EFFECTS OF GEOMORPHOLOGICAL PROCESSES AND PHYTOCLIMATE CONDITIONS CHANGE ON FOREST VEGETATION IN THE POMERANIAN BAY COASTAL ZONE (WOLIN NATIONAL PARK, WEST POMERANIA)

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Manuscript received: July 23, 2022
Revised version: January 9, 2023

Tylkowski J., Paluszkiewicz R., Winowski M., Czyryca P., Kostrzewski A., Mazurek M., Rachlewicz R., 2023. Effects of geomorphological processes and phytoclimate conditions change on forest vegetation in the Pomeranian Bay coastal zone (Wolin National Park, West Pomerania). *Quaestiones Geographicae* 42(1), Bogucki Wydawnictwo Naukowe, Poznan, pp. 141–160. 14 figs, 1 table.

Abstract: The functioning of plant associations, including forest associations, in the coastal cliff edge zone of the Pomeranian Bay in the Wolin National Park (WNP) is determined by short-term factors related to the dynamics of erosion and denudation processes and long-term phytoclimatic conditions' changes. The study presents a temporary analysis of the occurrence of sea abrasion and water and aeolian erosion, based on the applied hydrometeorological threshold values. The influence of changes in phytoclimatic conditions on the development and productivity of coastal forests with the dominant species of *Fagus sylvatica* was also presented. Assessments of spatial susceptibility to erosion of the cliff coast and the existing plant associations were also carried out in conditions of the risk of coast erosion. It was found that 55% of the cliff edge zone of the Pomeranian Bay of the WNP and the forest associations (mainly *Luzulo pilosae-Fagetum*) occurring there are in the zone of particular risk of increased erosion and denudation processes. In addition, unfavourable trends in changes in phytoclimatic conditions in the 21st century were found, which reflect climate changes unfavourable to the development of beech forests on Wolin Island.

Key words: forest vegetation, cliff edge zone, erosion and denudation processes, phytoclimatic conditions, Pomeranian Bay, Wolin Island

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Introduction

The current functioning of plant associations is determined both by global factors through climate change and local factors related to, *inter alia*, the dynamics of erosion-denudation processes. The stability of the substrate, resulting from the interaction of mainly abiotic properties of habitats, is an important factor responsible for the succession and harmonious development of plant associations, including forest associations. Therefore, it is of great importance to indicate the relationships between morpholithological and hydrometeorological conditions and the

https://doi.org/10.14746/quageo-2023-0010
ISSN 2082-2103, eISSN 2081-6383

intensity of the erosion-denudation processes. The above relationships determine the spatial and temporal transformations of habitats and the dynamics of vegetation development. Determining the impact of abiotic components of the natural environment on the development of plant associations is particularly important in edge zones that are characterised by the relief energy, in the form of e.g. significant height differences and slopes as well as the presence of active mass movements.

An example of an edge zone in which there is a significant influence of hydrometeorological conditions and the dynamics of geomorphological processes on the changes and development of plant associations is the part of terminal moraine occurring in the Wolin National Park (WNP) undercut by the cliff coast of the Wolin Island. Therefore, it is important to recognise the relationship between the features of glacial, fluvioglacial and aeolian topography and the activity of geomorphological processes and soil features in zones of high relief energy. In these zones, morphogenetic activity is the most intense, and sedimentary covers are the least stable, which has an impact on the dynamics and structure of the plant cover. Such a situation of increased erosion of quaternary sediments in the WNP occurs mainly in the zone of geomorphologically active cliffs of the Pomeranian Bay.

The individuality of the cliff topography, among other active elements, consists of landslides and rockfalls, and erosion-denudation valleys cutting through the cliff's top (Kostrzewski et al. 2015). An intensification of mass movements, water and aeolian erosion occurs mainly on the slope and at the foot of the cliff. Significant transformations of the topography occur especially during storm surges, efficient precipitation and strong winds (Tylkowski 2018).

Climate and sea level changes, also visible in the Southern Baltic coastal zone, affect the occurrence of geohazards (Paprotny, Terefenko 2017, Hojan et al. 2018, Tylkowski 2018, Winowski et al. 2019, Rutgersson et al. 2022, Meier et al. 2022a), such as intense shore erosion or rapid mass movements, resulting in e.g. degradation of coastal dunes associations and the development of specialised plant associations on the cliff top, e.g. thermophilic orchid beech (Tylkowski et al. 2021).

The morphodynamics of the top cliff edge does not currently show a clear increasing linear trend of its erosion. A general analysis of the linear trend in cliff top recession on a total coast length of 1.36 km tested area, registered since 1984, revealed no statistical dependence. Despite the increased frequency in recent years of extraordinary hydrometeorological events, no intensive cliff top abrasion has been observed. A distinctive feature of the coastal cliff is the cyclical activity of cliff top recession connected with occasionally occurring extreme phenomena. Twenty-year cycles of cliff recession activity were observed with 10-year intervals ±2–3 years between the maximum and minimum of the cycle (Kostrzewski et al. 2015). The greatest erosion of the cliff occurs during episodic, extreme storm surges, e.g. 3 and 4 November 1995 (161 cm above average sea level with maximum cliff top recession of 8.35 m). These extreme morphodynamic events are random, with no clear relationship to climate change. In the effect of predicted global sea level rise in 2100 in the range between 69 cm and 111 cm (Bamber et al. 2019), the frequency of extreme Baltic Sea levels will rise (e.g. Hieronymus, Kalén 2020). However, extreme changes of sea level in relation to average sea level will not be statistically important, because it is predicted that wind velocities will stay unchanged (Christensen et al. 2022). In the Polish coastal zone of the Baltic Sea, the mean annual air temperature may rise in the 21st century by 2–3°C, with a concurrent rise in total precipitation of 0–10% during summer and 10–20% during winter (Collins et al. 2013). Therefore, in the longer term, climate changes will cause changes in the species composition of forests (Tylkowski 2015a).

In the coastal cliff area, individual components of the natural environment have been well recognised, including: geological structure, lithology of surface sediments, and topography (Borówka et al. 1982, 1999, Kostrzewski, Zwoliński 1987a, b, Winowski 2015), morphodynamics of the cliff edge (e.g. Kostrzewski 1987, Kostrzewski, Zwoliński 1987c, 1995, Kostrzewski et al. 2015, 2017, Winowski et al. 2019, 2022), climatic conditions and the water cycle (e.g. Tylkowski 2013, 2018, Tylkowski, Hojan 2018). The type and occurrence of plant associations were also determined (e.g. Piotrowska 1955, 1979, 1993, 2003).

There are no studies showing the relationships and cause–effect relationships between abiotic conditions and the occurrence and functioning of plant associations. The existence and development of some forest habitats (e.g. the Baltic orchid beech *Cephalanthero rubrae-Fagetum* between Biała Góra and Grodno) is conditioned by the occurrence of secular erosive processes (Tylkowski et al. 2021), and, in turn, other plant associations (e.g. the *Elymo-Ammophiletum* between Grodno and Wisełka) are disappearing due to extreme erosion of the sea coast.

The dynamics of erosion and denudation processes and the development of plant associations in the area of the cliff coast are determined by hydrometeorological conditions. Occasionally, during the occurrence of extreme hydrometeorological events, rapid but spatially limited morphological changes of the cliff edge and degradation of phytocoenoses occur. The temporal distribution of hydrometeorological threshold values initiating mass movements as well as water erosion (Winowski 2015, Tylkowski 2018) and aeolian erosion (Hojan et al. 2018) was analysed.

The present study aims to determine the influence of cliffed coast morphodynamics and phytoclimatic conditions' changes onto the development of plant associations in the WNP coastal cliff zone in the second decade of the 21st century. The succeeding parts of the paper offer an elaboration concerning associations inferred between the floral diversity in the Wolin National Park and parts of a coastal cliff that are subject to coastal erosive activity and therefore undergoing rapid degradation.

Study area

The research area is located on the South Baltic Coast (313), in the Szczecin Coast macroregion (313.2-3), and in the Uznam and Wolin mesoregion (313.21) (Kondracki 1998). Morphogenetically active Pomerania Bay cliffed coast on Wolin Island is located on the territory of WNP. No activities of coast erosion protection are conducted within the Park area. Cliffed coast erosion is the effect of natural erosion-denudation processes' occurrence, induced mainly by storm surges. This is why, in this region, the morphodynamics of the Baltic Sea coastal cliff and changes in the type and extent of vegetation associations are especially important.

The studied cliff edge zone of the Pomeranian Bay, approx. 14.5 km long, extends in the section of the sea coast, between Międzyzdroje and Międzywodzie (Fig. 1), and constitutes a strip of the moraine plateau of the Wolin Range (Kostrzewski, Zwoliński 1994). The complex of terrain forms in the research area is a glacitectonically dammed moraine, built of heavily disturbed glacial and fluvioglacial sediments, cut by steep cliffs from the sea coast (Borówka, Tomaszewski 1978). The Wolin Range consists of extensive moraine surfaces, often as isolated hills, sometimes reaching heights of over 100 m a.s.l. and numerous depressions in the form of undrained hollows, deeply erosive valleys, and contemporary erosional cuts.

