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BALTICA Volume 22 Number 2 December 2009 : 77-88

Spatial diversity of modern geomorphological processes on a Holocene Dune Ridge on the Curonian Spit in the South–East Baltic

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Povilanskas, R., 2009. Spatial diversity of modern geomorphological processes on a Holocene Dune Ridge on the Curonian Spit in the South–East Baltic. *Baltica, Vol.22 (2)*, *77–88.* Vilnius. ISSN 0067–3064.

Abstract A precise high–resolution comparative cartometric survey was used to assess the modern geomorphologic changes of the Grand Curonian Dune Ridge in the South–East Baltic. The general geomorphologic trend is the flattening of the highest shifting dunes and the lowering of the average height of the shifting dune ridge. Yet, the overall acreage of the shifting sand (the 'white dune' landscape) is relatively stable: its annual loss did not exceed 0.1% during the second half of the 20th century. The Grand Curonian Dune Ridge can be divided into 14 different shifting dune areas according to a local pattern of the modern geomorphologic processes, human impact and the succession of vegetation. These areas could be grouped into two distinct sets according to their geomorphologic trends. Greater shifting dune areas contain relatively large and stable volumes of sand, both in the dune ridge itself and in the adjacent areas. Therefore these shifting dune areas enjoy a relative geomorphologic stability. The average annual deflation rate of the greater shifting dune areas does not exceed 0.1% of their volume. The isolated shifting dunes of the Grand Curonian Dune Ridge, which contain small volumes of sand, suffer from a disastrous degradation. They lack fresh sand supply sources as they are surrounded by forest. The average annual deflation rate of the isolated shifting dunes is ca 0.3% of their volume.

Keywords *Curonian Spit, Grand Dune Ridge, Holocene, coastal dunes, geomorphological processes.*

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INTRODUCTION

On the European scale, the shifting dune landscape is characterized by great geomorphological diversity. Doody (2005) distinguishes seven different morphogenetic landscape types of shifting dunes. The coastal dunes have many functions in modern society (Jungerius 2008): shoreline management; nature conservation; public drinking water extraction; recreation; housing and industry; agriculture; grazing; military defence. Dunes serve as geoecological indicators (Povilanskas *et al.* 2009) and ecotourism areas (Povilanskas 2004; Armaitienė *et al.* 2007). The aim of this paper is to analyze geomorphological changes of the Grand Curonian Dune Ridge by applying comparative cartometric analysis to provide a morphodynamic segmentation of the ridge and to analyze the geomorphologic development trends of the different remaining shifting dune areas on the Curonian Spit.

Study area. In 2000 the whole Curonian Spit was included into the UNESCO World Heritage List as a single cultural landscape of shifting and forested dunes of outstanding international importance, which is under constant threat from natural forces (UNESCO 2001). In our opinion, the Grand Curonian Dune Ridge, i.e., the part of the Curonian Spit which comprises the shifting barchans, is the main heritage landscape featuring the Curonian Spit on the global scale (Fig. 1). It is the third highest and the second longest shifting coastal dune ridge in Europe (Povilanskas *et al.* 2009). The shifting dune landscape forms the most distinctive natural heritage value of the spit, with the highest shifting dunes exceeding 50 meters in height. Due to its unique geomorphologic features, the Grand Curonian Dune Ridge could and should be recognized and protected by UNESCO as a national dune geopark, similar to other national dune geoparks: Sanin (Japan), Alshan (China) or Gulf Dunes (Florida, USA)

Fig. 1. The Southeast Baltic coastal region and the Curonian Spit.

There are five strips of shifting barchans remaining on the spit (Table 1). The total length of these strips is 32.6 km, 21.9 km being on the Russian part, and 10.7 km on the Lithuanian part of the spit.

Different from many other shifting dune areas in Europe, the Grand Curonian Dune Ridge is unique for its outstanding linear structure. Many other dune areas present a mosaic of white and grey dunes, dune slacks and heath areas on a vast coastal accumulative plain. They have preserved their original parabolic form till modern times (Doody 1991; Korneyevets, Volkova 1995; Fisher 2004; Jungerius 2008; Povilanskas 2009). On the other hand, the Grand Curonian Dune Ridge as a linear landscape resulted from dramatic changes, which took place from the 1600s to the 1800s (Fig. 2). During that time, the landscape mosaic of ancient parabolic dunes, which prevailed since the Holocene, was completely destroyed by the shifting sand and replaced by the chain of shifting barchans. Excess marine sand supplied from the seashore has formed the chain of barchans, which rapidly advanced eastwards across the spit under the prevailing westerly winds maintaining its linear structure while on the move (Mager 1938; Paul 1944–1951; Gudelis 1998). Therefore, in the case of the Grand Curonian Dune Ridge, it is difficult to apply any conventional dune–management measures, which are common in other dune areas throughout Europe, e.g., facilitation of the sand drift by destroying the foredune on the seacoast (Arens *et al.* 2005) or by mitigating degraded shifting dunes or dune slacks elsewhere on a vast dune field (Grootjans *et al.* 2002).

