and LIDAR information improved the accuracy of mapping salt marsh vegetation and the identification of some species. Belluco et al. (2006) proposed that overall balance of vegetation mapping comparing hyperspectral and multispectral sensors is obtained when adopting a higher spatial resolution with a small number of bands (4 bands) and that classification by hyperspectral data have relatively poorer performances with respect to with high spatial resolution multispectral sensors, particularly IKONOS. The identification of entire species assemblages as opposed to a species, may be more sensitive indicators of ecological stress (Spanglet, 1998) and therefore be more useful for wetland management.

Spatial resolution of 0.65 and 1 m are good enough to discriminate between plant groups as most of the species are distributed along the wetland in patches of vegetation, either as very dense mono cultures of cushion species or mixed patches of several grasses with sizes that can vary from 0.5-1 meter for the cushion plants to several meters of extension for the mixed grasses and despite the shortcomings, Geoeye-1 and IKONOS-2 satellite images are suitable for wetland discrimination at a plant community level.

Chapter 4: CONCLUSIONS AND RECOMMENDATIONS

4.1. Summary

The purpose of this research was to discriminate Altiplano wetland plant communities and their relation with environmental variables. To address that, two different approaches were used: a multivariate analysis was performed in order to define plant communities and to identify environmental variables that were most strongly associated with each plant group. The second approach considered the analysis of spectral characteristics from high resolution satellite images Geoeye-1 and IKONOS-2 to study the most suitable bands and vegetation indices for wetland plant community discrimination.

I found that Tarapacá region wetlands had a higher vascular plant richness, with 53 species recorded, compared to Atacama wetlands, where only 25 species were found. Most of the species belong to the plant families Poaceae, Cyperaceae and Juncaceae. Bryophytes were present in small proportions in some wetlands in the Tarapacá region, while in Atacama region wetlands, bryophytes where found in half of the sites measured. Plant composition in Atacama region wetland transects was very similar within wetlands with no more than 4 main dominant species (those that have the highest percent of cover), while Tarapacá sites had more than 10 dominant species. Tarapacá region wetland sites had more aquatic plant species recorded and the principal channels from the wetlands were deeper and wider than in Atacama region wetlands. Plant species abundance is more evenly distributed in Tarapacá region wetlands than in Atacama region. Wetland plant communities' abundance in Tarapacá region sites were strongly influenced by the patches of bare land, presence of organic matter and number of channels while plant abundance in Atacama region sites were more strongly associated by the width of the channels. The Peatland wetland type had the lowest levels of human intervention and grazing in both regions, while Wet meadows showed mostly medium levels and Tall grasslands high levels.

The results of the satellite image analysis concluded that vegetation classes did express different spectral behaviors using Geoeye-1 and IKONOS-2 satellites images. The mixed classes expressed more variation while vegetation types dominated by *O. andina*, *Z. atacamensis* and *F. chrysophylla* had the lowest variation on spectral values. The bands blue and NIR, and WDRVI vegetation Index were the most successful for discriminating differences between plant types.

The two methods can help potential users to discriminate between vegetation types on Altiplano wetlands, however, the type and detail of information is different. By using multivariate analysis we can determine which plant assemblages can be found on different wetland types and delineate plant communities. This information is extremely useful for reclamation initiatives and it is necessary to reproduce a wetland by recreating the original plant communities. The importance of identifying vegetation types for management purposes is that according to vegetation dynamics on Altiplano wetlands, they will change from one wetland type to another if they are going into a degrading status. Knowing original plant assemblages and their distribution will allows us to stablish the communities that can recreate the original ecological functions. Part of understanding wetland ecological functions are to address the relation between plants and the environmental variables. On one hand, through multivariate analysis plant assemblages are associated with the abiotic factors that more strongly influence plant abundance. This is extremely important for understanding the success of plant establishment and survival, particularly in Altiplano wetland ecosystems, as they are very dynamic systems, which have both terrestrial and aquatic ecosystems characteristics.

On the other hand, wetlands are complex systems that cannot be considered as isolated entities even though they appear as independent units in the middle of the desert. They are connected by superficial channels, streams and lakes from Andean glaciers to the valleys or by underground flows when those streams disappear in the middle of the desert. This landscape perspective must be considered when assessing wetlands and therefore mapping them. High spatial resolution satellite images from Geoeye-1 and IKONOS-2 satisfy the needs to identify wetland plant communities and assess Altiplano wetlands. Their spectral and spatial resolution is suitable for discriminating between plant groups at a community level, which is an excellent approximation for these wetlands. The results of this study illustrates that a combination of ecological and remote sensing techniques is an excellent approach and necessary for the accurate assessment of Altiplano wetland communities.

