EROSION CONTROL ECOSYSTEM SERVICE PROVIDED BY *SALIX ACUTIFOLIA* WILLD. NEOPHYTE ON THE SOUTH BALTIC COAST: INSIGHTS FROM WOLIN ISLAND, POLAND

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Manuscript received: January 17, 2024
Revised version: March 28, 2024

Borysiak J., Czyryca P., Stępniewska M., 2024. Erosion control ecosystem service provided by *Salix acutifolia* Willd. neophyte on the South Baltic coast: Insights from Wolin Island, Poland. *Quaestiones Geographicae* 43(3), Bogucki Wydawnictwo Naukowe, Poznań, pp. 5–19. 4 figs.

Abstract: Further global warming is projected to increase coastal erosion. Therefore, coastal protection is being intensified with a strong emphasis placed on environmental biotechniques. One such activity is anti-erosion planting using alien plant species. The aliens penetrate from the plant species into the natural ecosystems, reducing their biodiversity and ecosystem services. Parallel to coastal protection, measures for nature conservation are undertaken to eliminate invasive aliens from the natural ecosystems that take over. Such actions are featured in the master plans drafted for the Natura 2000 sites on the south Baltic coast. Although there is no sufficient scientific evidence, *Salix acutifolia* willow used in anti-erosion plantings was considered a neophyte invading white and grey dune habitats and reducing their biodiversity. The master plans mandated the elimination of the willow without considering the role of its spontaneous locations in providing erosion-control services. In 2017–2023, research was undertaken on the south Baltic coast (Wolin Island) on the arguments behind such a radical conservation action. We present the results of these studies. We consider the elimination of *S. acutifolia* from its spontaneous locations as a reduction in both its erosion-control services and the willow's role in nature conservation. We present some principles for action in case of a conflict between coast protection and nature conservation.

Key words: biological invasion, cliff, coast protection, dune, nature conservation

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Introduction

Global warming is accelerating coastal erosion (Mentaschi et al. 2018). The rate of erosion depends on sea abrasion, mass movements, and water and aeolian erosion. The dynamics of these processes are influenced by hydrometeorological and morpholithological conditions as well as vegetation. With above-average values of hydrometeorological parameters, such as heavy rainfall, heat waves, droughts, strong winds, and storm surges, significant transformations of the coastal topography and vegetation take place (Žilinskas 2008, Tylkowski et al. 2021, 2023a). Continued global warming is projected to exacerbate the frequency and intensity of severe events

https://doi.org/10.14746/quageo-2024-0023
ISSN 2082-2103, eISSN 2081-6383

(Arias et al. 2021). Coastal erosion will intensify along most coasts, especially on sandy shores (IPCC 2021).

Maritime administration intensifies coastal erosion-mitigation measures. Hard defences, artificial sand nourishments (Hanley et al. 2014), and soft strategies based on managing natural coastal ecosystems (Feagin et al. 2015, Gracia et al. 2018, Schernewski et al. 2022) are used to achieve this goal. However, these techniques are not fully effective. Sometimes, they are counterproductive (Nordstrom 2000, Pruszak, Zawadzka 2008). Biotechnical coastal protection measures used to control erosion cannot be equated with coastal nature-conservation tasks aimed at protecting biodiversity. However, the two types of measures can be skilfully combined (Feagin et al. 2015). Non-native plant species used for shoreline stabilisation may be invasive in coastal habitats and may threaten biodiversity (Weeda 2010, Hacker et al. 2012). However, they can benefit coastal protection (Charbonneau et al. 2017). Olšauskas (2009) listed publications on coastal erosion-control plantings that used geographically alien species such as *Salix daphnoides* Vill. and *Pinus mugo* Turra and *Rosa rugosa* Thunb., in the Curonian Spit, already in the years 1807–1938. The 14 villages were buried under the shifting spit sand at the end of the 18th and the beginning of the 19th centuries. For the same reason, these plant species (also *S. acutifolia* Willd.; syn. *S. daphnoides* Vill. var. *acutifolia* (Willd.) Döll.) were used on the Polish Baltic coast (Herbich, Warzocha 1998).

In the CICES V5.1 classification (Haines-Young, Potschin 2018), in the section Regulation & Maintenance (Biotic), the service 2.2.1.1 Control of erosion rates is indicated. It belongs to the group: Regulation of baseline flows and extreme events. It was highlighted that controlling erosion occurs owing to the stabilising effects of plant species and vegetation diversity (Science 2015). Therefore, protecting and restoring biodiversity and well-functioning ecosystems are targets in The European Union's biodiversity strategy for 2030 (European Commission, 2021). Mapping ecosystems and their ecosystem services are essential for measuring progress towards these targets.

In the European Union, to ensure the long-term sustainability of biodiversity and reverse the degradation of ecosystems, the Natura 2000 network has been established. The tool to achieve this goal is the management plan drafted for the N2000 site (Article 6 in Council Directive 92/43/EEC). Such a document is to ensure the favourable conservation status of the Natura 2000 species and habitats while considering human well-being. It outlines the actions needed to be taken to eliminate threats or mitigate negative influences that are associated with an unfavourable-bad status. Threats are identified according to the list of the European Environment Agency (European Environment Agency, 2019). One of the threats (code I01) is the biological invasion by an alien species. The management plan may mandate the elimination of invasive alien species (IAS). Thus, the way to restore ecosystems and enhance their services is to combat IAS. Combating IAS has started as the implementation of target 5 of the EU Biodiversity Strategy to 2020 (European Commission, 2011). It is continued with an emphasis on applying the new EU biodiversity management framework (European Commission, 2021).

In both the EU Biodiversity Strategies (2020 and 2030), the term biodiversity (biological diversity) is consistent with the definition given in the Convention on Biological Diversity. In the specific region, they are indigenous species (naturally occurring, natives). Non-indigenous plants (introduced accidentally or deliberately into natural or semi-natural ecosystems, aliens) can become IAS and develop their secondary range and cause severe damage to natives and their ecosystems, and therefore losses to ecosystem services. The Strategy to 2020 (European Commission, 2011) indicated the need to create a legal basis for combating IAS. Guidelines for adopting such formal acts have been published in the regulation on the prevention and management of the introduction and spread of IAS (Regulation 2014). It provides directions to the identifying of IAS, to controlling pathways of their unintentional introduction and to taking actions aimed at their early detection and rapid eradication. In 2021, the act on alien species was passed in Poland (Act 2021), which implements the EU Regulation guidelines.