Table 1. Shifting dune strips of the Grand Curonian Dune Ridge (Povilanskas *et al.* 2009).

Dune strip	White Dunes (Fig. 2)	Fringilla Dunes (Fig. 2)	Skilvit Dunes (Fig. 3)	Glider's Dunes (Fig. 4)	Grey Dunes (Fig. 5)
Length, km	5.9	7.5	6.1	5.7	7.4
Max. height, m	15.0	53.0	38.4	53.1	53.6
Annual shift of the lagoon coastline, m	0 – +3	-1 – +3.5	-1 – +4.4	-2 – 0	-1 – +1

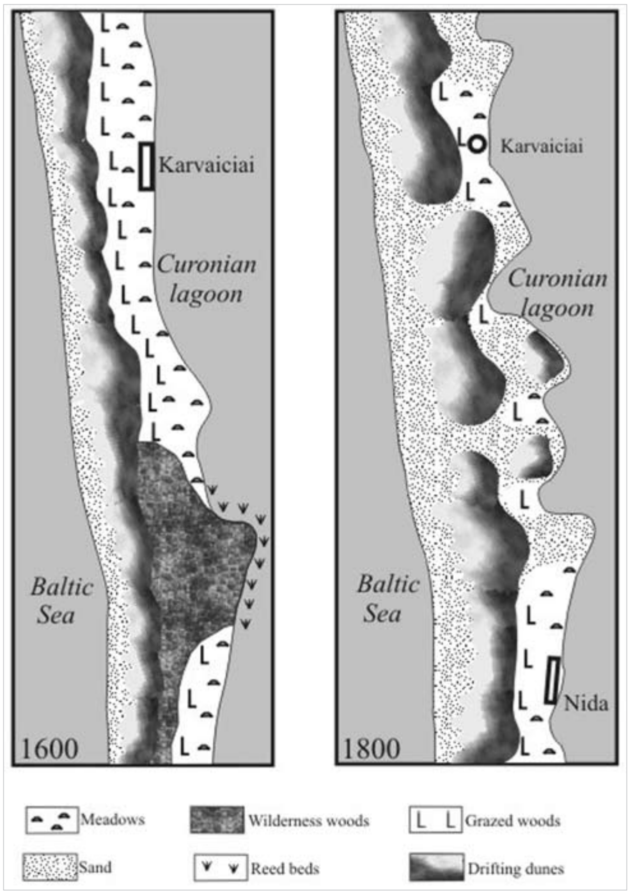

Fig. 2. Landscape development on the Curonian Spit, 1600–1800.

It is noteworthy, that as the chain of shifting barchans moved eastwards, the interface between the dune ridge and the Curonian Lagoon rapidly increased. In the 19th century there was an accumulative sandy plain (*palvė*. Lith.) stretching along the entire lagoon coast of the Curonian Spit, which separated the dune ridge from the lagoon (Berendt 1869; Heß von Wichdorf 1919). In contrast, in 2000 the Grand Curonian Dune Ridge was in direct contact with the Curonian Lagoon along 29.4 km length out of its entire 32.6 km length, according to our estimates.

Previous survey. Out of numerous publications–articles, books and reports—which highlighted the evolution of the Grand Curonian Dune Ridge during its most rapid development phase, from the early 1800s till the mid–1900s, the most noteworthy works were published by G. Berendt (1869), H. Heß von Wichdorf (1919), F. Mager (1938) and K.H. Paul (1944–1951).

After World War II, Lithuanian geographers examined and described the evolution of the Grand Curonian Dune Ridge during a new forestation drive from the 1950s to the 1980s, which was aimed to afforest most of the remaining shifting dunes and palvė (Gudelis 1960, 1998; Gudelis, Karužaitė 1962, 1993; Gudelis, Michaliukaitė 1959; Michaliukaitė 1967; Minkevičius 1968, 1969, 1972, 1982; Mardosienė 1988; Mardosienė, Vainauskas 1984; Kudaba, Mardosienė 1986; Gudelis, Kazakevičius 1988).

At the turn of the century, the current geomorphologic processes of the remaining shifting dune strips on the Lithuanian part of the Grand Curonian Dune Ridge were studied by R. Morkūnaitė, A. Česnulevičius and S. Paškauskas (Česnulevičius, Morkūnaitė 1997, 1998; Morkūnaitė 2000; Morkūnaitė, Česnulevičius 2005; Česnulevičius *et al.* 2006; Paškauskas 2006).