The cliff edge zone of Pomeranian Bay (Figs 2 and 3) is located within the northern part of the Wolin frontal moraine. It breaks off in the north with steep cliffs reaching 93 m a.s.l. (Gosań Hill), and its slope ranges from 30º to over 70º. The altitude of the terrain varies from 0 m to 108 m a.s.l. The lowest part of the area is the beach at the foot of the cliffs. The greatest relief diversity can be observed in the section Biała Góra – Świdna Kępa. The landscape features numerous hills separated by erosion-denudation valleys. Valleys have slopes with a gradient of up to 30–35°. The coastal zone is dominated by active cliffs of varied geological structures (sandy, loamy, sandy-loam). Most of the cliff coast slopes have a northwest aspect.

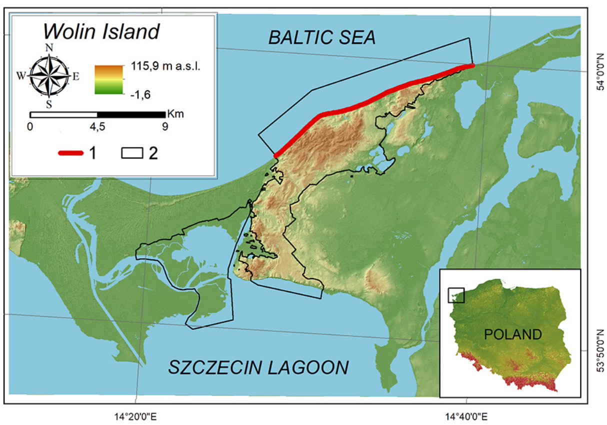

Fig. 1. Edge zone of Pomeranian Bay in the Wolin National Park – location of the research area; based on ISOK project (2011).
1 – edge zone of the Pomeranian Bay, 2 – Wolin National Park.

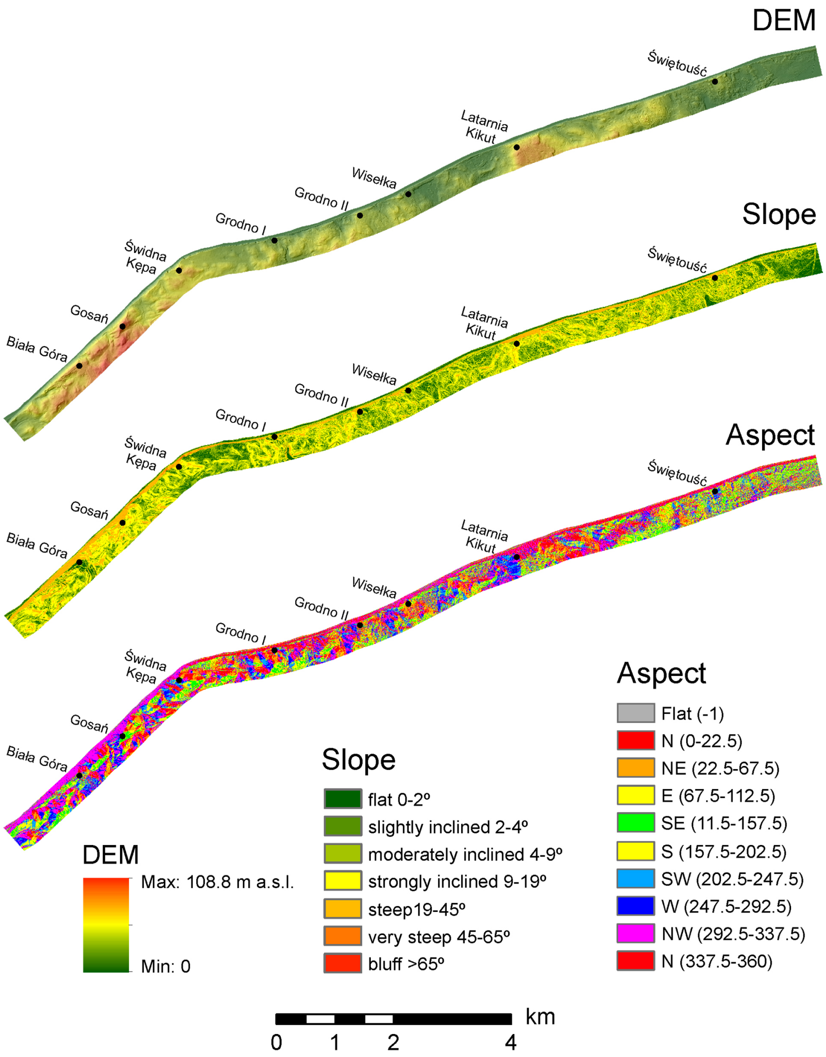

Fig. 2. Morphometric parameters of the Pomeranian Bay edge zone: terrain slopes and aspect based on digital elevation model (DEM) from ISOK project (2011).

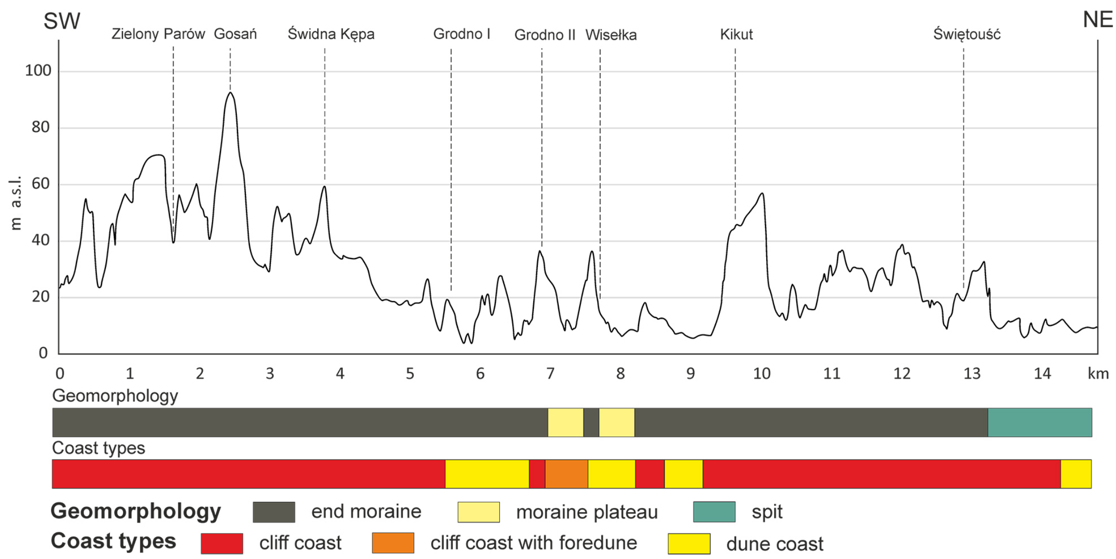

Fig. 3. Morphological profile of the Pomeranian Bay edge zone in the area of the Wolin National Park based on ISOK project (2011).

To the east of Świdna Kępa, the altitude of the terrain drops quite clearly to about 20 m a.s.l., while the cliff slopes assume the northern exposition. In the section between Grodno and Wisełka, the cliff coast is clearly stabilised by pine forests, and in its foreground there is a well-formed front dune. The part of the coast stretching to the east of Wisełka is characterised by an altitude of about 5–8 m a.s.l. This lowering of the terrain is crowned with a front-moraine hill with a level of up to 75 m a.s.l. For the next 4 km, the topography is characterised by a significant rhythm, with numerous elevations and depressions. The coastal zone is dominated by active, clay and sandy cliffs. The eastern part of the analysed area is a vast depression located near the base of the Dziwnów Peninsula. In this place, the cliff edges give way to dune coasts, and the altitude of the terrain is approx. 10 m a.s.l. in the crest of dunes and 2–5 m a.s.l. in their back.

Materials and methods

Coastal cliff morphodynamics, being the effect of erosional-denudational processes' occurrence, is mostly dependent on short-term hydrometeorological conditions' changes. Spatial differentiation of mass movements and coastal erosion geohazards has been described. Spatial valorisation of risk to forest stands of the cliffed coast of WNP has been performed, taking into account the type of plant associations and type and morphodynamics of the sea coast.

In arriving at a decision concerning the extent up to which there has been development of the dominating *Fagus sylvatica* forest stands in the coastal zone of WNP, it has been necessary to consider the threshold values corresponding to the changing phytoclimatic conditions characterising the cliffed coast zone. It also pointed to the climate aridity index (AI) and the temporal changeability and forest productivity index.

In this elaboration, hydrometeorological and phytoclimatological analyses based on raw data were used; additionally, results of earlier studies in the literature pertaining to coastal cliffs morphodynamics were used (Kostrzewski et al. 2015, Winowski et al. 2019, 2022). Cliff edge retreat rates data from the years 1984–2020 and results of morphometric measurements of the terrain surface from airborne scanning from the years 2012–2020 were also included. The analysis of the erosive events occurrence determined by exceeding the hydrometeorological threshold values and the phytoclimatic assessment for the period 2010–2020 based on the daily sea level data from Świnoujście (data from the Institute of Meteorology and Water Management) and own meteorological data from the Environmental Monitoring Station of the Adam Mickiewicz University in Biała Góra, which is located directly in the cliff edge zone of the Pomeranian Bay of the WNP. Hydrometeorological conditions for coastal cliff erosion analysis were assessed according to methods adapted from Winowski (2015), Hojan et al. (2018), Tylkowski (2018) and Tylkowski and Hojan (2018).