There are 14 Natura 2000 sites on the south Baltic coastline in Poland. Among other things, they protect 1628 ha of Natura 2000 habitat 2120 Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes) and 2144 ha of priority habitat 2130* Fixed coastal dunes with herbaceous vegetation (grey dunes). Both habitats occur in the coastal technical belt and constitute the area of direct interaction between the sea and the land. Its border is determined by the maritime office, considering the average sea level for the last 10 years. The task of the belt is to protect the coast against erosion while taking into account the conservation measures provided in the management plans for nature-conservation areas (Act 1991). Maritime offices implement the program for coastal protection 2003–2023, aiming to protect the coastline against shore erosion. They put into use hard and soft engineering techniques. From the first half of the 20th century, they performed windbreak planting. *S. acutifolia* and *S. daphnoides* were planted on the younger dunes, while also *P. mugo* and *R. rugosa* on the older ones. Both hard and soft techniques have a negative impact on N2000 habitats, directly or indirectly. Pruszak and Zawadzka (2008) found the intensification of erosive phenomena within all geomorphological landforms of the coastal system in Poland. They cite the accelerated sea-level rise and extraordinary processes (including storms more often, stronger, and longer lasting) under the influence of climate change as the reasons. Based on data from 1883 to 2000, they showed an increasing value of the average rate of coastal retreat (at an average rate of 10 cm $\cdot$ 100 a^{-1}) and a decrease in the accretion processes (sediment starvation). Their optimistic scenario assumes a sea-level rise of 30 cm, while the pessimistic one is by 100 cm. Łabuz et al. (2018) reported that only 15% of the foredune coast in Poland is in the accumulative phase. Protective systems have already been developed for 26% of the Polish coastline (Pruszak, Zawadzka 2008). The dynamics of open coast shoreline changes clearly indicate the need to intensify protective measures. Establishing the N2000 network almost along the entire length of the Polish coast prompts us to look for coastal hazard-protection measures with the least negative impact on biodiversity. Regional average relative sea-level rise will likely continue throughout the 21st century. Approximately two-third of the global coastline has a projected regional relative sea-level rise within ± 20% of the global mean increase. Coastal erosion will intensify along most coasts, especially on sandy shores (IPCC 2021). Forecasts indicate the necessity of developing adaptation strategies for coastal areas under erosion.

On the Polish Baltic coast, four out of fourteen N2000 sites have a management plan, and several drafts of the management plans are pending approval. In these documents, the occurrence of *S. acutifolia* in dune habitats has been classified as a threat of biological invasion. The willows were ordered to be gradually cut or uprooted manually, with the removal of biomass. It has been forbidden to use fences made of live willow shoots. *A. arenaria* and *Leymus arenarius* (native grasses) were ordered to be planted in the white dunes. In the draft of the management plan for Wolin National Park (N2000 site PLH320019 Wolin and Uznam), Ziarnek and Ziarnek (2013) classified this willow as alien species, particularly invasive in the habitats of white (Natura 2000 habitat type 2120) and grey dunes (2130). They ordered it to be 'cut regularly and dig up if possible'. The expected result of the willow removal is to be favourable conservation status of habitats 2120 and 2130. Popiela et al. (2015) recognised *S. acutifolia* as highly invasive on the whole coast of Wolin Island. The assessment of invasiveness was made only based on the number of records (natural and artificial sites) and the phytosociological diagnosis of vegetation at the sites. They have, however, not conducted detailed scientific studies authorising the inclusion of *S. acutifolia* in the list of IAS, i.e. IAS taxa 'whose introduction or spread threatens biodiversity and related ecosystem services with a significant contribution to human well-being' (Regulation 2014). Mandatory studies include the analyses of those features of the structure and dynamics of the IAS population that determine the degree of invasiveness of the species, especially to the extent necessary to enable the regression of these features to a non-invasive state. Only the results of such studies oblige to determine the ways of restoring the natural state of ecosystems degraded by IAS. All dune habitats lie within the technical belt of coastal protection (Regulation 2016). In the management plans, the institutions designated to carry out active conservation measures in the technical belts are the maritime offices that once introduced *Salix* sp. plantings as biotechnical anti-erosion protection and still use it as essential protection. Biotechnical coastal protection efforts are, therefore, contrary to coastal nature conservation. There is an urgent need to reach a consensus between coastal protection and nature conservation.

We adopted the thesis that removing *S. acutifolia* to achieve favourable conservation status can radically weaken the erosion-control service. There is also an apparent conflict between coast protection and nature conservation. To provide premises for management decisions, we undertook research on the spontaneous occurrence of the *S. acutifolia* neophyte on the south Baltic coastline in Poland, on Wolin Island. The research aimed to analyse: (1). the distribution pattern of *S. acutifolia* and their plant communities; (2). the role of *S. acutifolia* in 2.2.1.1 Control of erosion rates ecosystem service; (3). plant biodiversity of embryonic dunes with *S. acutifolia*; and (4). the biological invasion forecast for *S. acutifolia*.

Study area

The study area was the coastline of Pomeranian Bay on Wolin Island. It was the entire strip (meter by meter) of 22 km between the seashore and the top edges of foredunes or cliffs, from 53°54'47.7"N, 14°18'56.3"E to 54°00'22.04"N, 14°40'50.13"E excluding Międzyzdroje resort where only random observations were made (Fig. 1). Most of the area was located in the Wolin National Park (N2000 site PLH320019 Wolin and Uznam). In the physics-geographical regionalisation of Europe (Borzyszkowski et al. 2021), it is the Uznam and Wolin Islands mesoregion (313.21) in the province of Central European Lowland (31).