4.2.Research improvement and future directions

Most of the research published on ecological analysis of high altitude wetlands in the Andes are from the northern Andes in Venezuela, Colombia and Ecuador in the ecosystem called Páramo, which is quite different as it receives abundant rainfall from the Tropics. The drier Central Andes Puna ecosystems had received much less attention and most of the publications are from Bolivia, Perú and Argentina (Adler & Morales, 1999; Halloy et al., 2008; Ruthsatz, 2012). There is little published scientific research in the Chilean Puna ecosystems and most of those are floristic descriptions that do not tell much about possible interactions with the environment (Squeo et al., 1993; Teiller, 1998; Rundel & Palma, 2000; Teiller & Becerra, 2003; Squeo et al., 2006). More information has been developed by local agencies, NGOs and private and Governmental institutions regarding Altiplano wetlands assessment in Chile, but none of them study environmental variables with multivariate analysis. Using similar methods as in this research, Cooper et al. (2010) in his study of Alpine peatland ecosystem in Perú concluded that wetland plant diversity was supported by geochemical gradients, identifying water chemistry (pH and HCO_3) and water table depths, soil temperature and peat thickness as the main environmental variables associated with plant distribution in a CCA analysis. Squeo et al. (1993) explained that for high mountain vegetation in the Andes desert of Chile, soils showed a great variation in chemical and drainage characteristics which will explain the distribution of plant species on the general scale (altitudinal vegetation belts). In addition, other environmental variables, like slope, aspect and substrate may affect plant distribution.

More recent studies in southern high-altitude wetlands of the Andes, which share some floristic components with Tarapacá and Atacama region wetlands, suggested that water chemistry factors, particularly pH and dissolved Cu, may reduce species abundance and diversity (Ginocchio et al., 2008). Also Squeo et al. (2006) proposed that water pH and nutrient availability (N, P, K, Ca and Mg) and toxic elements (As, B, Fe, and Al) was one of the four factors that interacts with vegetation for the Altiplano peatlands among other abiotic factors, like grazing and human impact, measured in this research. Similar results had been described for high altitude wetlands in Argentina, where Alder and Morales (1999) found that the main environmental factors affecting Andean grasslands were aspect, soil type and season of grazing (based on precipitation). Some of these environmental variables were also found in Northern hemisphere wetlands, where plant communities were determined by a thermal and moisture gradient, geographic position and soil condition in the Ngari basin in

Tibet (Chang and Gauch, 1986); by water table depth and peat moisture in bogs and peatlands (ter Braak & Wiertz, 1994; Welztin et al., 2000; Haapalehto at al., 2010; Palanisamy & Chui, 2013); by microtopography (hummock/hollow to lawn/carpet wetlands) for bogs in Québec (Poulin et al., 1999) and by salinity gradients (Mullan et al., 2004).

Differently from North American or European high altitude environments, mountain ecosystems on the Andes occurs in very high elevation, comparable to the Himalayas, and Altiplano wetlands occur from 3,000 to 5,000 meters above sea level. Such elevations makes all the logistics associated with sampling Altiplano wetlands very difficult. It is not only the harsh environmental conditions associated with mountain ecosystems that makes the sampling physically demanding (low temperatures, intense solar radiation, rain, snow, winds, altitude sickness, etc.), but also the lack of roads and human development makes any research in these environments very costly and time consuming. Also the short period of the year where vegetation is exposed without the snow pack, requires a lot of field work planning prior to the start of any sampling. To tackle this, remote sensing techniques are an excellent way to assess vegetation systems in remote areas, however, because more accurate new satellites technologies are coming out constantly ground truthing is necessary in order to test them and build spectral libraries that could standardize the information between different satellites.

Altiplano wetlands have a very complex configuration of different vegetation patches that are distributed along water-dependent gradients in between bare land, rocks, streams, pools and shallow waters. Wetland transect results were shown to be an efficient way to assess that complexity and vegetation variation across the wetland, and was an appropriate method for this study. However, because of this spatial variation, more transects would have been better in order to improve the field-based information and assess variation among wetlands. The study was focused on covering a range of wetlands across an area, which could provide a good representation of the wetland region as a first approach, but for a second step in this research I strongly recommend extracting more information on each wetland and assess possible variation in plant communities from the upper part of the wetland to the lower end.

Also, because most of the vegetation on the wetlands are patches of a group of plants and not pure patches of one dominant species, more sampling on those pure patches of vegetation in different parts of the wetland would have been useful in order to calibrate the satellite images' spectral values. The methods used in this research were sufficient to discriminate satellite image's spectral responses of different plant communities and address which of the environmental variables measured were more related with plant distribution. Nevertheless, more field data on the one-species dominant plant patches would help managers to map wetlands and thereby extrapolate transect information into a wetland scale that could reflect more accurately the wetland as an ecological entity. The combination of flora plots, description of dominant species on vegetation patches and transects is a very detailed means to assess wetland vegetation, and is appropriate for these wetlands considering their complexity. This method, combined with a more detailed sampling isolating one-species vegetation types would collect all the information needed for a complete assessment of Altiplano wetlands.