Analyses of plant associations' occurrence in the cliffed coast zone based on the real vegetation map from 2014 (WNP data) and filed mapping from 2021 were also performed. Plant associations were determined based on Matuszkiewicz's (2014) classification.

The analysis of coastal, fluvial and aeolian erosion events' frequency was performed for the cliffed coast based on the occurrence of hydrometeorological threshold values in the second half of the 21st century. Many years of research on the cliff coast have made it possible to distinguish the threshold value of sea level for cliff abrasion. When the maximum water level is at least 90 cm higher than the average, the foot of the cliff is abraded (Winowski 2015, Tylkowski 2018). Research conducted on the coast of Pomeranian Bay (Tylkowski 2015b) showed that on the dune coast, sea abrasion occurs most often when the water level exceeds the mean sea level by 94 cm. Then, the frontal dune is abraded, e.g. in the edge zone near Grodno. In the case of atmospheric precipitation, the criterion for the occurrence of mass movements (e.g. landslides) was the amount of precipitation within 15 days ≥90 mm and the simultaneous precipitation within 2 days ≥40 mm (Winowski 2015). The study included the threshold values of weather elements that trigger deflation on the cliff slope as well as the transport of mineral matter and its accumulation at the top of the cliff, such as: average daily wind speed ≥4.4 m $\cdot$ s^{-1}, average daily air temperature >0°C and no precipitation atmospheric conditions for 2 days. It was assumed that aeolian processes occurred while meeting all the above threshold values (Hojan et al. 2018). For this purpose, the daily data of sea level, air temperature, precipitation and wind speed were considered. The time analysis of exceeding the hydrometeorological threshold values for the research period 2010–2020 allowed to indicate the long-term and seasonal distribution of abrasion events, mass movements and deflation, which consequently cause floristic changes. Direct studies of mass movements on the cliff coast of Wolin Island allowed for the determination of threshold values initiating geomorphological processes such as landslides, sediment fall, and slumping (Kostrzewski et al. 2015, Winowski 2015).

The trend of changes in phytoclimatic conditions was determined based on the following indicators (Mayr 1909, De Martonne 1926, Ellenberg 1988, Tylkowski et al. 2021): De Martonne AI, Ellenberg quotient (EQ), Forestry Aridity Index (FAI), and Mayr tetratherm (MT) index. The application of the above phytoclimatic indexes will allow the presentation of annual thermal-precipitation changeability in the context of forest stands' development. Multi-annual (2010–2020) tendency and the classification of following years in the scope of optimum or restrictive thermal-precipitation conditions for the development of the dominating tree species, that is *Fagus sylvatica*, were determined. Phytoclimatic indices were compared to the threshold values of the species *Fagus sylvatica* (Budeanu et al. 2016): De Martonne AI (De Martonne 1926) with optimal thresholds for the beech forest in the range of 35–40 (Satmari n.d.), EQ (Ellenberg 1988) with an optimal threshold favourable for beech development <30 and its disappearance threshold >40 (Stojanovic et al. 2013), FAI with climatic conditions favourable for beech trees <4.75 (Führer et al. 2011) and MT (Mayr 1909) with optimal thermal conditions for a beech forest of 13–18°C (Satmari n.d.).

In addition, to show the relationship between weather conditions and biomass productivity, the radiant index of climate aridity (RIA) (Budyko 1975) was analysed and the forest productivity of the WNP cliff edge zone was assessed based on the climate vegetation productivity (CVP) index (Paterson 1956).

Research of cliffed coast morphometrics and morphodynamics influencing the functioning of forest stands was performed in the 500-m land stripe extending inland from the shoreline, based on terrain altitude data from airborne laser scanning (ALS, ISOK project, 2011) and ALS data from 2012–2020, gained from the Marine Office in Szczecin. The point cloud density ranged from 3 pts $\cdot$ m^{-2} to 8 pts $\cdot$ m^{-2}. Owing to these data it was possible to delimit cliff sections of different erosion dynamics (m^3 $\cdot$ m^{-1} $\cdot$ a^{-1}): low ≤5.25, moderate 5.26–9.50, high 9.51–13.75 and very high >13.75 (Winowski et al. 2022).

Based on geoinformation analyses and direct field studies, the areas particularly vulnerable to the intensification of erosion and denudation processes, which may lead to the degradation of plant associations, especially forest associations, have been identified. The valorisation was based on the coast type and its morphodynamics and occurrence of forest associations. To determine the degree of erosion risk of forest associations in the cliff edge zones of the WNP, a three-level scale was created: class 0 – no risk, class I – moderate risk and class II – high risk. Sections showing no risk (class 0) were separated, corresponding to the fragments that are usually protected by the dune belt. These are primarily stabilised cliffs and inactive cliffs, where mass movements occur in points or are not currently found, and thus they do not affect the neighbouring forest habitats. Sections of the active cliff that are subject to the influence of sea abrasion, resulting in intensification of the processes of loose sediment sliding (for which phenomenon rinsing processes also serve as a secondary causative factor), were assigned a moderate level of risk (class I). In the event of high risk (class II), on very active cliff sections, the risk of degradation of forest associations due to the increased susceptibility of erosive processes, the formation of landslides and increased intensity of aeolian processes, also extends inland, beyond the area of the cliff top itself, resulting in, on the one hand, its accelerated withdrawal, and on the other, the instability of the subsoil, leading to significant surface changes in the morphometric and soil structure of the forest.

Results

Plant associations

Based on the real vegetation map from 2014 and plant mapping in 2021, it can be indicated that many valuable and unique plant associations can be found in the cliff edge zones of the WNP, e.g. *Cephalanthero-Fagenion*. There were no significant changes in the occurrence of plant associations in the examined edge zone. The dynamics of the cliff top erosion in the analysed time interval (2014–2021) was low and the land cover structure was stable. The largest part of it is occupied by *Luzulo pilosae-Fagetum* (4.75 km of cliff coast, 32.0% of the cliff top), *Cephalanthero rubrae-Fagetum* (2.71 km, 18.3%), *Empetro nigri-Pinetum* (2.57 km, 17.3%), *Betulo-Quercetum roboris loniceretosum xylostei* (2.46 km, 16.6%), *Galio odorati-Fagetum* (1.88 km, 12.7%), *Fago-Quercetum petraeae* (0.32 km, 2.2%) and *Leucobryo-Pinetum* (0.15 km, 1.0%). The plant associations of *Luzulo pilosae-Fagetum*, *Cephalanthero rubrae-Fagetum* and *Fago-Quercetum petraeae* are characteristic for the edge zone of the Pomeranian Bay of the WNP. One of the typical plant associations in this zone is *Luzulo pilosae-Fagetum*. This type of beech forest is characterised by a dense tree layer that consists of almost only *Fagus sylvatica* with a low species of undergrowth, covered with a thick layer of litter. On the other hand, a unique and one of the most important forest associations for the edge zone of the Pomeranian Bay is the *Cephalanthero rubrae-Fagetum*. It occurs in a narrow (up to 100 m wide), discontinuous strip about 3 km long from Biała Góra to Grodno, between the cliff edge and the *Luzulo pilosae-Fagetum* phytocoenoses. Its presence is strongly related to the morphodynamics of the cliff coast and the specific soil – the cliff naspas (Prusinkiewicz 1971, Hojan 2009). The formation of naspas is strongly related to the interaction of active, continuous erosion and accumulation of aeolian processes. The cliff wall is exposed to the wind, and the sands and carbonate dust blown on the top of the cliff de-acidify the soil, resultant to which *Orchidaceae* plants can develop in this zone (Tylkowski et al. 2021).

Cliff morphodynamics

The measurements of the abrasion rate (loss of the cliff's top), conducted annually since 1984, on five test sections, allow for the quantification of the rate of the cliff coast retreat in the cliff edge zone of the Pomeranian Bay and the possibility of degradation of plant associations. Currently collected measurement data (Kostrzewski, Zwoliński 1986a,b, 1987c, 1988, 1995, Kostrzewski et al. 2015, 2017, Winowski 2020) make it possible to determine the average abrasion rate of cliffs at about 7.5 m in the last 35 years. The lowest annual dynamics were recorded in the sandy-clay sections of 0.12 m · a^{-1}, where the geological structure has a relatively large share of clay sediments resistant to erosion. On the other hand, the greatest erosion was recorded in typically sandy sections, 0.32 m · a^{-1}, which is characterised by very low cohesion and is subject to fairly rapid degradation. As a result of storm surges, sand cliffs are rapidly washed away and the processes of shedding and landslides are started. Increased dynamics of 0.28 m · a^{-1} were also observed on sections built of clay and sandy formations, where groundwater outflows occur.