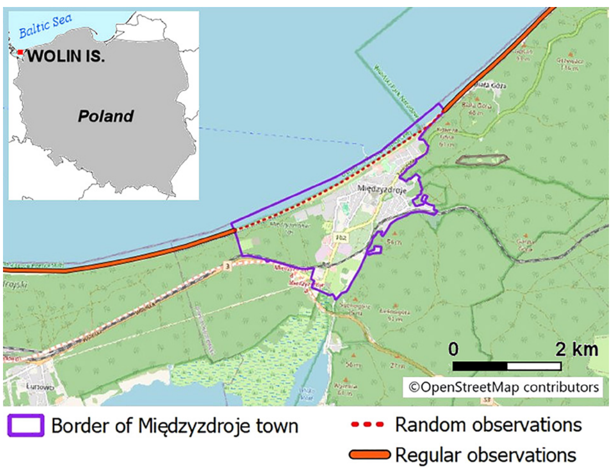

Fig. 1. The location of the study area.
Reference data: OpenStreetMap contributors.

On the southern coast of the Baltic Sea of Wolin Island, in the years 1960–2019, the mean annual air temperature was 8.7°C, with a statistically significant upward trend of 0.3°C every 10 years. Significant warming has been observed since the 1990s. In the indicated 60 years, the mean annual precipitation reached 546.7 mm. The annual sum of precipitation did not show a statistically significant long-term trend. From 2010 to 2020, a statistically significant trend of extending the vegetative season by 3 days every 10 years has been stated. The mean sea-level rise of ~2 mm · a^{-1} was found. The dynamics in the maximum level rise was twice as high and amounted to 4 cm every 10 years. Environmental changes lead to the high frequency of severe winter storms causing the increased intensity of sea erosion in the coastal zone (Winowski et al. 2022, Tylkowski et al. 2023a; Fig. 2A).

In 2017, when sites of *S. acutifolia* and their ecological conditions were studied, the mean annual air temperature was 9.6°C. From June to August, the average monthly air temperature exceeded 15°C, and the maximum in August was 18.7°C. In these months, 20 hot days were recorded (T_{max} >25°C). The hottest day temperatures (T_{max} >30°C) did not occur. There were 55 days with ground frost. The average annual relative humidity was 79.6% and 669.3 mm of the annual total precipitation. There were 182 days with precipitation, mainly with low rainfall <10 mm. The lowest value was recorded in February (21.6 mm) and the highest in July (147.2 mm). The snow cover remained for 43 days in 2 months and had an average thickness of 4 cm, with a maximum of 14 cm. The growing season lasted 235 days, from 11 March to 31 October. The prevailing winds were from the NW and SE–SSE directions. The winds with the highest average speeds (~4 m · s^{-1})blew from WNW and NW (October–December, February), and the lowest winds (~1.5 m · s^{-1}) came from the ENE–E sector. The average speed was 1.5 m · s^{-1} (Tylkowski et al. 2018). From 2009 to 2022 (Tylkowski et al. 2023b), winds from the NW and SSE directions were dominant based on the annual frequency of wind directions. However, the wind distribution differed if we consider the average wind speed from a particular direction. Notably, there was an increase in the percentage of stronger winds from the SSW–NW sector. The average annual wind speed in 2009–2022 was 2.8 m · s^{-1}. The maximum average value of 3.3 m · s^{-1} was recorded in 2009, while the minimum average speed of 2.4 m · s^{-1} was noticed in 2012 and 2016. The highest average wind speeds (≥3 m · s^{-1}) were recorded in the cold half-year months (November–February) and in July and October.

About 15 km of the examined coastline was a flat coast covered by dunes in different development stages (Fig. 2B). The sediment sources for dune development included fluvioglacial sands from eroded shores, river-discharged sand and older eroded dunes. Only a few kilometres of coastline (Świna Gate Sandbar) were in the accumulative phase. The chain of embryonic dunes and foredunes together was up to 60 m wide. In Poland, it was one of the largest coastal aeolian areas, nourished by the Świna river mouth. A new, 5–7 m high foredune was developed every 10–15 years. The diameter of sand found in the foredunes of the Polish sea coast ranged from 0.16 mm to 0.25 mm. About 90% of its composition was light quartz grain. Aeolian processes leading to the development of dunes occurred mainly in spring and autumn. The springtime allows for dune development due to the increase in wind speed from a direction oblique to the coast. During autumn, stronger onshore winds reappeared with offshore directions (Hojan 2009, Łabuz 2013). In late autumn and winter, we observed the degradation of the landforms (Fig. 2C).

The next analysed coastal segment (7 km) was the sandy clay moraine cliff coast (Fig. 2D), up to 93 m asl, sloping 30–700 towards the northwest. The cliffs were areas of active litho- and morphological processes. Great dynamics of mass slope movements (Fig. 2E, F), water (Fig. 2G, H) and aeolian (Fig. 2I) erosions characterised them. The