Wetlands assessment and management needs to be understood as a dynamic, complex system. Altiplano wetlands sustain their ecological function based on the type of plants that exist and their properties to retain clean water, develop organic matter and soil, feed animals and provide refuge for species, including humans. Plants depend on water availability, which is driven by several factors that interact above and below surface level. An appropriate assessment of wetlands and their functions as part of a much bigger system connected in the landscape, is not yet perceived by all the sectors. Wetland ecosystems cannot be studied by one component at a time and more research that relates plant dynamics with water table fluctuations is needed. Water sources are the critical element for these ecosystems and for sustaining development on the Altiplano arid zone. Despite this, there is little knowledge about groundwater recharge functions and storage on Altiplano wetlands and fossil versus modern water recharge in the basins. Messerli et al. (1997) studied water availability in the Altiplano Andean Desert and concluded that modern hyper-arid climatic conditions have little or no effect on the recharge of water resources in the Atacama area. Modern recharge, in very limited areas, is restricted to small high elevation catchments in the Altiplano. Thus, modern economic development depends largely on these fossil water reserves which are barely renewable or even non-renewable. Scientific knowledge in this field is far from what it is needed and more studies related to groundwater recharge functions in the Altiplano basin and research that can support the ecological connections between vegetated areas and groundwater sources is needed in order to clarify and explain the importance of protecting the Altiplano area.

4.3.Policy makers and managers recommendations

Discussion of conservation programs and protected areas in the Andes are usually focused on forested ecosystems and their huge variety, ranging from tropical forests to sub-Antarctic temperate ones. However, the Andes Cordillera has a vast central, semi-arid area, where unique ecosystems occur. High altitude wetlands on the Altiplano plateau of the Andes are extremely sensitive to climate change and human disturbances (Squeo et al., 2006; Ahumada

& Faúndez, 2009). Chilean Altiplano wetlands occur in the driest part of the ecological range where the wetlands appears as a green oasis surrounded by the desert. They are extremely rare and a very small number of them are located in protected areas on the territory. Even though their protection is regulated by international strategies like the Ramsar Convention, the application of the norms for management lacks a clear convergence on the criteria regarding management and impact assessment regulation, such that they do not guarantee their protection. Regulations that address the conservation of water resources as a whole have been mainly aimed to develop economic activities related to the exploitation of a natural resource (Möller & Muñoz-Pedreros, 2014). It is evident, however, that the key element for support of life in this zone is water availability. Therefore, any discussion about protecting areas must acknowledge that the water resource is not only for flora and fauna, but also it has been the basis of human activities, in the past and present.

Protecting the wetlands as an ecosystem in the first place is the main purpose for conservation strategies. Nevertheless, for management purposes, an important reason for maintaining the ecosystems as pristine as possible, is that as an oasis they have all the genetic material that is needed to restore new wetlands. Restoration of vegetation systems, such as wetlands, can be very challenging as Altiplano wetland's regeneration rates are very slow because of the harsh environmental conditions of high altitude and desert environments (Squeo et al., 2006). We have to consider their complexity, where plants are organized along environmental gradients, depending on humidity and combining vascular terrestrial plants, bryophytes and aquatic plants.

The concept of protecting the watershed because they are water catchments is not considered in the Chilean legislation yet and the conflict between natural resources management and economic development is a fact in this region that has been growing rapidly during recent years. In Chile, the protection of water sources has never been a priority in conservation strategies. Government and policy makers are aware of the overuse of water in the Chilean Altiplano, but there is a challenge for them to focus the discussion more on a) the limitation of water sources, b) the potential danger to the regional economy and development because of habitat destruction, c) develop long-term solutions in protection programs and d) to promote an open discussion across all levels between researchers, managers and policy makers where they can understand each other and share information.

Finally, restoration initiatives should be seriously taken into account under the decreasing rain scenario and the increasing demand for water resources on the Altiplano basin by the mining industry. Conservation policies, including restoration plans, for Altiplano wetlands are urgently needed. Water availability is becoming progressively more critical. If the highest priority is not given to the protection of water sources, especially in the most arid ecosystem in the world, natural habitats will be under threat and not only will natural patrimony be in danger but also agricultural, tourism and mining will be at risk. Altiplano ecosystems depend on past and present water recharge conditions. This implies that any changes regarding water usage on the basin, must be carefully assessed in order to prevent damage and a watershed approach is mandatory when the boundaries from superficial, underground, upper and lower lands are all connected through these unique terrestrial-aquatic ecotone ecosystems, the Altiplano wetlands.