Episodic extreme, erosive events play the most important role in shaping the Wolin Island cliffs. During extreme storm surges, permanent abrasive undercuts occur, which, later, in subsequent time sequences, cause destabilisation of the upper cliff segments and degradation of forest associations. Depending on the geological structure of the cliff, the slope response takes place at different timescales. Sandy cliffs have the fastest reaction time, while clay cliffs have the longest reaction time. In the case of sandy cliffs, the most common process leading to their intensive development is landslide and scree. On the other hand, for clay cliffs, the primary process disturbing the state of equilibrium is the process of stripping. For example, the occurrence of extreme, short-term storm surges in 1995, 2004 and 2017 caused the cliff top to recede to an average distance of 2.74 m, which accounted for as much as 35% of the total coast loss in the period 1984–2020. Between these episodes, there were periods of relative cliff stability. The length of the stabilisation periods ranged from 9 years to 13 years, with an average of 11 years. It can be initially concluded that the morphodynamics of the edge zone of the Pomeranian Bay in the WNP is characterised by a distinct development stage, during which the cliff sections change their morphodynamic functions, during episodes of intense erosion (mainly extreme events) separated by stabilisation periods (about 11 years). Considering the relatively short measurement period (~35 years) of the cliff top retreat, the presented cyclicity of the cliff morphodynamics will be modified along with the length of the measurement series. However, the presented conditions and the course of development of the cliff coast in the annual and multi-annual cycle (1984–2020) are closely related to the degradation of the range of plant associations in the edge zone of the cliff top.

The largest erosion was observed on sandy cliffs, and the smallest on clay cliffs and on cliffs that are densely covered with vegetation. The average annual dynamics (based on ALS data 2012–2020) of the all cliff edge erosion (from the base to the top of the cliff slope) on the WNP is approx. 6.6 $m^3 \cdot m^{-1}$ and 0.17 $m^3 \cdot m^{-2}$. During the 2012–2020 period, from the cliff coast measuring approx. 10 km, almost 510,000 m^3 of sediment was discharged into the sea (Winowski et al. 2022). Low and mean sediment loss (≤9.50 $m^3 \cdot m^{-1} \cdot a^{-1}$) were detected especially within the stabilised cliff parts, which were densely covered with forests, and the areas built with glacial tills demonstrated a greater resistance to erosional processes. The lowest erosion intensity was observed in the section between Międzyzdroje and Biała Góra and from Świętouść to Międzywodzie. This is why on these cliffed coast segments, the low potential of erosion-denudation processes is not generating important changes in plant associations, including forests. In turn, high and very high erosion (>9.50 $m^3 \cdot m^{-1} \cdot a^{-1}$) were observed over the section from Gosań hill to Świdna Kępa hill (about 0.8 km) and in Świętouść (about 1.2 km). Resultantly, the erosion-denudation process's high dynamics are causing the limitation of habitat extents, including types of vegetation associations. In these areas especially exposed to changes are both *Cephalanthero rubrae-Fagetum* and *Luzulo pilosae-Fagetum.*

Potential occurrence of cliff edge erosion events based on exceeding the threshold values of hydrometeorological conditions

In the coastal zone of Wolin Island, in the period 2010–2020 (Biała Góra in WNP), a statistically significant ($p < 0.05$) increase in the mean annual air temperature (mean 9.8°C; +0.24°C $\cdot a^{-1}$) and a decrease in the annual sum of atmospheric precipitation (mean 590.0 mm; −23.5 mm $\cdot a^{-1}$) were observed. Sea level rise (~2 mm $\cdot a^{-1}$) and a high frequency of storm surges were also found. The above hydrometeorological conditions intensify erosion and denudation processes, which result in changes in the topography (e.g. increased erosion of the coastal zone and changes in the terrain morphometry) and soil covers (changes in the extent of soils in the immediate vicinity of the cliff face slope, e.g. on the cliff side). In addition, climate change, through an increase in thermal conditions, limited precipitation, high evapotranspiration, frequent droughts and heat waves, stress the development of plant associations, including forest associations.

In the period 2010–2020, hydrometeorological conditions favouring the launch of mass movements (landslides and falls) were present only for 27 days. Favourable conditions for the cliff abrasion occurred during 20 days of storm surges (Fig. 4), and only during 7 days was water erosion possible, initiated by the occurrence of efficient precipitation (Fig. 5).

No correlation was found between the annual dynamics of the cliff top retreat and the occurrence of erosive hydrometeorological events (Table 1). Sea level erosion events (days with sea level ≥0.9 m above average) do not show a clear relationship with the immediate loss of the cliff top. For example, in 2012, the average dynamics of the cliff top retreat was 0.25 m. At that time, 5 days with erosive sea level and 2 days with the possibility of mass movements during efficient precipitation were found. However, in 2017, when a similar number of hydrometeorological erosion events occurred, the average withdrawal of the cliff top was more than three times smaller and amounted to only 0.07 m. Very often,

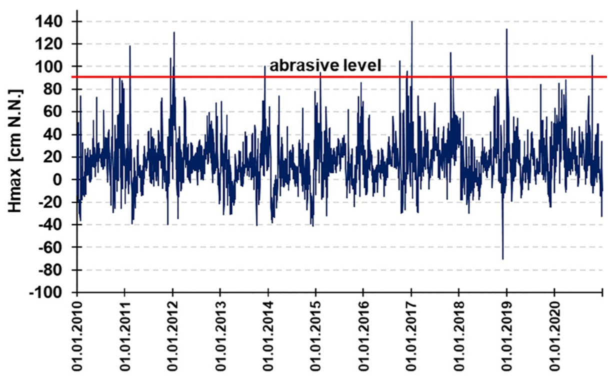

Fig. 4. Time distribution of abrasive level (maximum sea level Hmax>90 cm above N.N. – Normal Null sea level) generating the initiation of mass movements on the cliff coast of the Pomeranian Bay of the Wolin National Park; based on raw data of the Institute of Meteorology and Water Management in Warsaw.

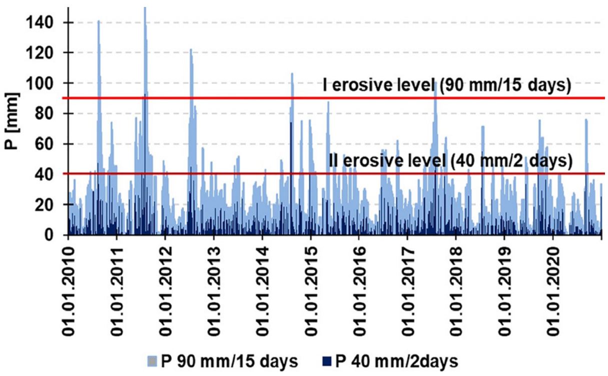

Fig. 5. Time distribution of threshold values of daily precipitation sums (P≥90 mm in 15 days and at this time P ≥40 mm in 2 days) generating the initiation of mass movements in the edge zone of the Pomeranian Bay of the Wolin National Park; based on the data from the meteorological station in Biała Góra.

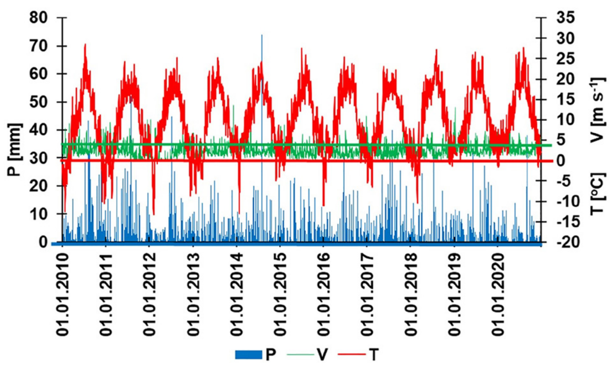

Fig. 6. Time distribution of threshold values of aeolian processes in the edge zone of the Pomeranian Bay of the Wolin National Park, (P represents daily sums of precipitation, with a threshold value of 0 mm in 2 days; V average daily wind speed, threshold value ≥4.4 m · s^{-1}; and T average daily air temperature, threshold value >0°C); based on the data from the meteorological station in Biała Góra.

significant erosion concerns only the base of the cliff, and its top and forest communities occurring there are not subject to increased degradation. Thus, not every erosive storm surge causes erosion of the cliff wall along its entire height. Such effects cause episodic, extremely erosive storm surges with a threshold value that is difficult to define.

Aeolian processes are an important factor shaping the topography of the WNP cliff edge zone, especially on the cliffs without vegetation, and are responsible for the formation of contemporary aeolian covers and the change in soil conditions by reducing their acidification. As a result of the aeolian supply of sandy and dusty material, aeolian covers are formed with a maximum range of up to 200 m from the cliff's top, which, together with the annual deposition of organic matter (including beech leaves), form the embankment near the cliff. In the period 2010–2020, 196 days were found with potentially favourable weather conditions for the occurrence of aeolian processes in the edge zone (Fig. 6).

Genetic determinants of the erosion processes of the cliff edge zone are characterised by a significant seasonal discrepancy (Fig. 7). The erosion of the coast by mass movements (landslides, slumps, falls, undercuts, etc.) is mainly caused by storm surges, which occur mainly in the cool half-year, from October to March. On the other hand, the processes of slope denudation (mass movements and water erosion) caused by intense rainfall are characterised by high episodic nature and occur only in the summer period, mainly in July. In turn, aeolian erosion of cliffs and the deposition of mineral matter at the cliff top occurred throughout the year, but most often such events were recorded in spring and autumn.

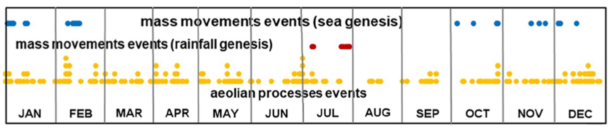

Fig. 7. Seasonality of the occurrence of geomorphological processes' events in the edge zone of the Pomeranian Bay of the Wolin National Park in 2010–2020; based on the average data from the meteorological station in Biała Góra and mareographic station in Świnoujście.