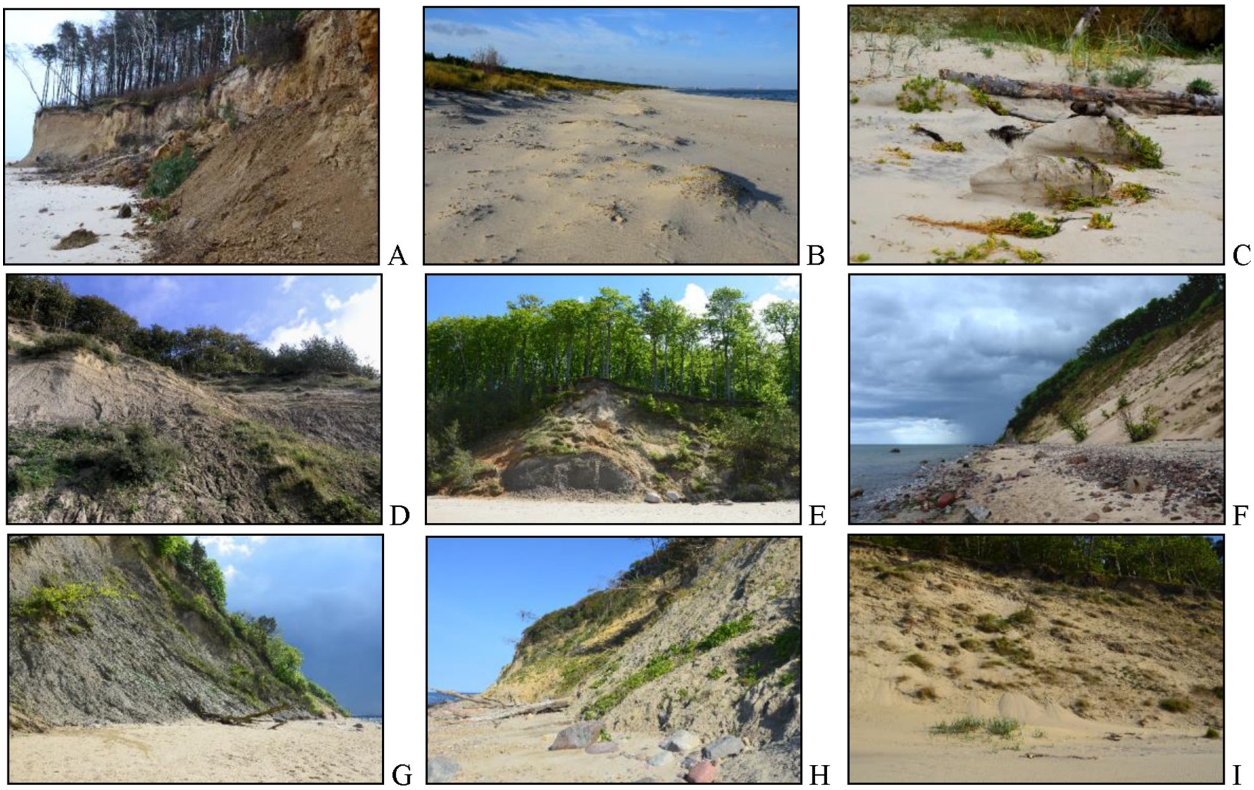

Fig. 2. Natural conditions in the study area from 53°54'47.7"N, 14°18'56.3"E to 54°00'22.0"N 14°40'50.1"E on Wolin Island: A – transformations of the cliff topography as a result of strong storms with a violent wind (Barbara 28–29.12.2016, Axel 04–06.01.2017), photo 17.02.2017; B – embryonic dunes formed from sand trapped by *Honckenya peploides*; C – phytogenic aeolian microforms with *H. peploides* that are degraded during autumn storms; D – a sandy clay terminal moraine cliff; E – rapid transformation of the cliff foot due to rockfall; F – sandy talus cones at the cliff foot; G – alluvial deposits overlapping talus cones at the cliff foot; H – mass movement and water-erosion processes on the slopes of a clay cliff; I – a phytogenic aeolian pattern with *L. arenarius* formed from wind-blown sediments.
Photo by J. Borysiak.

greatest morphodynamics was observed in the section Biała Góra – Świdna Kępa. Significant transformations occurred, especially during storm surges, efficient precipitation, and strong winds. The feet of the cliffs were abraded when the maximum water level was at least 90 cm higher than the average. The average abrasion rate of cliffs was 7.5 m in the last 35 years. The greatest annual dynamic was recorded in typically sandy sections, 0.32 m · a^{-1}. The lowest was in the sandy-clay parts, at 0.12 m · a^{-1} (Kostrzewski et al. 2015). Extreme, short-term storm surges in 1995, 2004 and 2017 retracted the cliff by an average of 2.74 m, accounting for 35% of the total coastal land loss in 1984–2020 (Tylkowski et al. 2021, Winowski et al. 2022, Tylkowski et al. 2023a).

Materials and methods

In 2017, we examined the locations of spontaneous *S. acutifolia* Willd. (syn. *S. daphnoides* Vill. var. *acutifolia* (Willd.) Döll.) and their ecological conditions during the growing season. We also conducted occasional field observations between 2018 and 2023. Willow was used there for anti-erosion plantings in the technical-protective coastal strips. It escaped from these strips and became a neophyte in the spontaneous flora of dune vegetation. All spontaneous locations of *S. acutifolia* in the study area have been documented, and the data have been archived. In natural plant communities with the share of spontaneous locations of *S. acutifolia*, 30 phytosociological relevés were taken using the Braun–Blanquet method, as well as 10 such relevés in *Salix* plantings located in technical coastal belts in the national park and the Międzywodzie resort. The relevé area depended on the patch's homogeneity and ranged from 30 m^2 to 120 m^2. The syntaxonomic rank of developed vegetation among both spontaneous and *Salix* plantings was analysed using Matuszkiewicz's (2022) classification. The results were used to identify the N2000 habitats with the Herbich (2004) manual. Names of plant species were given after Mirek et al. (2020). The length of the parent (main) stem of each *S. acutifolia* individual was measured. Germination strength of willow was tested in laboratory conditions. Ripe seeds collected from 23 individuals were placed immediately after being sown on wet sand collected from the beach where these individuals were found. The results of 7-year observations of vegetation dynamics against the background of morphodynamic processes were used. Data from environmental monitoring were taken into account in the interpretation of the results.

Results

The distribution pattern and plant communities of *S. acutifolia*

There were 199 *S. acutifolia* Will. (synonym *S. daphnoides* Vill. var. *acutifolia* (Willd.) Döll. individuals from spontaneous colonisation (i.e. not planted). The length of the main stem of willows reached 2.5 m (Figs 3 and 4A). Probably most of them were rooted shoots from maintenance cuts made in the plantings of *S. acutifolia* in Międzywodzie resort close to the eastern border of the study area. Randomly dug-up juveniles or those found on the beach often had bevelled ends on rooted branches. Cuttings not removed from the plantation immediately after the shrub rejuvenating treatment (Fig. 4B), dispersed by