5. References

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6. Appendix

Table 6. 1. Diversity indices of species per Region extracted from wetlands transects plants abundance matrix. Richness (S) is the regional average of the total number of species per wetland. Evenness (E) reflects how equal the community is; an E≥1 implies a minimum variation within the communities. Shannon diversity index (H) reflects how many types and how evenly distributed individuals are among the types; in a bigger H, types are more equally abundant (more homogeneous distribution). Simpson diversity index measures the probability that two species taken at random, represent the same type; with a lower D the dataset increases its diversity. Skewness and Kurtosis are properties of the normality of the curve.

Region	Richness (S)	Evenness (E)	Shannon (H)	Simpson (D)	Skewness	Kurtosis
Tarapacá	11.4 [8-16]	0.78	1.88	0.79	3.59	14.31
Atacama	7.2 [5-11]	0.68	1.32	0.67	4.15	18.00

Table 6. 2. Environmental variables Axis score table of the 15 strongest explanatory variables on Principal Component Analysis (PCA). Type of variable quantitavive (Q) or categorical (C).

N	NAME	VAR ID	AX1	AX2	Environmental Variable	Description	Type of Variable
1	DO	22	-0.9538	-0.2497	Dissolved oxygen	Dissolved Oxygen (mg/L)	Q
2	TEMP	23	-0.8833	0.1895	Temperature	Temperature (Celsius degree)	Q
3	WID	20	-0.8249	-0.1212	Principal channel width	Width of Channel (cm)	Q
4	SHW	10	0.1518	-0.8143	Shape of wetland	3 shape forms	C
5	SHA	12	0.1185	-0.7775	Shallow water	% Wetland	Q
6	SAL	11	0.4157	-0.6752	Salty patches	% Wetland	Q
7	Str_ m	8	0.1221	-0.675	Stream with macrophytes	Proportion of Transect	Q
8	Chnl	2	0.6533	-0.0066	Channel	Proportion of Transect	Q
9	PCH	15	0.5853	-0.0237	Principal channels	Number	Q
10	Barr	1	-0.1999	0.5269	Barren land	Percentage of Transect	Q
11	Sha_ w	6	-0.009	-0.492	Shallow water	Percentage of Transect	Q
12	WETS L	14	0.4991	-0.3081	Wetland slope	% Wetland	C
13	WILD	29	0.4788	-0.0036	Wildlife footprints	Presence/Absence	C
14	DEPT	21	-0.3321	0.4301	Principal channel dept	Depth of Channel	Q
15	ANTR	27	-0.4156	0.1052	Anthropogenic Intervention	Anthropogenic intervention	C

Table 6. 3. Environmental variables Lambda score table of the 15 strongest explanatory variables from Automatic Forward Selection method. Type of variable quantitavive (Q) or categorical (C).

N	NAME	VAR ID	LAMBDA	Environmental Variable	Description	Type of Variable
1	DO	22	0.51	Dissolved oxygen	Dissolved Oxygen	Q
2	OM	4	0.36	Organic matter	Proportion of Transect	Q
3	WID	20	0.36	Principal channel width	Width of Channel (cm)	Q
4	PCH	15	0.35	Principal channels	Number	Q
5	Rck	5	0.33	Rock cover	Proportion of Transect	Q
6	ANTR	27	0.33	Anthropogenic Intervention	Anthropogenic intervention	C
7	MACRO	25	0.32	Macrophytes presence	Presence/Absence	C
8	Barr	1	0.30	Barren land	Percent of Transect	Q
9	HE	17	0.26	Heterogeneity	Heterogeneity of the wetlands plants communities	C
10	WILD	29	0.26	Wildlife footprints	Presence/Absence	C
11	Sha_w	6	0.25	Shallow water	Percent of Transect	Q
12	BORD	18	0.25	Wetland border shape	Regular/Irregular	C
13	ALTITUDE	9	0.25	Meters above sea level	-	Q
14	HILLSL	13	0.25	Hill slope interval	3 Interval within 0-100%	C
15	Chnl	2	0.24	Channel	Proportion of Transect	Q

Table 6. 4. Environmental variables weight score table of the 15 strongest explanatory variables from Manual Forward Selection method. Type of variable quantitavive (Q) or categorical (C). The selected 15 environmental variables explains 95.94% of the total variation of the data.

N	NAME	VAR ID	Weight (mean)	Environmental Variable	Description	Type of Variable
1	DO	22	84.4	Dissolved oxygen	Dissolved Oxygen	Q
2	WID	20	28.1	Principal channel width	Width of Channel (cm)	Q
3	SHA	12	19.2	Shallow water	% Wetland	Q
4	TEMP	23	10.9	Temperature	Temperature (Celsius degree)	Q
5	Sha-w	6	8.9	Shallow water	Percent of Transect	Q
6	Barr	1	6.5	Barren land	Percent of Transect	Q
7	Str_m	8	4.2	Stream with macrophytes	Proportion of Transect	Q
8	CATT	28	2.5	Cattle Intervention	Presence/Absence	C
9	Chnl	2	1.2	Channel	Proportion of Transect	Q
10	D_pl	3	1.9	Dead Plants	Proportion of Transect	Q
11	OM	4	1.5	Organic matter	Proportion of Transect	Q
12	Rck	5	1.9	Rock cover	Proportion of Transect	Q
13	STR	16	1.9	Stream cover	Proportion of Transect	Q
14	HE	17	0.7	Heterogeneity	Heterogeneity of the wetland	C

Table 6. 4. Environmental variables weight score table of the 15 strongest explanatory variables from Manual Forward Selection method. Type of variable quantitavive (Q) or categorical (C). The selected 15 environmental variables explains 95.94% of the total variation of the data.