Quite a few works of the researchers from other countries are dedicated to study the current geomorphologic processes on the Russian part of the Grand Curonian Dune Ridge, the most noteworthy ones being a monograph by D. Mader (1995) and a few recent papers by Russian researchers (Korneyevets, Volkova 1995; Litvin *et al.* 1995; Volkova 1998; Kozminskaya *et al.* 2003; Cherednichenko *et al.* 2007).

In 1996–2000, the author of this paper investigated the geomorphologic dynamics of the Grand Curonian Dune Ridge along its entire length and its impact on the morphodynamics of the coastal zone of the Curonian Lagoon (Povilanskas 1998a; Povilanskas, Chubarenko 1998, 2000). In 2002–2004, having new institutional, financial and technological capacities at his disposal, the author together with a large team of investigators repeated these investigations and made a more detailed and more precise comparative cartometric analysis of the geomorphologic development trends on various strips of the Grand Curonian Dune Ridge (Povilanskas 2004, 2009; Povilanskas *et al.* 2006, 2009; Armaitienė *et al.* 2007).

In this paper, we aim to present the detailed analysis of the geomorphologic development patterns in different remaining shifting dune areas of the Grand Curonian Dune Ridge.

MATERIAL AND METHODS

The long–term net volumetric changes in the shifting dunes and the coastal zone of the Curonian Spit between 1910 and 2000 were estimated by applying a comparative cartometric survey. Quite a few comparative cartometric surveys have been carried out on the Curonian Spit since the pioneering study of Berendt (1869). However, different from other studies, we have applied a precise high–resolution comparative cartometric survey to assess the modern geomorphologic changes of the entire Grand Curonian Dune Ridge.

Due to very large time gaps and different methods in the production of cartographic materials used for comparative surveys (Lodovisi, Torresani 1996), some experts have doubts about the applicability of the comparative cartometric survey as an effective tool for the assessment of long term coastal changes (Williams, Davies 1987).

From our personal experience, we admit that these doubts are justified, but only when the retreat rate of steep cliffs is assessed. Numerous studies prove that comparative cartometric surveys can be successfully applied as a rather trustworthy tool for the assessment of net quantitative linear or volumetric changes in coastal areas outside cliffs, if the accuracy of measurements is high enough against the changes assessed (cf. Kazakevičius 1985; Brivio, Zilioli 1996; Lodovisi, Torresani 1996; Povilanskas 1999; Bessa Junior, Angullo 2003).

The cartographic materials, which were used for this comparative survey and the verification of the results, included topographic maps and 3D satellite images of the Curonian Spit from different years (Table 2). All these cartographic information sources were digitized, transformed and compared in the UTM geographical reference system, WGS84 projection. The net volumetric changes of the shifting dunes during the periods of 1910–1955, and 1955–2000 were assessed using the software programs Carta Linx, ArcGIS 8.1 (module ArcTools), Idrisi 32 and Surfer 7 (Povilanskas et al. 2009).

The minimal accuracy of the comparative cartometric analysis was limited by the accuracy of the historic geodetic measurements of the dune height ($\delta y = \pm 0.5$ m),

Table 2. Cartographic materials applied to analyze the dynamics of the Grand Curonian Dune Ridge from 1910 to 2000.

No.	Source of information	Mapping year	Executive agency	Scale
1.	Topographic map of the entire Curonian Spit	1909	German Cartographic Survey	1:25’000
2.	Topographic map of the entire Curonian Spit	1954	Agency for Geodesy and Cartography of the USSR	1:25’000
3.	Topographic map of the Lithuanian part of the Curonian Spit	1990	Lithuanian Aerogeodetic institute	1:10’000
4.	Topographic map of the Russian part of the Curonian Spit	1990	Russian Geodetic Survey	1:25’000
5.	3D satellite image of the Lithuanian part of the Curonian Spit	1999	Lithuanian Aerogeodetic institute	1:10’000
6.	3D satellite image of the Russian part of the Curonian Spit	2003	Euro Space Imaging Ltd	1:25’000

and by the accuracy of the original topographic maps. The minimum accuracy of the estimated linear changes of the shoreline from the maps with a scale of 1:25’000 is δ (x) = ±10 m (Gudelis, Kazakevičius 1988). 3D satellite images of the Grand Curonian Dune Ridge from 1999 and 2003 were used to verify the results of planimetric and volumetric calculations. The standard error of all metric, planimetric and stereometric computation procedures does not exceed ±0.1%.

RESULTS AND DISCUSSION

Our comprehensive investigations of the geomorphologic dynamics of the Grand Dune Ridge on the Curonian Spit have revealed that the various strips of the Grand Dune Ridge have experienced different development processes and trends. The average resulting annual drift of the ridge eastwards under the prevailing westerly winds was 2.5–3.8 m per year in 1910–1984 (Michaliukaitė 1967; Mardosienė, Vainauskas 1984; Gudelis, Kazakevičius 1988). Without any steady sand supply sources, the activity of the Aeolian dynamics was declining in most places on the Grand Curonian Dune Ridge throughout the 20th century. Yet, some strips of the shifting dune ridge experienced fast evolution in various episodes of the last century, depending on the local aeolian, groundwater and human impact conditions (Mardosienė, Vainauskas 1984).