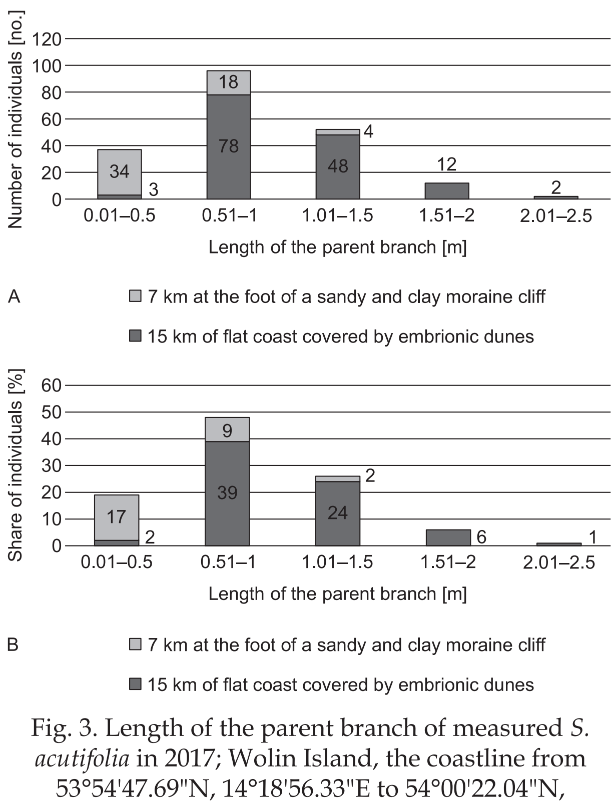

Fig. 3. Length of the parent branch of measured *S. acutifolia* in 2017; Wolin Island, the coastline from 53°54'47.69"N, 14°18'56.33"E to 54°00'22.04"N, 14°40'50.13"E: A – ranked by the number of individuals, B – ranked by the share of individuals.

the wind, were vegetative propagules that found favourable growth conditions. Dry and not rooted cuttings scattered by the wind were found on the beach. Some specimens may have come from shoots broken off during a storm.

Spontaneous locations of *S. acutifolia* occurred in the 5–10 m wide area adjacent to the sandy clay foot of the moraine cliff (28% of individuals). More often (72%), they grew in the zone of the flat coast on the embryonic dunes, sometimes forming short chains. Almost half of the shrubs (48%) grew singly on bare sand. These often were hidden among fallen trees or accumulations of drift material brought by storms (Fig. 4C). Individuals recorded at the foot of the cliff were smaller and less frequent due to the high morphodynamics of the foothills. The habitats adjacent to the slopes of the cliffs were a buffer zone for the erosion of the cliffs by marine activity. They was a deposition zone for sediments transported from the upper parts of the moraine cliff (from mass movements). Colluvial landforms were in the shape of alluvial fans and talus cones at the foot of the cliff and often were

A B C D E F G H I J K L

Fig. 4. Adaptive strategy and habitats of *S. acutifolia*: A – size and habitat of the most common individuals, B – clippings as a source of vegetative propagules colonising the beach, C – shrub hidden in accumulations of drift material brought by storms, D – willow at the foot of the cliff, on the colluvium covered by windblown deposits, E – adventitious roots on stems buried by sand, F – rhizosphere of planted *Salix* stabilising the soil, G – growth keeping abreast of the sand sedimentation, H – orthotropic shoots growing out of branches contacting with sand, I – accumulation of sand in the shade of a willow and *F. villosa*, J – leafy shoot from the long-sleeping bud, K – willow locations (1D) covered with colluvial deposits from mass movements on the cliff in 2018, L – degradation of anti-erosion plantings in Międzyzdroje resort.
Photo by J. Borysiak.

covered by windblown deposits (Fig. 4D). They were developed towards the sea and were the first to be subjected to sea erosion. Habitats in contact with the foot of the cliff often were saturated with water seeping from the lower parts of the cliff slopes. Juvenile willow individuals that took root in *Elymo-Ammophiletum* patches were recorded many times.

The role of *S. acutifolia* in controlling erosion rates

S. acutifolia, in its spontaneous locations, controlled aeolian erosion by implementing an adaptive strategy that allowed it to exist well in sand-burdened conditions. The natural aeolian process was the driving force behind the development of willow ecological functions that provided an anti-erosion ecosystem service. The willow used its potential for morphological and developmental features in this strategy. The following features were critical in the accumulation of sand and the formation of the aeolian landform: (1) the development of adventitious roots on stems buried by sand (Fig. 4E); (2) the branching of the root system in all directions, stabilising a large volume of sand (Fig. 4F); (3) the fast-developing shoot branching network and growth keeping abreast of the sand sedimentation (Fig. 4G); (4) development of orthotropic shoots and adventitious roots from branches lying on the sand and buried (Fig. 4H); (5) after removing sand, development of shoots from sleeping buds; and (6) mechanical safety due to crown volume and elasticity of the shoots. During 7 years of observation, no *S. acutifolia* seedlings were found in any habitat.

S. acutifolia was a species that shaped the morphology in the coastal zone of the sea. The sand brought by the wind was trapped among its shoots and also among accompanying plants. As a result of the accumulation of sand, shady dunes (Fig. 4I) and larger phytogenic aeolian forms were developed. Sometimes, these landforms formed short chains. The physiognomy of hillocks consisted of two layers – shrubs and herbs. The shrub layer was built by *S. acutifolia*. The components of the herb layer were: *A. arenaria*, *Festuca villosa* and *L. arenarius*. In larger hillocks, the root systems of these grasses were intensively developed and bound a large volume of soil. Owing to this, these forms survived after the heavy washing with the water of numerous extreme storms occurring in the 7 years of research. In the aeolian sediment-deposition gradient, they were rebuilt.

In the Międzyzdroje resort, the extraordinary vitality of the willow was observed on the degraded foredune. The shoot uncovered during the storm developed a leafy stem from the long-sleeping bud (Fig. 4J).

It was found that willow viability depended on continuous backfilling, which stimulated the development of newly rooted above-ground shoots. For the willow and many accompanying *rhizome caulophytes* or *rhizocaulophytes*, blowing sand was more beneficial than blowing away, which exposed and dried the systems of young adventitious roots growing from underground shoot bases. A root life form such as rhizome *caulophyte* is known for its ability to develop many strong adventitious growing from the base of numerous underground shoots. *Rhizocaulophyte* is characterised by producing well-built primary roots and many adventitious roots on underground shoot bases. In habitats not subjected to aeolian accumulation, shrubs reached a terminal stage of development and died out.

