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Salt intrusion in tidal wetlands: European willow species tolerate oligohaline conditions

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A B S T R A C T

Tidal wetlands experience salt intrusion due to the effects of climate change. This study clarifies that the European flood plain willows species *Salix alba* and *Salix viminalis* tolerate oligohaline conditions. *Salix alba* L. and *Salix viminalis* L. are distributed on flood plains up to transitional waters of the oligohaline to the mesohaline estuarine stretch in temperate climates. They experience spatial and temporal variations in flooding and salinity. In the past, willows dominated the vegetation above the mean high water line, attenuated waves and contributed to sedimentation. In recent centuries, human utilization reduced willow stands. Today, the Elbe estuary – a model system for an estuary in temperate zones – exhibits increasing flooding and salinity due to man-induced effects and climatic changes. Willows were described as having no salinity tolerance. In contrast, our soil water salinity measurements at willows in tidal wetlands prove that mature *Salix* individuals tolerate oligohaline conditions. To assess immature plant salinity tolerance, we conducted a hydroponic greenhouse experiment. Vegetative propagules originating from a freshwater and an oligohaline site were treated in four salinities. Related to growth rates and biomass production, we found interspecific similarities and a salinity tolerance up to salinity 2. Vitality and chlorophyll fluorescence indicated an acclimation of *Salix viminalis* to oligohaline conditions. We conclude, that the survival of *S. alba* and *S. viminalis* and the restoration of willow stands in estuarine flood plains – with regard to wave attenuation and sedimentation – might be possible, despite increasing salinity in times of climate change.

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1. Introduction

Estuaries form a major transition zone between land and sea with steep gradients in energy and physicochemical properties (Jennerjahn and Mitchell, 2013). Variable and fluctuating salinity is the principal stressor estuarine organisms have to cope with (Odum, 1988; Mc Lusky and Elliott, 2004). Estuarine flood plains are affected by disturbance, such as floods and storms (Mitsch and Gosselink, 2000) and are characterized by two major environmental gradients: the salinity gradient and the flooding gradient. Abiotic stress and disturbance become more severe with increasing salinity and flooding from high to low elevation in estuarine flood plains (Engels and Jensen (2009). Estuarine organisms have to cope with natural disturbances and with effects of increasing pressures due to climate change, human activities and extreme events (Jennerjahn and Mitchell, 2013). In subtropical and tropical climate, mangroves are daily subjected to tidal changes in water and salt exposure and their typical plant species are adapted to live under these harsh conditions (Alongis, 2008). In temperate climate, life characteristics of riparian willows can be interpreted as adaptations to the flood plain environment, which also contribute to high genetic variability and predispose hybridization (Karrenberg et al., 2002). In general, local adaptations can be caused by small scale differences in the environment (Lipowsky et al., 2011). Whether this is also the case in willow species with different origin from flood plains along estuarine salinity gradients has not yet been investigated.

Willow soft wood forests are a characteristic feature of riverine and estuarine flood plains in temperate zones. Willows in these forests are part of the species rich genus *Salix*, which contains numerous flood plain species (Newsholme, 1992; Karrenberg et al., 2002). Many flood plain willows establish right above the mean

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water level. Here, both bush-shaped species, such as *Salix viminalis* L., and tree-shaped species, like *Salix alba* L., cope with disturbances such as waves and ice scouring by their high regeneration capacity (Ellenberg and Leuschner, 2010). Comparable to the contribution of mangroves to societal goods and services in subtropical and tropical coastal areas (Alongis, 2008; Li et al., 2013), flood plain willows in temperate climate contribute to ecosystem services such as coastal protection by attenuating waves and stabilizing sediments (Borsje et al., 2011; Radtke et al., 2012). Furthermore, they might contribute to trap sediments during flooding events similar to the effect which has recently been shown for herbaceous coastal salt marsh vegetation (Callaghan et al., 2010; Suchrow et al., 2012).

Along the coasts, human interventions are mirrored by erosion and subsidence, eutrophication and salinization. These problems are now global and particularly severe at coastal “hot spots” such as river-mouth systems (Newton et al., 2012). However, salinization, generally regarded as a stressor, also facilitates adapted estuarine organisms, which has recently been shown in the east of the Amazon mouth where an extensive mangrove belt increased in the upper river reaches due to salt water intrusion (Nascimento et al., 2013). In the temperate zone, tidal wetlands historically were locations for the establishment of human settlements and today many large cities (e.g., London, New York, Shanghai) are located here (Baldwin et al., 2009). In Europe especially tidal freshwater wetlands have become scarce due to human alterations such as diking, harbour expansion and land use changes for agricultural purposes. Nonetheless, substantial areas of tidal freshwater areas with high tidal amplitude still occur today at the Scheldt (Belgium) and the Elbe (Germany). Here, the remaining woody communities in tidal wetlands are dominated by willows (Struyf et al., 2009). Thus, willows in tidal freshwater wetlands can be seen as the temperate counterpart of mangroves in subtropical and tropical haline tidal flood plains. Both willows and mangroves are experiencing severe impacts: Beyond human activities, anthropogenic climate change and extreme events are identified as major hazards in estuarine environments (Jennerjahn and Mitchell, 2013). For tidal freshwater wetlands, reduced freshwater discharge and a rising sea level might both contribute to a rapid loss of habitats and biodiversity or to a conversion of vegetation caused by increased salt water intrusion (Baldwin and Mendelsson, 1998; Neubauer and Craft, 2009). Furthermore, periodic salt-water pulses during storms and periods of low precipitation might contribute to increasing soil water salinity and stress willows in estuarine flood plains.