N	NAME	VAR ID	Weight (mean)	Environmental Variable	Description	Type of Variable
					plant communities	
15	MACRO	25	0.7	Macrophytes presence	Presence/Absence	C

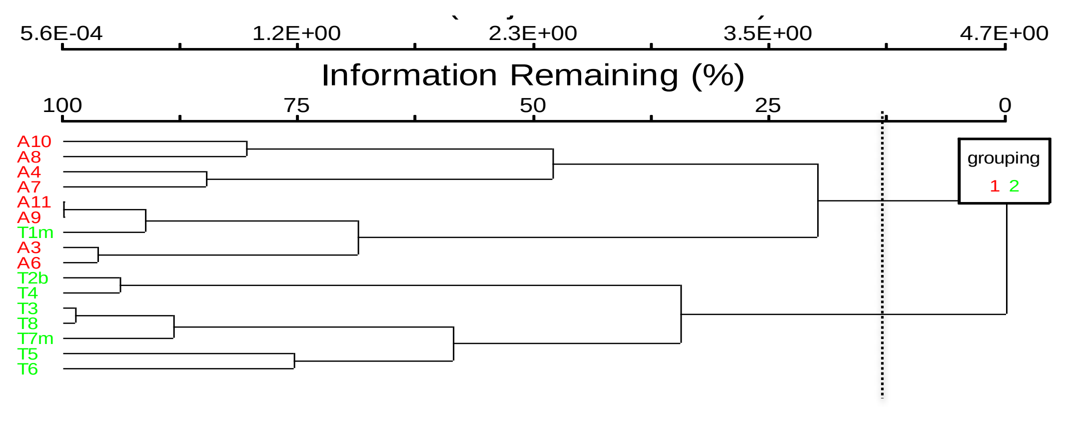

Figure 6. 1. Hierarchical Cluster Analysis dendrogram of the 16 wetlands transects. The clustering of two groups at a 12.5% of similarity threshold remaining information (dotted line) is indicating the separation of the two regions.