Plant biodiversity of embryonic dunes with *S. acutifolia*

The vascular flora of natural plant communities with *S. acutifolia* comprised 65 species. It was composed of 58 genera and 28 families. *Magnoliopsida* dominated (48 species, 19 families). The richest families were: *Asteraceae* (12 species), *Poaceae* (8), *Rosaceae* (7) and *Salicaceae* (4). Plants constituted 7 life forms of Raunkiaer's system. Phanerophytes were numerous (25%). Aliens comprised 11% (2 archaeophytes and 5 neophytes).

Embryonic dunes were stabilised by vegetation of 20–90% coverage. Plant communities consisted of 8–23 plant species (65 in total). Totally, 55 characteristic species from 15 phytosociological classes have been recorded. The others were rankless. The most numerous were: *Koelerio-Corynephoretea* (11 species), *Artemisietea* (8), *Ammophiletea* (5) and *Molinio-Arrhenatheretea* (5). Most of the species (72%) occurred sporadically (1–3 relevés). They belonged to characteristic taxa from 12 phytosociological classes, which testified to the high lability of plant community compositions. *S. acutifolia* occurred in patches composed of representative species not only for white dune 2120 *Elymo-Ammophiletum* (5 species), but also for grey dune 2130* *Helichryso-Jasionetum* (11, very often *Artemisia campestris* subsp. *sericea* and *Hieracium umbellatum* var. *dunense*). *A. arenaria, F. villosa and L. arenarius* were almost constant components. These grasses usually formed sod directly around the willow, regardless of whether it was a lee side or exposed to the wind. They were not woven into the *Salix's* shoots. Three *Cakiletea maritimae* therophytes grew in several patches with *S. acutifolia*, typical for the initial stages of white dunes. They were: *Atriplex prostrata* subsp. *prostrata* var. *salina*, *Cakile maritime* and *Salsola kali*.

Biological invasion forecast for *S. acutifolia*

Only 23 out of 199 spontaneously occurring (not in biotechnical willow plantings) *S. acutifolia* individuals had capsule fruits with cottony masses of seeds. Under laboratory conditions, on moist sand taken from the beach, only seeds of four of them were germinated, with a germination strength of 2%, 3%, 5%, and 7% approximately. No seedlings from seed dispersal were recorded in any phenological season during the 7 years of field research. The 5 m wide zone with *S. acutifolia* embryonic dunes was influenced by radical relief changes basically all year round. Aeolian processes favouring sediment trapping and vertical accretion occurred in spring and autumn. In summer, under the cliff, the habitats were covered with colluvial deposits from mass movements on cliff slopes (creep, sliding, flow, fall) – Fig. 4K. In winter, the beach and dune erosion during severe storm surges occurred. Thus, throughout the year, the morphodynamic state of the habitats served poorly to maintain spontaneous willow sites. Only larger willow individuals, well-anchored, survived (e.g. in the shade of fallen trunks and other organic debris). The erosion of dunes stabilised by *S. acutifolia* planting was observed in the technical and protective coastal strips of Międzyzdroje and Międzywodzie resorts. In many places, remains of willow shrubs only existed (Fig. 4L). This results in the depletion of the source of the unintentional introduction of vegetative propagules creating spontaneous, pioneering locations on the beach. In such dynamic habitats, the biological invasion forecast for the neophyte *S. acutifolia* is optimistic for biodiversity conservation. The willow has little chance of spontaneous development of its invasive secondary range.

Discussion

Our multi-aspects research has shown that *S. acutifolia* is characterised by a low degree of invasiveness, soft intervention on biodiversity and a high level of the provision – the ecosystem service 2.2.1.1 Control of erosion rates. Considering several environmental reasons, there are no grounds for performing such radical active protective treatments such as cutting or removing the root system.

We found that the primary source of propagules forming spontaneous locations of *S. acutifolia* were biotechnical plantings of this shrub in the coastal protection zone. During maintenance pruning, the wind-dispersed cuttings of shoots remained within the plantings and took root in the cliff side habitats. In this way, pioneer sites of the secondary geographical range of *S. acutifolia* have been developed. The aeolian process in such locations drove the willow adaptive strategy, simultaneously activating several ecological functions (morphological and developmental features of the willow) constituting the ecosystem service 2.2.1.1 Control of erosion rates. Hein et al. (2006) pointed out that natural processes at a sandy shore are the mainspring for creating ecosystem services. Adapting *S. acutifolia* to aeolian processes resulted in phytogenic aeolian forms in the shape of shadow dunes or small hillocks. The latter can be considered as aeolian landforms analogous to phytogenic forms created by vascular plants, typically by shrubs and small trees, in desert areas (Wang et al. 2006, Li et al. 2007, Zhang et al. 2011, Pool et al. 2013, Quets et al. 2013, Yang et al. 2014, Zhou et al. 2015). El-Bana et al. (2002) named such sites 'vegetation islands' and those landforms of aeolian accumulation he recognised as good indicators of aeolian erosion. Rahmanov et al. (2011) discussed the formation of fertility islands under canopies of *S. acutifolia* in plantations controlling aeolian erosion. Knowledge of biogeomorphological mechanisms in the evolution of phytogenic aeolian forms was used in environmental bioengineering to control desertification (El-Bana et al. 2003, Zhao et al. 2011, Lavaine et al. 2015). On Wolin Island, *S. acutifolia*, at its spontaneous locations, created habitats with ecological niches favourable for numerous native psammophytes from *Elymo-Ammophiletea* and *Koelerio-Corynephoretea*. These habitats were also favourable for the development of many plants' characteristic of these phytosociological classes (including *Artemisietea, Molinio-Arrhenatheretea, Querco-Fagetea*), which, according to Matuszkiewicz (2022), are bioindicators of plant communities with higher trophic requirements. The source of soil fertility is probably the annual *in situ* decomposition of litter and also matter brought by the wind. By developing aeolian phytogenic landforms of the 'fertile islands' character, *S. acutifolia* contributes to the increase of biodiversity, not the loss of biodiversity. Within the forms, plant species absent from neighbouring habitats occurred relatively often. Fałtynowicz (2018) reported 24 species of lichens on the bark of *Salix* individuals occurring on the shore of the Baltic Sea in Poland. Six are on the red list of threatened species (four endangered [EN], two vulnerable [VU]), and two are protected species in Poland. The cutting of willows required by the management plans for N2000 sites on the Polish coast is therefore tantamount to destroying a microhabitat important for biodiversity.