Table 1. Annual average retreat of the cliff top and hydrometeorological erosive events' frequency in the 2010–2020 period on the Wolin National Park cliff coast.

Parameter/year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2010–2020
Average rate of the top cliff (m · a^{-1}) on a 1.36 km cliff coast tested area	0.25	0.10	0.25	0.12	0.09	0.24	0.10	0.07	0.06	0.14	0.14	0.14
Events of abrasive sea level (days)	0	3	5	0	2	1	0	4	3	1	1	20
Events of erosive precipitation (days)	0	3	2	0	0	0	0	2	0	0	0	7

Episodically in the winter season, niveoaeolian processes were also observed. On the other hand, a relatively lower frequency of aeolian processes on the cliff occurred in summer, especially from July to October, when the wind speed was lower and higher precipitation caused the surface of the land to become moist.

For the cliff edge zone of Pomeranian Bay, based on the dominant NW wind direction, areas exposed to deflation and aeolian accumulation can be determined (Fig. 8). The values of the wind efficiency index WE >1 define areas subject to intense aeolian processes (non-forested area – mainly deflation from the cliff and forested area – mainly accumulation of blown matter from the cliff). On the other hand, the values of the WE <1 determine the area lying in the aeolian shadow, with a negligible intensity of aeolian processes. Thus, the windward slopes of the cliffs devoid of vegetation have WE values >1 and are mainly deflated. On the other hand, forested windward slopes, also with WE >1 values, constitute the area of aeolian accumulation and are responsible for the formation of the aeolian covers with which the cliff tops undergo deposition; this phenomenon is noticed inter alia with the naspas cliff, wherein it determines the pace of development of the habitat of the *Cephalanthero rubrae-Fagetum* orchid beech forest. In the cliff edge zone of Pomeranian Bay, there is a greater share of the area with a potentially significant role of deflation processes (WE >1) in shaping the topography and changes in soil cover. A relatively greater morphodynamic and soil-forming role of aeolian processes was found, especially in the area of the cliff edge and in its vicinity. Due to the dominance of active cliffs devoid of vegetation, aeolian processes are common and therefore the designated areas of aeolian erosion and accumulation (WE >1) are real.

The influence of climatic changes on the directions and rate of changes in forest associations

Phytoclimatic indicators are a manifestation of the changing climatic conditions in the cliff edge zone of the WNP. In the years 2010–2020, there were rather unfavourable phytoclimatic conditions (Fig. 9). The AI, EQ, FAI and MT indices show statistically significant (p <0.05) trends in changes in climatic conditions beyond the climatic optimum for *Fagus sylvatica*. The AI index, on the other hand, shows changes from very humid conditions (optimal for the Pomeranian beech forest) towards sub-humid and Mediterranean conditions. In 2020, there were even semi-dry phytoclimatic conditions. All phytoclimatic

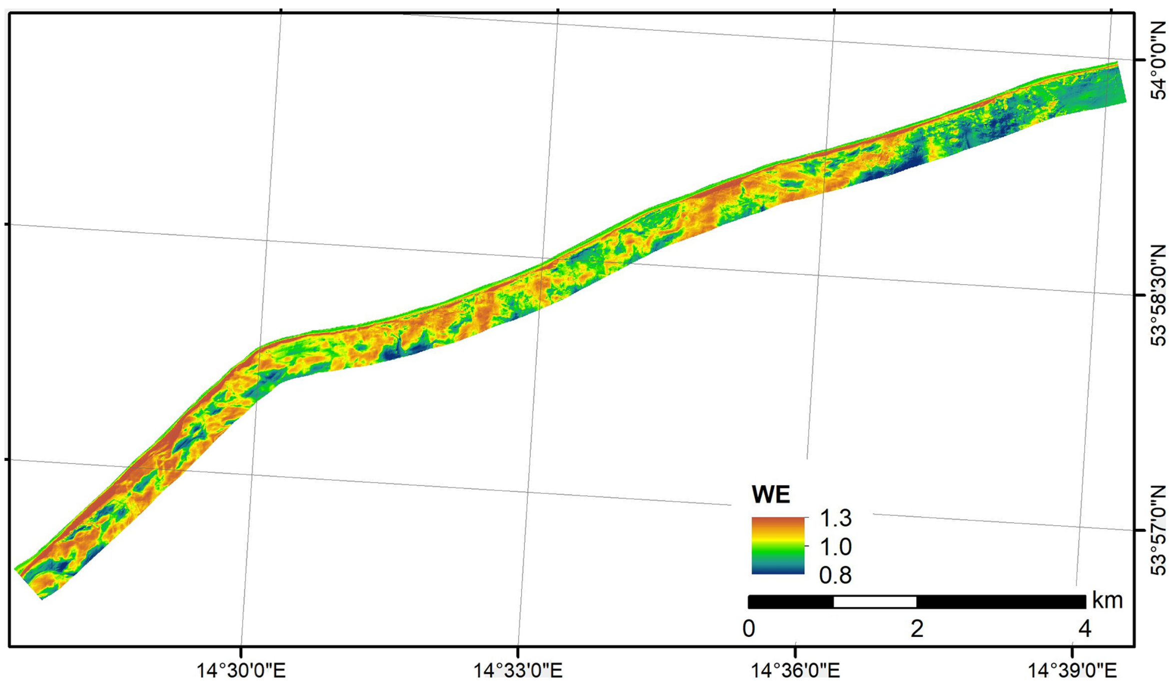

Fig. 8. Activity zones of wind efficiency index: WE >1 and restrictions WE <1 aeolian processes in the edge zone of the Pomeranian Bay of the Wolin National Park based on ISOK project (2011).

indicators confirm the climatic stress, especially in the last 3 years, for the tree species *Fagus sylvatica*, which is dominant in the cliff edge zone of the WNP. The current climatic conditions are too warm and too dry for boreal conifers. Climate change is particularly unfavourable for *Pinus sylvestris* in the cliff edge zone of the Pomeranian Bay. For example, the MT index, which is the value of the average air temperature in the period from May to August on the cliff coast of Wolin Island, is 17.1°C (Biała Góra 2010–2020). It is believed that the average air temperature in the four warmest months (May–August) has the greatest impact on the development of vegetation (Dahl 1998). Currently, the thermal conditions in the cliff edge zones of the WNP are not favourable for the development of forest associations with low thermal requirements of the *Piceetum* type (tetraterma 10–14°C). However, currently there are favourable thermal conditions for the development of forest associations with higher thermal requirements of the *Fagetum* type (tetraterma 13–18°C) (Budeanu et al. 2016). However, the thermal conditions for *Fagus sylvatica* are in the upper threshold of the thermal optimum; and taking into account the dynamics of the average air temperature increase of 0.3°C · 10 years^{-1} (Tylkowski 2013) and the expected increase in the average air temperature by 2–3°C by the end of the 21st century, in the coming 100 years, unfavourable conditions for the development of beech forests will emerge, whereas potentially favourable conditions will arise for the expansion and development of forest associations with very high thermal requirements, e.g. the *Castanetum* type. If the above scenario turns out to be true, then in the second half of this century, higher thermal conditions will be too demanding for the functioning of *Fagetum* forest associations. It can therefore be assumed that for the dominant forest associations of the WNP cliff edge zone, the phytoclimatic conditions in the next decades of the 21st century will be too difficult for the development of beech and may cause gradual degradation and, in the longer term, reconstruction of the existing tree stands.

The radiation dryness index (RIA) proves the unfavourable climatic conditions for the development of forest associations. For the cliff edge zone of the WNP, the RIA index (2010–2020) was 1.08, which proves that the threshold values of the climatic optimum for forests (RIA 0.8–1.0) were exceeded and the production of biomass decreased (Fig. 10). A statistically significant increase in the