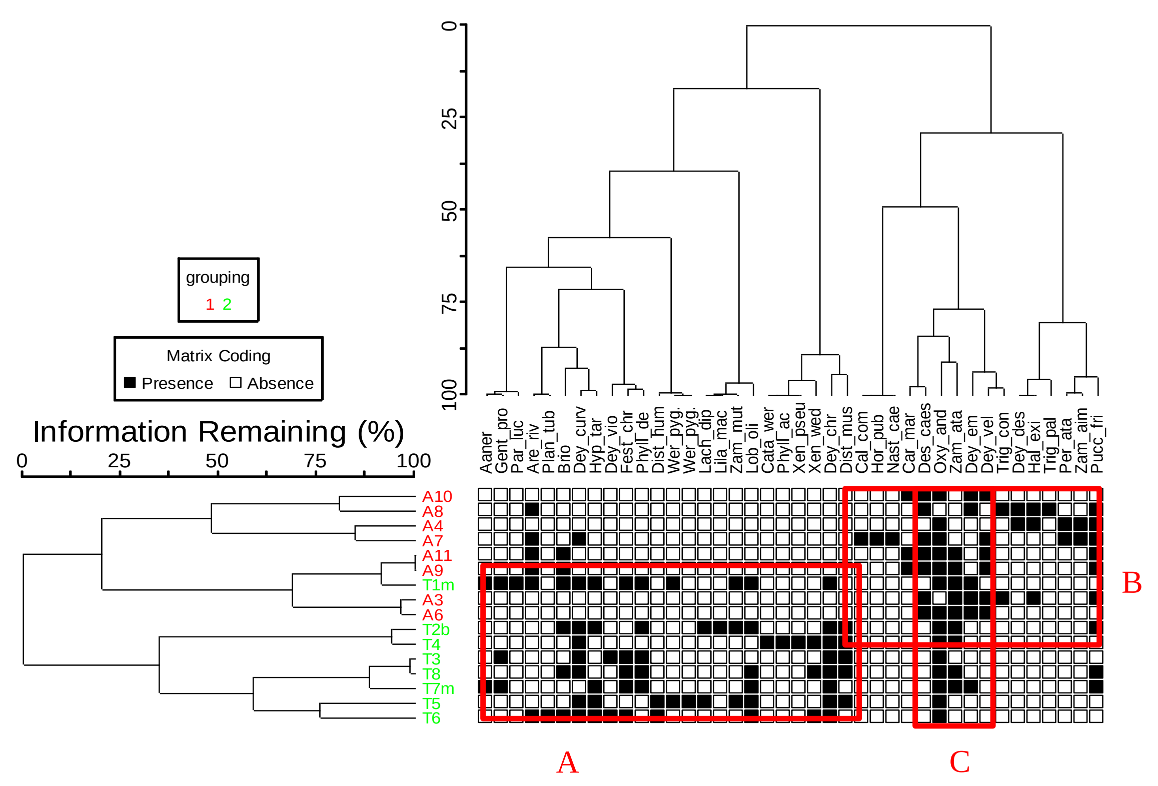

Figure 6. 2. Two-way Hierarchical Cluster Analysis Dendrogram. Rows correspond to the 16 different wetlands, ordered by clustering them into Atacama sites (A) and Tarapacá sites (T), using all the plant sample information. Columns correspond to all the plants species of the study area, defined with the first letters of each genera and species. Species are clustered according to the participation on transects. The matrix box corresponds to the presence/absence of each species on the wetlands and it is a good visualization of the distribution of the species on each region.

Table 6. 5. Final sorted species data table, produced by TWINSPAN. Identifies three levels of division for wetlands and five for the species. On the first level of horizontal division (A) it is possible to identify the two regions, with plots from 1 – 8 for the Atacama region and 9 to 16 for Tarapacá sites. On the table, it is also possible to see the group of species associated with each region. Table 6.6 shows which wetland corresponds to each PCOrd ID code on the TWINSPAN. In each region wetlands are divided in three subgroups. Tarapacá: 3 subgroups - Wetlands: T2b - T4- T5 / T1m-T6 / T3 - T7m – T8. Atacama 3 subgroups - Wetlands: A10-A11-A6-A9 / A3 / A4-A7-A8. On the other hand, plants are grouped in 5 division classes, where it is possible to identify 5 plants communities for Tarapacá wetlands and 4 for Atacama wetlands:

```
TWO-WAY ORDERED TABLE

                   111 1111
   Tarapa                              Atacama

                   0239415612583467

   6  Cata_wer  -2--------------  00000
  21  Lach_dip  4-1-------------  00000
  22  Lila_mac  2---------------  00000
  28  Phyll_ac  -2--------------  00000
  35  Wer_pyg.  --5-------------  00000
  36  Xen_pseu  -1--------------  00000
  40  Zam_mut   3-11------------  00001
   9  Dey_chr   23321122--------  0001
  14  Dist_mus  551--4-2--------  0001
  15  Dist_hum  --1-1-----------  001
  23  Lob_oli   3-111-12--------  001
  34  Wer_pyg.  --11------------  001
  37  Xen_wed   -2--2--1--------  001
   3  Brio      2--22--3-1-1----  010
  10  Dey_curv  124443-3------1-  010
  20  Hyp_tar   2-233-1---------  010
  29  Phyll_de  3--1-422--------  0110
   1  Aaner     ---3--2---------  01110
  17  Gent_pro  ---2-11---------  01110
  26  Par_luc   ---1------------  01110
  30  Plan_tub  ----1-----------  01110
   8  Dey_vio   ----12----------  01111
  16  Fest_chr  ---23434--------  01111
   2  Are_riv   ---13----1-1--11  10
  25  Oxy_and   113515555535-35-  10
  31  Pucc_fri  1-----42-1-11412  10
  12  Dey_em    ---1--5-3-2-4--3  1100
  38  Zam_ata   34-4--11-5555---  1100
   5  Car_mar   --------31-1----  1101
   7  Des_caes  --------53433-25  1101
  13  Dey_vel   --------21112-1-  1101
  32  Trig_con  ------------2--1  1101
  18  Hal_exi   ------------13-3  1110
   4  Cal_com   --------------1-  1111
  11  Dey_des   -------------4-4  1111
  19  Hor_pub   --------------4-  1111
  24  Nast_cae  --------------1-  1111
  27  Per_ata   -------------21-  1111
  33  Trig_pal  ---------------4  1111
  39  Zam_aim   -------------55-  1111
                0000000011111111
                0001111100000111
                   0011100001
```

Table 6. 6. Wetlands name to PCOrd ID codes in matrix 1B.

PC-Ord ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wetland name	A10	A11	A3	A4	A6	A7	A8	A9	T1m	T2b	T3	T4	T5	T6	T7m	T8

Table 6. 7. Species list of Study Area and plant code ID used for ordination analysis.