The level of ecosystem service 2.2.1.1 provided by vegetation-forming phytogenic aeolian forms with spontaneous locations of *S. acutifolia* was affected by a high share (72% in the total list of flora) of species sporadically co-occurring with willow. Among them, there were numerous perennials that represented rhizome caulophytes (e.g. *Epipactis atrorubens*) or rhizocaulophytes (as *Calamagrostis epigeios, Tussilago farfara*), according to the classification developed by Łukasiewicz (1962) for the dune species of the Łebska Spit. Their common features comprising the biology of development, important for the adaptation to the conditions of aeolian erosion, were the ability to develop a dense network of rhizomes, i.e. underground creeping shoots, as well as a highly developed system of adventitious roots growing from shoots covered by windblown deposits (Borysiak 2022). Due to the latter feature, willow was used to control aeolian erosion in the degraded areas of the Błędów Desert (Rahmanov et al. 2009, 2021).

Alien plants can get out of their intentional plantings, stabilising coastlines and reaching the stage of biological invasion that reduces biodiversity (Weeda 2010, Hacker et al. 2012). In the study area, the degree of invasiveness of *S. acutifolia* can be considered very low. Among other things, no seedlings were found for 7 years of observation (2017–2023). The reason for this could be the very low germination capacity of the willow seeds, confirmed in the laboratory. The willow was planted far from its natural range, which includes areas in Eastern Europe and Central Asia with a different climate than on Wolin Island, which may be the reason for the very poor generative reproduction, and therefore invasiveness.

It was found that only remnants of anti-erosion plantings with *S. acutifolia* remained within the boundaries of the national park, and the erosion of sea waters was the destructive factor. It cannot be ruled out that they could also be (and will still be) the source of pioneering individuals developing spontaneous sites originating from the rooting of shoots that were mechanically torn off by the wind or sea waves. Together with the remnants of plantings destroyed during dune scarping generally in periods of high-water level, the potential source of vegetative and generative propagules will undoubtedly disappear. As previously mentioned, the main source of willows growing in spontaneous sites were cuttings from *S. acutifolia* plantings in the technical belt protecting the coastline. In turn, this potential source of spreading geographically and ecologically alien species can be easily eliminated. Cuttings must be removed immediately after maintenance cuts have been made to landfills far enough under the coastal line.

Significant losses were observed in the remnants of not only the oldest plantings of *S. acutifolia* located within the national park's boundaries but also in spontaneous sites of the willow's secondary range. In both cases, they were the result of coastal erosion. Pruszak and Zawadzka (2008) found that the western regions of the southern coastline of the Baltic Sea in Poland (including Wolin Island) in 1883–2000 were characterised by a gradually increasing trend of average rates of the recession of the cliff and dune foot and general shoreline, and also a decrease in the accretion processes. They considered that the increased rate of coastal change mainly reflected the increasing number of storms, which was one of the main factors for sea coast erosion. Winowski et al. (2022) found statistically significant upward trends for the mean and maximum levels of the Baltic Sea. This is related to the rising threat of cliff coast abrasion in the future. Such a forecast is sufficient reason to believe that, in the long-term perspective, the willow will not maintain its spontaneous positions along the cliffs. Therefore, it should not be treated as a potential invasive species.

Winowski et al. (2022) found that during weak and moderate sea dynamics on Wolin Island, sediments eroded in the upper parts of the sandy clay moraine cliff coast systematically pass into the lower parts. At the foot of the cliff, sediments develop alluvial fans and talus cones. Then, windblown deposits cover these newly formed landforms. During such periods of geodynamics, on these colluvial-aeolian units, we observed rooted vegetative propagules of *S. acutifolia* brought by the wind from anti-erosion plantings, where maintenance treatments were performed. It is possible that willow seeds would be able to germinate there if they were present there. During storm episodes following a period of weak and moderate sea dynamics, the colluvial sediments are rapidly accumulated at the foot of the cliff as a result of mass movements. They partially or completely cover the habitats created and occupied by the willow in the previous period of geodynamics. At the same time, there are episodes of dune scarping. The periodically alternating morphodynamics in the sea–land interaction zone undoubtedly is the reason for the small size of *S. acutifolia* we found (26% of individuals up to 1 m of the length of the parent branch) and their less frequent occurrence than on the sandy flat coast sections. Due to the low stability of habitats, the service 2.2.1.1 Control of erosion rates is provided by *S. acutifolia* only periodically.