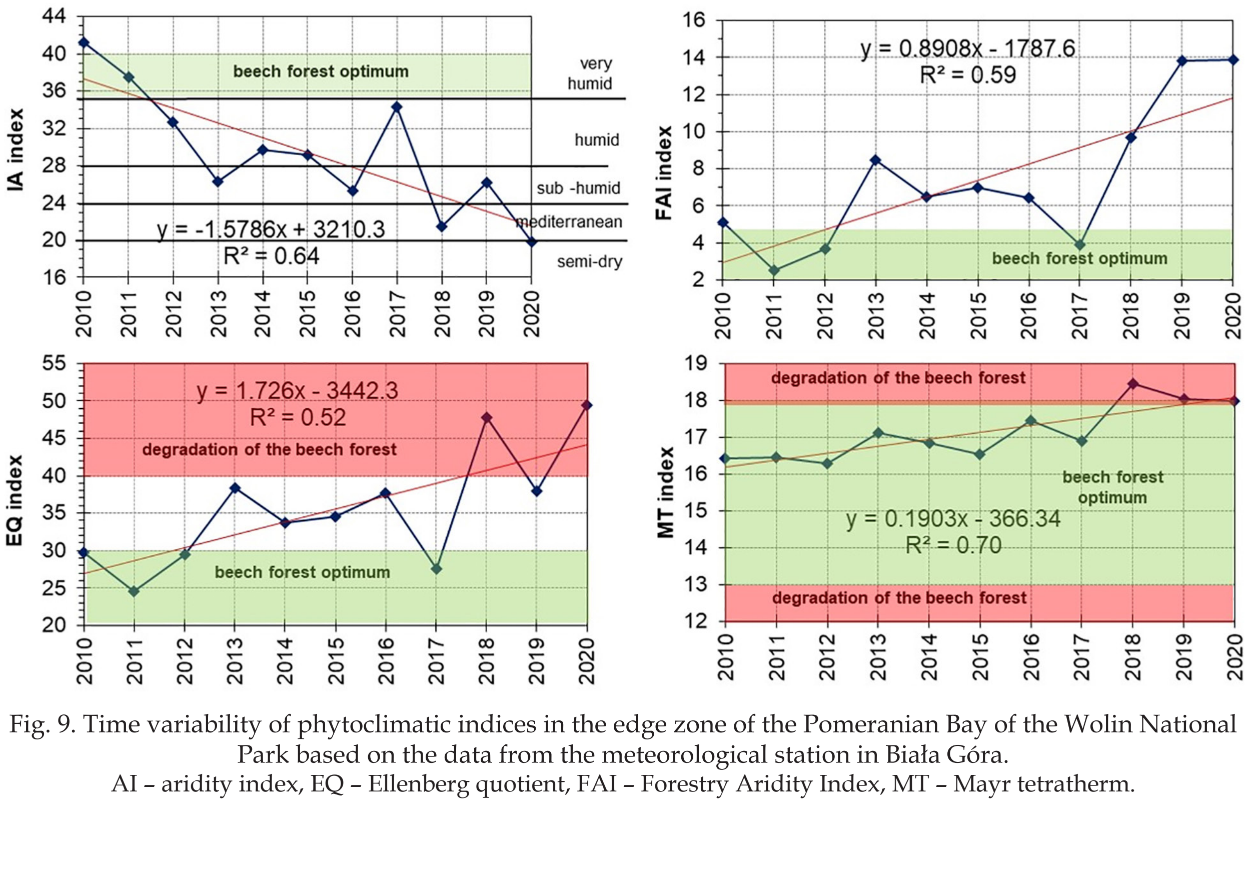

Fig. 9. Time variability of phytoclimatic indices in the edge zone of the Pomeranian Bay of the Wolin National Park based on the data from the meteorological station in Biała Góra.
AI – aridity index, EQ – Ellenberg quotient, FAI – Forestry Aridity Index, MT – Mayr tetratherm.

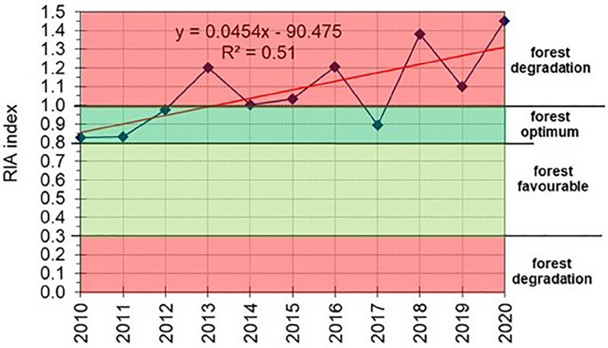

Fig. 10. Time variability of the RIA radiation dryness index based on the data from the meteorological station in Biała Góra.

RIA index was found, at a rate of 0.4 · 10 years^{-1}, which confirms a high threat to the functioning of forests due to the shortage of rainfall and the risk of drought. The sum of annual precipitation Pa that meets the RIA = 0.8 condition is the optimal precipitation height (Popt). For the cliff edge zones of the WNP it is about 755 mm. However, in the period 2010–2020, such optimal precipitation conditions were not found. On the other hand, the sum of rainfall, which meets the condition RIA = 1, can be called the critical amount of rainfall (Pcr), which determines the limit of optimal and insufficient climate humidity. Thus, the annual rainfall of at least 604 mm is the threshold for forest development in the edge zones of the WNP. In the period 2010–2020, only 4 years were found with annual rainfall ≥604 mm (2010–2012 and 2017). Moisture conditions, which were particularly unfavourable for the development of forests, occurred in the last 3 years of the studied period (Fig. 10). Unfavourable humidity conditions caused, among others, early leaf shedding by *Fagus sylvatica* – even in September.

The decrease in the CVP index in the area of the WNP, including the studied zone adjacent to the sea coast, results in the deterioration of the health condition of the forest as a result of drought. In addition, biomass productivity decreases, and the risk of fire and pest infestation increases (Siedlecki 2018). For the forests of the WNP cliff edge zones, the biomass productivity calculated based on CVP in the period 2010–2020 was on average 13.03 m^3 · ha^{-1} · year^{-1}. The potentially highest value of biomass production was found in 2010, 13.93 m^3 · ha^{-1}, and the lowest in 2020, 12.22 m^3 · ha^{-1} (Fig. 11). In the study area, there is a statistically significant (p < 0.05) trend of decline in productivity, at a pace of –0.1 m^3 · ha^{-1} · a^{-1} (Fig. 11).

Valorisation of threats to forest associations caused by geomorphological processes

Threats to plant associations in the edge zone of the Pomeranian Bay are mainly conditioned by mass movements regulating the state of the denudation system of the Wolin cliffs. The highest rate of top retreation occurs primarily on sandy cliffs, and it is in their case that the greatest threat to forest associations is observed. Of course, this threat varies across time and space as the morphodynamic functions of the cliff change. It should be emphasised that for the active cliffs, the greatest degree of risk occurs during the autumn and winter periods of storm surges, when the cliff is undercut and landslides are mobilised. Mass movements within the deeper hinterland contribute to the irreversible destruction of the forest, among others *Betulo-Quercetum lonicceretosum xylostei* (Fig. 12). Cliff top erosion can also

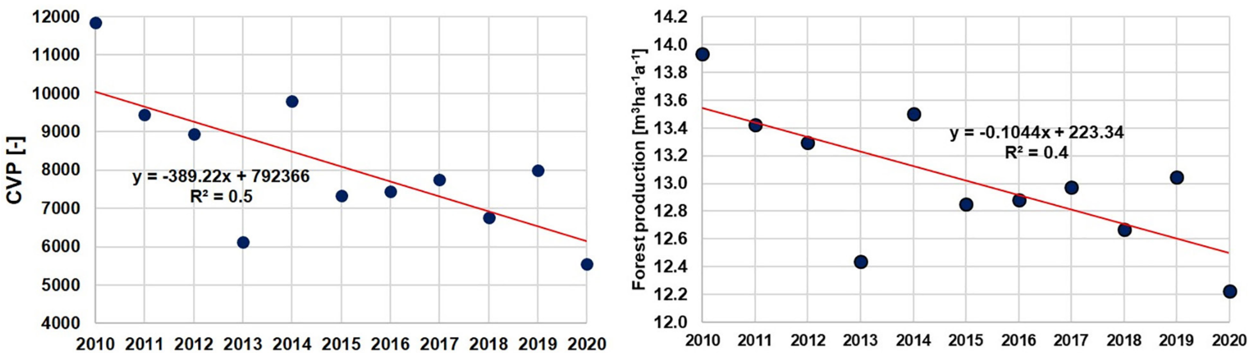

Fig. 11. Variability of the climate vegetation productivity CVP index and potential forest productivity in the edge zone of the Pomeranian Bay of the Wolin National Park based on the data from the meteorological station in Biała Góra.

Fig. 12. Degradation of the *Betulo-Quercetum loniceretosum xylostei* as a result of extreme storm surge in Świętouść (photo by M. Winowski, January 2017).

Fig. 13. The effect of turbulence erosion in *Cephalanthero rubrae-Fagetum* association on the cliff top between Gosań-Świdna Kępa (photo by J. Tylkowski, February 2012).