Plant ID	**Species**	**Tarapacá**	**Atacama**
1	*Aa nervosa (Kraenzl.) Schltr.*	x	
2	*Adesmia aff. hystrix*	x	
3	*alga sp.*	x	x
4	*Arenaria rivularis Phil.*	x	x
5	*Azolla filiculoides Lam.*	x	
6	*Azorella cryptantha (Clos) Reiche*		x
7	*Baccharis tola Phil. ssp. altiplanicola F.H. Hellwig*	x	
8	*Bryophyta sp.*	x	x
9	*Caiophora rosulata (Wedd.) Urb. & Gilg rosulata*	x	
10	*Calandrinia compacta Barnéoud*		x
11	*Calceolaria pinifolia Cav.*		x
12	*Carex maritima Gunnerus*	x	x
13	*Catabrosa werdermannii (Pilg.) Nicora & Rúgolo*	x	
14	*Deschampsia caespitosa (L.) P. Beauv. var. caespitosa*		x
15	*Deschampsia sp.*		x
16	*Deyeuxia aff. violacea*	x	
17	*Deyeuxia chrysantha J. Presl. var. phalaroides (Wedd.) Villav.*	x	
18	*Deyeuxia curvula Wedd.*	x	
19	*Deyeuxia deserticola Phil.*		x
20	*Deyeuxia eminens J. Presl*	x	x
21	*Deyeuxia hackelii (Lillo) Parodi*	x	
22	*Deyeuxia sp.*	x	x
23	*Deyeuxia velutina Nees & Meyen*		x
24	*Distichia muscoides Nees & Meyen*	x	
25	*Distichlis humilis Phil.*	x	
26	*Fabiana squamata Phil.*	x	
27	*Festuca chrysophylla Phil.*	x	
28	*Festuca deserticola Phil.*	x	
29	*Festuca ortophylla Pilg.*	x	
30	*Gentiana prostrata Haenke*	x	
31	*Halerpestes exilis (Phil.) Tamura (sin= Ranunculus exilis Phil.)*		x
32	*Hordeum pubiflorum Hook. f. ssp. halophilum (Griseb.) Baden & Bothmer*		x
33	*Hypochaeris eremophila Cabrera*	x	
34	*Hypochaeris taraxacoides (Walp.) Benth. & Hook. f.*	x	
35	*Lachemilla diplophylla (Diels) Rothm.*	x	
36	*Lachemilla pinnata*	x	
37	*Lemna minor*	x	
38	*Lilaea scilloides (Poir.) Hauman*	x	
39	*Lilaeopsis macloviana (Gand.) A.W. Hill*	x	
40	*Lobelia oligophylla (Wedd.) Lammers*	x	
41	*Mimulus glabratus Kunth*	x	
42	*Myriophyllum quitense Kunth*	x	x
43	*Nastanthus caespitosus (Phil.) Reiche*		x
44	*Oxychloe andina Phil.*	x	x

Table 6. 7. Species list of Study Area and plant code ID used for ordination analysis.

Plant ID	Species	Tarapacá	Atacama
45	*Oxychloe sp.*		x
46	*Pappostipa frigida (Phil.) Romasch.*		x
47	*Parastrephia lucida (Meyen) Cabrera*	x	
48	*Parastrephia quadrangularis (Meyen) Cabrera*	x	
49	*Perezia atacamensis (Phil.) Reiche*		x
50	*Phylloscirpus acaulis (Phil.) Goetgh. & D.A. Simpson*	x	
51	*Phylloscirpus deserticola (Phil.) Dhooge & Goetgh.*	x	
52	*Plantago tubulosa Decne.*	x	
53	*Polylepis tarapacana Phil.*	x	
54	*Puccinellia frigida (Phil.) I.M. Johnst.*	x	x
55	*Pycnophyllum molle J. Remy*	x	
56	*Ranunculus aff. uniflorus*	x	
57	*Ranunculus sp.*	x	x
58	*Senecio nutans Sch. Bip.*	x	
59	*Senecio sp.*	x	
60	*Stuckenia filiformis (Pers.) Boehm. ssp. alpina (Blytt) R.R. Haynes, Les & M. Král*		x
61	*Stuckenia striata (Ruiz & Pav.) Holub*		
62	*Triglochin concinna Burtt Davy*		
63	*Triglochin palustris L.*		
64	*Werneria pygmaea Gillies ex Hook. & Arn. var. apiculata (Sch. Bip.) Wedd.*	x	
65	*Werneria pygmaea Gillies ex Hook. & Arn. var. pygmaea*	x	
66	*Werneria sp.*	x	
67	*Xenophyllum pseudodigitatum (Rockh.) V.A. Funk*	x	
68	*Xenophyllum weddellii (Phil.) V.A. Funk*	x	
69	*Zameioscirpus atacamensis (Phil.) Dhooge & Goetgh.*	x	x
70	*Zameioscirpus gaimardioides (E. Desv.) Dhooge & Goetgh.*		
71	*Zameioscirpus muticus Dhooge & Goetgh.*	x	