Salix alba L. and *Salix viminalis* L. (hereafter referred to as *S. alba* and *S. viminalis*) are characteristic willow species in flood plains in temperate zones (Struyf et al., 2009; Ellenberg and Leuschner, 2010). In our investigation, they serve as model species since they are the most widespread willow species in the flood plains of the Elbe estuary (Raabe, 1986). Willows are generally described as glycophytes (Newsholme, 1992), contrary to mangroves, which are found in saline coastal environments around the tropical and subtropical latitudes (Li et al., 2013). In specific, Ellenberg et al. (1992) assigned the above mentioned species as being “not salt tolerant”. In contrast, we hypothesised that both species are able to tolerate oligohaline conditions. This hypothesis is of high relevance with regard to increasing salinity in tidal wetlands and due to their possible contribution to ecosystem services in tidal wetlands (see Borsje et al., 2011; Radtke et al., 2012). Against the background of salt intrusion in estuarine ecosystems, we investigated the salt tolerance of European willow species in tidal wetlands. In specific we aimed to answer the question (i) up to which soil water salinity do *S. alba* L. and *S. viminalis* L. occur along the salinity gradient of the Elbe estuary. We further asked, (ii) which salinity the species are able to tolerate and whether interspecific differences are existing with regard to salinity tolerance. Concerning intraspecific differences we aimed to answer the question (iii) if the salinity tolerance of these species differs between populations with origin from tidal wetlands at the freshwater stretch and the brackish water stretch.

2. Materials and methods

2.1. Study area and study species

The study was conducted on willows in flood plains at the Elbe estuary in Germany. The Elbe estuary exhibits a 142 km long tidal stretch with a salinity gradient from the upstream border at a weir in Geesthacht to the river mouth at the North Sea (Fig. 1, A). In the mid-20th century, the tidal freshwater zone (salinity < 0.5) was found between Geesthacht and Glückstadt, the oligohaline zone (salinity 0.5–5) between Glückstadt and Brunsbüttel, and the mesohaline zone (salinity 5–18) between Brunsbüttel and the mouth of the estuary (Caspers, 1959). In the 21st century, variations in precipitation pattern caused by climate change are expected to lead to earlier river discharge maxima and the minimum discharge is predicted to be more pronounced. Furthermore, sea level rise will lead to increasing mean high tide level (Von Storch and Claussen, 2011) and thus, upstream directed shifts in salinity levels can be expected.

Two sites were selected, which represented close to nature flood plains at the freshwater and at the brackish water stretch, respectively (Fig. 1, B). At these sites, the transition zone from reed to woody communities is dominated by shrubs like *Salix viminalis*. At higher elevations, the zonation continues with trees like *Salix alba* Newsholme, 1992; Ellenberg and Leuschner, 2010).

2.2. Soil water salinity

At the freshwater and the brackish water site, *Salix* stands were marked in aerial images at randomly generated plots. Here, *Salix alba* and *Salix viminalis* individuals were chosen as sources for cuttings. Within these plots, we determined *S. alba* and *S. viminalis* individuals as sources for cuttings by the presence of stem near-straight shoots. At nine willow stands per site, soil water was sampled seasonally in 2010 and 2011 under those willow individuals which served as donors for cuttings. Salinity was measured using the Practical Salinity Scale by a Multi-Parameter-Analyser (Eijkelkamp ecoTech 18.28).

2.3. Hydroponic greenhouse experiment

2.3.1. Experimental design and salinity treatment

We carried out a three factorial greenhouse experiment on cuttings of (i) two species (*Salix alba* and *Salix viminalis*), (ii) from two origins (freshwater and brackish water site), (iii) in four salinities (0.3, 2, 4 and 6) during ten weeks from February to April 2011. We determined the used salinity levels based on the distribution of both species in the flood plains of the Elbe estuary, ranging from the freshwater stretch to the lower limit of the mesohaline tidal stretch. The experiment was conducted in hydroponics in order to measure leaf and root development during the course of the experiment. Non-transparent plastic boxes (18 cm wide, 36 cm long and 20 cm high) were used as experimental mesocosms to avoid algae growth. The mesocosms were filled with well water and supplemented during the experiment. Additive-free sea salt (Meersalz, Alnatura, Bickenbach, Germany) was added to reach the salinity levels 2, 4, 6. Salinity was measured using the Practical Salinity Scale by a Multi-Parameter-Analyser (Eijkelkamp ecoTech 18.28). At the lowest salinity level, well water with salinity 0.3 was used (hereafter referred to as salinity 0). The experiment

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