Phytogenic aeolian hillocks with *S. acutifolia* along the flat coast provided the service 2.2.1.1 Control of erosion rate at a much higher level. Sand accumulation around the willows was on a similar basis as in Dryas aeolian landforms in the Arctic deflationary tundra described with quasi-continental polar climate conditions (Borysiak et al. 2020) or phytogenic aeolian forms in desert regions (Goudie 2022). Plant species' role in forming phytogenic aeolian hillocks varies depending on the life form (Gilbert, Ripley 2010). For life forms most effectively trapping sand, Mycielska-Dowgiałło et al. (2008) recognised small- and medium-sized phanerophytes. Therefore, the willow which can reach up to 5 m in height (Seneta et al. 2021), during maintenance in the technical belt of coastal protection is cut to small sizes. This treatment stimulates the development of many shoots, which raises the level of service provision. The adaptability of *S. acutifolia* in the areas under aeolian erosion effects was used to stabilise the dunes of the Baltic coast (Herbich, Warzocha 1998, Olšauskas 2009). The use of *S. acutifolia* to reduce deflation in the anthropogenic Błędów Desert is another example (Rahmanov et al. 2021). More pronounced phytogenic aeolian hillocks in this desert were formed by *S. repens* L. subsp. *repens* var. *arenaria* introduced for the same purpose as *S. acutifolia*. It effectively controlled erosion with extensive horizontal physiognomy (Rahmanov et al. 2009). In Poland, on the Baltic coast, *S. repens* subsp. *repens* var. *arenaria* is a native species. It forms natural thickets low to the ground. They are the stage of succession following the *Helichryso-Jasionetum* grey dune swards. Forest succession is limited by very strong winds (Matuszkiewicz 2022). *S.* repens subsp. repens var. *arenaria* occurs on the Wolin Island (e.g. in location 53°59'03.45"N, 14°34'57.46"E in 2023, our observation). Due to the relatively high level of the ecosystem service 2.2.1.1 provided, it could be used in N2000 sites instead of the alien *S. acutifolia*. It would be an example of effectively using natural shoreline defence (Hanley et al. 2014). Feagin et al. (2015) provided management considerations for using plant species to protect high-energy shorelines. Rahmanov et al. (2021) proved that in anti-erosion plantings, *S. repens* subsp. *repens* var. *arenaria* meets many of these considerations, and natural processes can continue to evolve sustainably, despite a soft intervention.

We observed the extraordinary vitality of old willows on the Wolin Island in Międzyzdroje, on the front dune degraded by storms (see chapter 2). Shrubs were planted there by testing the horizontal laying of cuttings of *S. acutifolia*, replacing vertical planting (Błaszczak 1979). In the first year, the cuttings rooted strongly, developing adventitious roots and sprouting shoots of about 1 m in good vitality. In order to maintain this vitality, 3-year protection with brushwood fences against backfilling and erosion was necessary. The test results confirm the possibility of rapid rooting of vegetative propagules of *S. acutifolia* blown from the places where anti-erosion plantings are cared for. At the same time, the lack of technical protection would probably cause the newly rooted willows to retreat from their pioneering positions quickly. This proves low species' invasiveness. Olšauskas (2009) reported that during Hurricane Anatoly, on the Curonian spit seashore in 1999, anti-erosion willow plantings had suffered severely. In the spring of 2000, part of the willow was reborn from its living roots. *Salix* regenerated there much better than other phanerophytes used for erosion control. Generally, however, the willow is gradually disappearing under the influence of, among others, the activity of seawater, similar to our study area.

An alternative to anti-erosion *S. acutifolia* plantings along the coastal line is constructing sand-trapping fences with *Ammophila* species. We recorded a constant share of *A. arenaria* (with a cover of 25–75%) in natural phytocenoses with spontaneous *S. acutifolia* sites. Keijsers et al. (2015) found that the level of aeolian control in frontal dunes covered by *A. arenaria* increases with higher vegetation cover. To remain vigorous in this psammophilous grass, however, it is necessary to bury its individuals in a certain amount of sand trapping on a year-to-year basis. This biological feature is responsible for the dune system's ability to keep up with rising sea levels. Van der Biest et al. (2017) estimated the volume of sand accumulated per year by *Ammophila* vegetation using an indicator of the sedimentation rate. Multiplying it with the area of dunes covered by *Ammophila* grasses, they estimated the value of the natural supply of sand. They used the cost to replace the natural supply of sand with artificial nourishments of dune feet as an indicator of the economic value of sand accumulation. They also calculated that dunes dominated by young vegetation successional stages might create up to ~50% higher economic benefits than complexes dominated by the vegetation of late stages of succession (shrub formations), developing in response to the interruption of sand transport between the sea, the beach and the dunes. Thus, they showed that as the early, dynamic stages of plant succession subside, there is a change in the provision of ecosystem services. Earlier, Everard et al. (2010) noted the potential public value of coastal dune systems.

Based on the indicator for the maintenance of coastal safety provided by Van der Biest et al. (2017), it can be concluded that in the case of the coexistence of *A. arenaria* with *S. acutifolia* in the phytogenic aeolian hillocks in Wolin National Park, there is an enhancement of the ecosystem service 2.2.1.1. Control of erosion rate. *A. arenaria, F. villosa* and *L. arenarius*, which co-built the *Salix* hillocks-controlled erosion independently of the service provided by the willow. All three species of grass are rhizomatous caulophytes forming one complex adaptative system of tangled roots under the conditions of aeolian processes (Łukasiewicz 1962, Borysiak 2022), overgrowing the freshly trapped sand. The coexistence of willow and grasses (also other accompanying plants) gives a higher level of vertical accretion. It contributes to the faster development of dunes less susceptible to degradation in response to severe storms under the continued global warming. In the case of habitats 2120 (white dunes) and 2130 (grey dunes) of Natura 2000 sites, ordering the removal of neophyte *S. acutifolia* in management plans to ensure their favourable conservation status would reduce the level of erosion control service 2.2.1.1 and its role for nature conservation.

Conclusions

The study has shown that the neophyte *S. acutifolia* in its spontaneous locations in Wolin National Park is not an invasive species and does not threaten biodiversity. On the contrary, it contributes to developing biodiversity patterns and provides erosion-control ecosystem services. Therefore, the current conservation practice of removing the willow from coastal habitats is not justified. We have formulated the scope of scientific research that should be conducted before making any management decisions regarding the elimination of neophyte in order to achieve a favourable conservation status of dune habitats.

Acknowledgments

The authors would like to thank the anonymous reviewers for their valuable comments,

which contributed to the scientific improvement of the manuscript.

Funding

The research is a part of the project 'Services provided by main types of ecosystems in Poland – an applied approach' and received funding from Iceland, Liechtenstein and Norway within the EEA Financial Mechanism 2014–2021 and from the budget of Poland.

Authors contribution

J. Borysiak: conceptualization-discussion, methodology-discussion, literature review, data collection, data analysis and interpretation, writing-original draft preparation and revising, figure creation. P. Czyryca: conceptualization-discussion, methodology-discussion, data collection, writing-revising. M. Stępniewska: conceptualization, methodology, funding acquisition, literature review, data collection, data analysis and interpretation, writing-original draft preparation and revising, figure creation.

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