Table 6. 8. PCA Correlations applied to bands and Vegetation Indices

	b1_B	**b2_G**	**b3_R**	**b4_NIR**	**SR**	**NDVI**	**EVI**	**CLIG**	**WDRVI**	**CLVI**	**Green NDVI**
b1_B	1.00	0.92	0.94	0.22	-0.48	-0.70	0.25	-0.16	-0.60	-0.10	-0.59
b2_G	0.92	1.00	0.94	0.16	-0.58	-0.78	0.15	-0.28	-0.71	-0.19	-0.76
b3_R	0.94	0.94	1.00	0.27	-0.57	-0.78	0.16	-0.19	-0.70	-0.12	-0.61
b4_NIR	0.22	0.16	0.27	1.00	0.21	0.29	-0.01	0.14	0.28	0.10	0.44
SR	-0.48	-0.58	-0.57	0.21	1.00	0.78	-0.04	0.30	0.94	0.20	0.72
NDVI	-0.70	-0.78	-0.78	0.29	0.78	1.00	-0.13	0.27	0.93	0.17	0.90
EVI	0.25	0.15	0.16	-0.01	-0.04	-0.13	1.00	-0.01	-0.07	-0.01	-0.12
CLIG	-0.16	-0.28	-0.19	0.14	0.30	0.27	-0.01	1.00	0.33	0.98	0.35
WDRVI	-0.60	-0.71	-0.70	0.28	0.94	0.93	-0.07	0.33	1.00	0.22	0.86
CLVI	-0.10	-0.19	-0.12	0.10	0.20	0.17	-0.01	0.98	0.22	1.00	0.24
Green NDVI	-0.59	-0.76	-0.61	0.44	0.72	0.90	-0.12	0.35	0.86	0.24	1.00

Table 6. 9. Multivariate Test of Significance (Wilks) to Selected variables after PCA

	Test	Value	F	Effect df	Error df	p
Intercept	Wilks	0.12	23.9	10	50	0.0
b1_B	Wilks	0.5	4.4	10	50	0.08
b4_NIR	Wilks	0.6	3.5	10	50	0.001
SR	Wilks	1.0		0		
NDVI	Wilks	1.0		0		
CLIG	Wilks	1.0		0		
WDRVI	Wilks	0.6	2.3	10	50	0.03
CLVI	Wilks	1.0		0		

Table 6. 10. Forward stepwise selection applied only to the bands

	Steps		Degr. of Freedom	F to remove	P to remove	F to enter	P to enter	Effect status
ATMC_b1_B	Step Number	1	10			5.454481	0.000017	Entered
ATMC_b2_G			10			2.995241	0.004682	Out
ATMC_b3_R			10			3.955322	0.000479	Out
ATMC_b4_NIR			10			3.748208	0.000777	Out
ATMC_b1_B	Step Number	2	10	5.454481	0.000017			In
ATMC_b2_G			10			1.223651	0.298871	Out
ATMC_b3_R			10			1.310192	0.250442	Out
ATMC_b4_NIR			10			3.270918	0.002478	Entered
ATMC_b1_B	Step Number	3	10	4.867112	0.000065			In
ATMC_b4_NIR			10	3.270918	0.002478			In
ATMC_b3_R			10			1.544485	0.151714	Out
ATMC_b2_G			10			1.136308	0.355244	Out

Table 6. 11. General Discriminant analysis (GDA) classification matrix for selected variables after PCA.

Vegetation types	p	Percent Correct	Oa	mix Oa	Salt	Dcu	Fch	mix 13	Za	Dem	Dde	Dve	Dca
Oa	0.06	50.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mix Oa	0.33	85.7	1.0	18.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0
Salt	0.05	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
Dcu	0.48	0.0	0.0	2.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Fch	0.08	40.0	1.0	2.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
mix 13	0.11	0.0	0.0	4.0	1.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0
Za	0.08	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Dem	0.06	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dde	0.05	50.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0
Dve	0.05	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Dca	0.08	60.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Total		42.9	4.0	41.0	1.0	0.0	5.0	0.0	0.0	0.0	6.0	1.0	5.0

Table 6. 12. General Discriminant analysis (GDA) classification matrix for spectral bands.

Vegetation types	p	Percent Correct	Oa	mix Oa	Salt	Dcu	Fch	mix 13	Za	Dem	Dde	Dve	Dca
Oa	0.06	0.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mix Oa	0.33	95.2	1.0	18.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0,00	0.0
Salt	0.05	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
Dcu	0.05	0.0	0.0	2.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Fch	0.07	20.0	1.0	2.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
mix 13	0.11	0.0	0.0	4.0	10.	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0
Za	0.08	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Dem	0.04	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dde	0.06	50.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0
Dve	0.04	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Dca	0.08	60.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Total		41.3	4.0	41.0	1.0	0.0	5.0	0.0	0.0	0.0	6.0	1.0	5.0