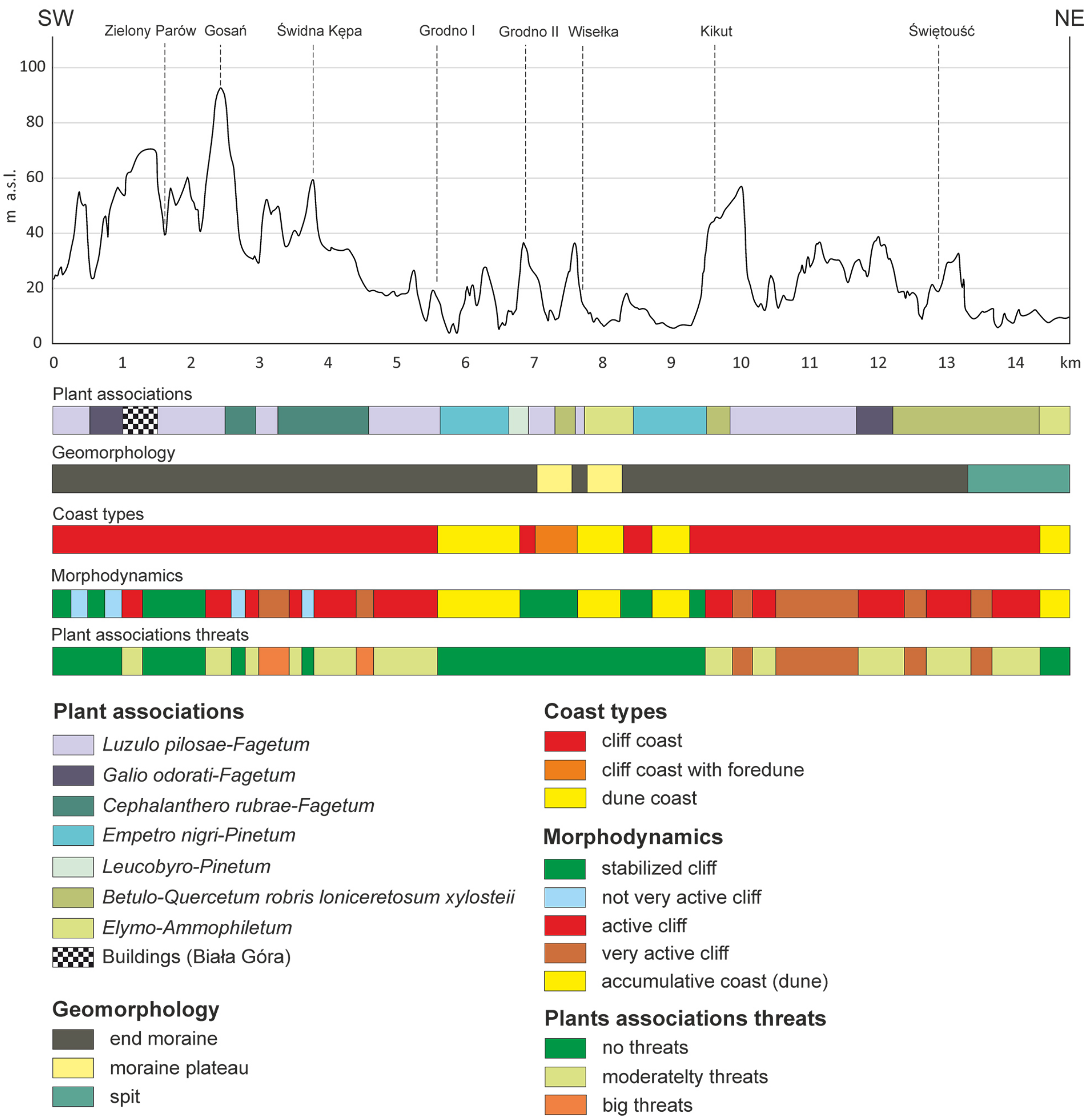

Fig. 14. Spatial valorisation of threat for forest communities in the edge zone of the Wolin National Park (coast of the Pomeranian Bay).

take place successfully in dry periods of summer seasons, when dry sandy sediments are blown away and subject to shedding, and trees growing on the cliff top (e.g. *Cephalanthero rubrae-Fagetum*) often fall over and slide down the slope (Fig. 13).

The valorisation was carried out for >14 km of the Pomeranian Bay coast, lying within the borders of the WNP (Fig. 14), within which 45% are classified as areas with no significant threat (stabilised cliff or accumulative dune coast, ≤5.25 $m^3 \cdot m^{-2} \cdot a^{-1}$ in the 2010–2020 period) to forest associations, whereas for 36% the threats (not very active cliff, 5.26–9.50 $m^3 \cdot m^{-2} \cdot a^{-1}$ in the 2010–2020 period) are moderate. On the other hand, for 19% of the length of the studied coastal section, plant associations are exposed to high threats (active or very active cliff, >9.50 $m^3 \cdot m^{-2} \cdot a^{-1}$ in the 2010–2020 period) due to the impact of erosion and denudation processes. Among the forest associations most exposed to the impact of geomorphological processes (in class II) are *Luzulo pilosae-Fagetum* on sections 5.10 km long, *Betulo-Quercetum loniceretosum xylostei* on 1.53 km sections of the coast and *Cephalanthero rubrae-Fagetum* on 0.85 km sections. Moderate threats (class I) affect the habitats of *Luzulo pilosae-Fagetum* along the 5.61 km coast, the *Cephalanthero rubrae-Fagetum* habitats on 3.06 km long sections of the cliff coast and *Betulo-Quercetum loniceretosum xylostei* on 5.44 km long sections of the coast.

Discussion

Erosion of the cliff edge zones of the Pomeranian Bay of the WNP is mainly caused by sea abrasion, initiating mass movements. The measurements of the rate of the cliff top recession carried out annually since 1984 on five test sections showed that the average annual rate of cliff recession was 0.22 m (Winowski et al. 2019). Geomorphological changes in the cliff edge zone of the WNP, especially the slopes and the top of the cliffs, depend mainly on the dynamics of sea abrasion and slope erosion (Tylkowski 2018). The moraine coast of the southern Baltic Sea area is under the most threat of retreat, particularly as the projected sea-level rise accentuates its vulnerability to storm surges and wave erosion (Räisänen 2017). The high sea level during storm surges, intense rainfall and strong winds lead to the transformation of the cliff coast, which is manifested, among others, by the retreat of the cliff top and disappearance of forest associations (Czyryca et al. 2021, Tylkowski et al. 2021). The largest changes were observed in the upper parts of the active cliff as a result of mass wasting triggered by the loss of the slope stability due to erosion of the lower part of the slope, e.g. in the time period 2008–2012, on the 2 km of the Wolin cliff coast, a negative sediment balance of −33,000 m^3 was found (Dudzińska-Nowak, Wężyk 2014). As a result of morphodynamic processes, the vegetation in the dune edge zone is also subject to changes (Łabuz 2004, 2015). Also, the foredunes of the Pomeranian Bay are objects to significant morphodynamic changes (Tylkowski 2014). Coastal dunes are eroded especially during storm surges with sea level >1 m above the average level (Łabuz 2013). The highest storm surges in the time period 2002–2019, with the highest storm sea level >1.3 m (the Amsterdam mean sea level), triggered a heavy erosion of the dune coast at the Świna Gate Sandbar (Łabuz 2022). Such erosive storm surges occurred almost every 2 years. The heaviest surges resulted in an average 5.2 m and 7.0 m dune retreat on the high-beach-accumulative coast and on the low-beach-erosive coast, respectively (Łabuz et al. 2018). Therefore, for the Pomerania Bay cliffed coast, the threshold value of erosive sea level is 0.9 m above the mean sea level (Winowski 2015, Tylkowski 2018), which is about 0.1 m lower than that for the dune coast (Łabuz 2013).

In the cliff edge zone of the WNP, exceeding the threshold values of hydrometeorological conditions (including maximum sea level, total precipitation and wind speed) (Winowski 2015, Tylkowski 2015b, 2018, Hojan et al. 2018) generates intensive erosion and denudation processes causing coast erosion and stimulates the evolution of landforms and phytocoenotic changes (the disappearance of the stand on the slope and top of the cliff). In the long term, due to bank erosion, the extent of the soil cover, e.g. of the cliff naspas, changes. Therefore, the evolution of the habitat conditions in the cliff edge zone causes changes in the range and species composition of plant associations. Climate change will affect the distributions of native species too. An increase in the proportion of deciduous tree species (except *Alnus incana*) and some reduction in the proportion of conifers (*Picea abies* and *Pinus sylvestris*) are expected in the Baltic region (Ozolinčius et al. 2014). The dominant conifers of the mixed conifer/northern hardwoods zone, *Picea abies* and *Pinus sylvestris*, retreat from the south and west while *Fagus sylvatica* and other temperate hardwoods spread to the north (Sykes and Prentice 1996). Generally, climate changes are projected to lengthen the growing season for terrestrial plants, and to promote northward shifts in the boundaries of species occurrence (Smith et al. 2008). Increased temperatures in the Southern Baltic coast may reduce the growth of coniferous trees, where the growth tends to be limited by water availability (Lindner et al. 2010).

Changing climatic conditions affect the limitation of water resources in the cliff edge zone of Pomeranian Bay, which is clearly illustrated by the clustering (2013–2016 and 2018–2020) of high values (>1) of the RIA index. If the RIA >1, then in a given year there are conditions typical for drought, because most of the precipitation evaporates, and thus, there is no possibility of increasing water resources and there is limited availability of water for the development of vegetation. On the other hand, if RIA <1, this can be taken as an indication of the prevalence of humid conditions, owing to rainfall remaining as the principal mode of liquid water supply and water retention being possible. The Earth's forest ecosystems occur in climates with a dryness index of 0.33 < RIA < 10. The most favourable ecological conditions for vegetation are provided by climates with values of 0.8 < RIA < 1.0 (Kożuchowski 2013). The analysis of the relationship between the annual value of net primary production (PPN) and the climate also allows the assumption to be made that the maximum PPN corresponds to the value of RIA = 0.8. The value of the radiation dryness index RIA = 0.8 is therefore the optimal relation for forests between the radiation balance and precipitation (Budyko 1975).

Among the many methods of assessing forest productivity, Paterson's (1956) CVP index is suitable for determining the productive potential of forests in the cliff edge zones of the WNP. The CVP index does not apply to stands or species; hence, it can be used for the general assessment of forest and vegetation productivity (Siedlecki 2018). Unfavourable phytoclimatic conditions, and frequent and long-lasting droughts as reflected by RIA >1, result in a decrease in CVP and a reduction in the productivity of coastal forest ecosystems.

The geomorphological development of the cliff edge zone and the dynamics of changes in forest associations largely depend on meteorological and hydrological conditions. In the Polish coastal zone of the Baltic Sea in the 21st century, the average annual air temperature may increase by 2–3°C, with an uncertain increase in total precipitation by 0–10% in summer and a more possible increase by 10–20% in the winter season (Collins et al. 2013). The frequency and duration of droughts (Orlowsky, Seneviratne 2012) and heat waves (Nikulin et al. 2011) are also expected to increase. The increase in air temperature is likely to be accompanied by higher precipitation, especially in the winter season. However, in the growing season, the sum of precipitation is unlikely to increase, which, with increased thermal conditions and high evapotranspiration, will reduce the resources of surface and ground waters. Plant associations, including forest ecosystems, will therefore have limited access to water.

For the Baltic Sea, the current rate of sea level changes is approx. 2–3 mm · a^{-1} (Stramska, Chudziak 2013, Tylkowski et al. 2021, Weisse et al. 2021). According to various scenarios, based on the forecasts of emissions to the atmosphere of compounds resulting from the combustion of fossil fuels (mainly CO_2 and CO, and CH_4), it is expected that by 2100 there will be a further global sea level rise from 0.82 cm (RCP 8.5) to 26 cm (RCP 2.6) (Nauels et al. 2017). Thus, the forecast of the average global sea level increase (including the Baltic Sea), also taking into account the instability of the Antarctic and Greenland ice sheets in the RCP 8.5 scenario, is about 1 m for 2100 (Grinsted 2015), over 7 m for 2200 and almost 15 m for 2500 (Popkiewicz et al. 2018). In the RCP 8.5 scenario (IPCC 2022) for the Baltic Sea, the occurrence of sea level Historical Centennial Events (IPCC 2022) is predicted to take place in about 50 years, for a study area amounting to approx. 1.7 m of the Normal-Null reference level (Wolski et al. 2014, Tylkowski, Hojan 2018). Thus, the long-term functioning of the edge zones of the WNP and their forest associations will be exposed to degradation caused by a high frequency of extreme sea levels, increased erosion and probably a rapid and significant retreat of the cliff edge. Mean annual Baltic Sea surface water temperature may rise until the end of the 21st century by about 2–4°C, with a frequency and periods of marine heat waves surface water temperature ≥20°C. These changes will be especially visible south from 60° N and in the near coast area (Meier 2022b).

However, it should be emphasised that within the cliff coast of Wolin Island there are also unique plant associations, the functioning of which is conditioned by the geomorphological activity of the cliffs' slope. Such a community is the thermophilic orchid beech (*Cephalanthero rubrae-Fagetum*). In the case of orchid beech trees, the appropriate degree of morphogenetic activity of the cliff is the basic factor determining the good condition of the community (Tylkowski et al. 2021). This is related to the formation of a specific type of soil – the cliff naspas, the genesis of which is closely related to the aeolian deposition of material originating from the cliff face slope (Prusinkiewicz 1971, Hojan 2009). Along with the change of morphogenetic activity to the stabilisation of the cliff, the gradual disappearance of this valuable plant community is noticeable.

Conclusions

The morphodynamics of the edge zone of the Pomeranian Bay within the WNP is clearly characterised by the stages of development during which the cliff sections change their morphodynamic functions, in the form of extreme episodes of intense erosion separated by periods of coast stabilisation. Thus, the dominance of the sea factor was found, through abrasive storm surges with a sea level 90 cm above mean sea level, which generates the greatest geomorphological transformations of the cliff edge and coastal plant associations. The processes of water and aeolian erosion are relatively less important in the dynamics of erosion-denudation processes and in habitat changes. In the edge zone in the period 2010–2020, for only almost a month, there were favourable hydrometeorological conditions for the initiation of mass movements (landslides, falls). Then, for 3 weeks, there were favourable conditions for cliff abrasion during storm surges, and only 1 week for slope erosion as a result of efficient precipitation. In the analysed 11-year period, favourable meteorological conditions for the occurrence of aeolian processes in the edge zone occurred for almost 7 months.

Cyclical dynamics of coast erosion as a result of storm surges were observed, which is manifested in relatively short periods of increased degradation with a relatively higher frequency of events with exceeding abrasive sea level (2011–2012 and 2016–2019), separated by a period of relative stabilisation with sporadic abrasive floods storms (2013–2015). Mass movements in the coastal area of the cliffs show a clear seasonal disconnect. They are most often initiated during storm surges, especially from October to March. On the other hand, water erosion and mass movements caused by precipitation occur rarely and mainly in the summer season. For mass movements, no significant statistical tendency was found to change their annual turnout. On the other hand, aeolian processes do not show such a clear seasonal regularity, they appear throughout the year and there is a statistically significant increase in the annual frequency of their occurrence.

Phytoclimatic indicators AI, EQ, FAI and MT show a statistically significant trend towards climatic conditions beyond the climatic optimum for *Fagus sylvatica*. The indicators confirm the climatic stress, especially in the last 3 years, for the dominant tree species, which is the common beech. The consequence of climate change is a high RIA index, the values of which reflect unfavourable conditions for the development of forests and a decrease in their productivity expressed by the CVP index. In the forests of the cliff edge zone of the Pomeranian Bay of the WNP, there is a statistically significant trend of decline in their productivity, at a rate of $-0.1\ m^3 \cdot ha^{-1} \cdot a^{-1}$. In the longer term, it is also possible to reconstruct the species composition of forests in Wolin, as the phytoclimatic conditions for boreal species will be unfavourable, and thermophilic trees will enter.

Ongoing climate changes, for a longer time, will cause the transformation of forest associations. We anticipate that the effects of phytoclimatic condition changes that play a significant role in determining the pace of forests' development will be altogether perceptible, especially during the second half of the 21st century. The transformation of forest associations will cover the whole WNP area. However, currently observed plant associations changes are of restricted spatial range and limited mostly to the cliffed coastal zone of Pomeranian Bay, owing to plant associations growing on the edge zone of the Pomeranian Bay being mainly related to mass movements regulating the state of the denudation system of the cliffs in Wolin Island. The highest rate of top retreation occurs primarily on sandy cliffs, and it is in their case that the greatest threat to forest associations is observed. This risk varies across time and space as the morphodynamic functions of the cliff change. The spatial analysis of the threat to plant associations for the more-than-14-km section of the Pomeranian Bay coast showed that 45% are classified as areas with no significant threat to forest associations, whereas for 36% of the coastal zone length these threats are moderate, and for 19% of the length of the studied coastal section, there is exposure to big threats. The most vulnerable to the impact of geomorphological processes are *Luzulo pilosae-Fagetum* along the 5.1 km section, *Betulo-Quercetum robris loniceretosum xylostei* along the 1.53 km section and *Cephalanthero rubrae-Fagetum* along the 0.85 km section.

It is worth emphasising that, while cliffed coast morphodynamics and phytoclimatic changes are both causing modifications in the type and extent of plant associations, these two factors are not correlative, because their various influences on plant associations pertain to different time scales. Short-term (seasonal and few-years’) changes of cliffed coast morphodynamics are mostly influencing the limitation of plant association occurrence, e.g. the vanishing of *Cephalanthero rubrae-Fagetum* association. On the other hand, long-term (multi-decadal) changes of phytoclimatic conditions are transforming forest associations with the domination of boreal species, *i.a. Empetro nigri-Pinetum*.

It should be emphasised, however, that the cause–effect relationships between hydrometeorological conditions and the dynamics of erosion-denudation processes and the transformation of forest associations are complicated and heterogeneous for individual sections of the coastal zone. The dynamics of erosion of the Pomeranian Bay cliff edge zone are determined by many other conditions that disturb the simple relationship between hydrometeorological conditions and the intensity of erosion. The most important factors influencing the dynamics of the erosion of the sea coast include: morpholithological conditions of the cliff, slope exposure towards the sea wave approach, morphology of the underwater slope, qualitative and quantitative conditions of sediments on the beach and shallow coastal zones, dynamics and frequency of extreme hydrometeorological events in the preceding period, as well as anthropogenic factors.

Due to phytoclimatic conditions’ changes and sea level rise, as well as the expected intensification of erosion and denudation processes in edge zones in the 21st century, effective forms of protection of coastal forest associations are difficult to define and there is no such need in the area of WNP. The inferences gleaned from the present study indicate that possible future changes of forest associations in the edge zones of the Pomeranian Bay can be anticipated to arise as a consequence of global and regional conditions, and that the application of local safeguards would most likely prove ineffective in the long term.

Acknowledgements

The authors would like to thank the Polish Institute of Meteorology and Water Management in Warsaw for the provided sea level data. We would also like to thank the management of Wolin National Park for their consent and assistance in scientific research. The authors would like to thank the anonymous reviewers for their insightful and constructive comments.

Funding

The research was supported mainly by the Forest Fund, within the scope of funding admitted by the General Directorate of the State Forests National Forest Holding for Wolin National Park (grant No. EZ.0290.1.22.2021 of 27.08.2021, “Interakcja procesów erozyjno-denudacyjnych i zbiorowisk leśnych w strefach krawędziowych na obszarze Wolińskiego Parku Narodowego”).

Authors’ contribution

JT, RP, MW: Conceptualisation, Data curation, Investigation, Formal analysis, Methodology, Software, Writing – original draft, Writing

– review and editing, Visualization. PC, AK, MM, GR: Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review and editing.

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