According to our investigations, currently the fast evolution of the shifting dunes is occurring in the Fringilla Dunes in the south of the spit (see Fig. 3), and the Nagliai shifting dune area of the Grey Dunes (the northernmost shifting dune strip of the Curonian Spit; see Fig. 6).

Throughout the 20th century, the overall dynamics of the shifting dunes were relatively higher in the southern part of the Grand Curonian Dune Ridge than in the northern part. In 1910–1955, the annual eastward advance of the northernmost Grey Dunes was just 0.5–2.8 m compared to a 3–5 m annual advance of the shifting dunes in the southern and central parts of the Grand Curonian Dune Ridge (Michaliukaitė 1967). Our calculations prove that in the surveyed period of 1955–2000, all three—southern, central and northern—parts of the shifting dune ridge experienced a similar annual eastward advance rate as the previous period.

The general geomorphologic trend of the entire Grand Curonian Dune Ridge is the flattening of the highest shifting dunes and the lowering of the average height of the entire shifting dune ridge. Yet, these processes did not have any noticeable impact either on the resulting eastward advance of the shifting dunes, or on the resulting average reduction of the acreage of the shifting sand.

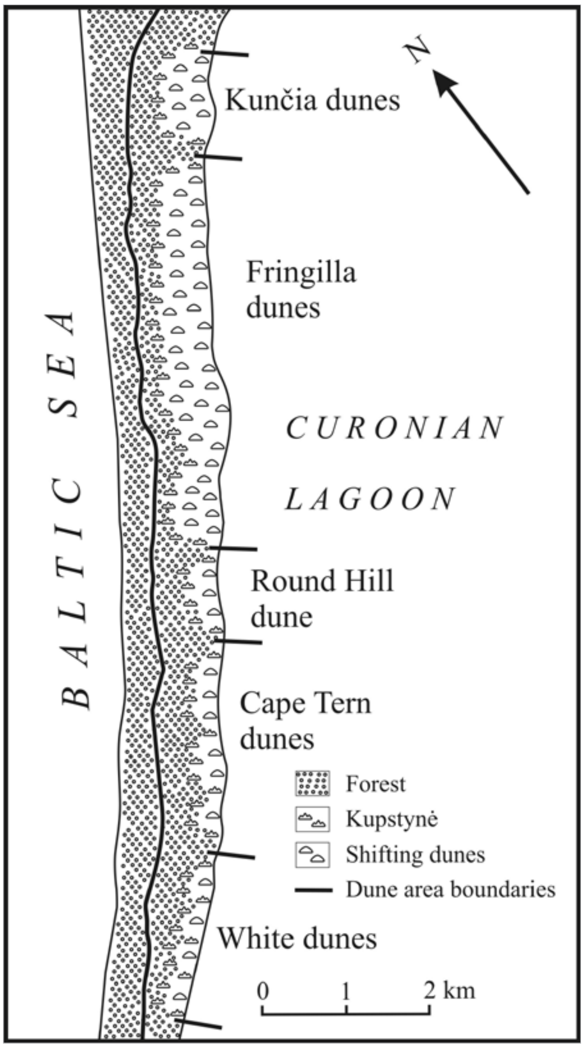

Fig. 3. The White Dunes and Fringilla Dunes of the Grand Curonian Dune Ridge.

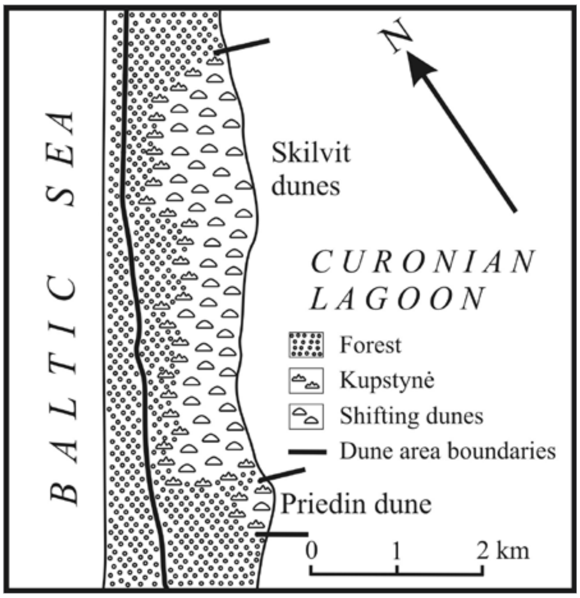

Fig. 4. The Skilvit Dunes of the Grand Curonian Dune Ridge.

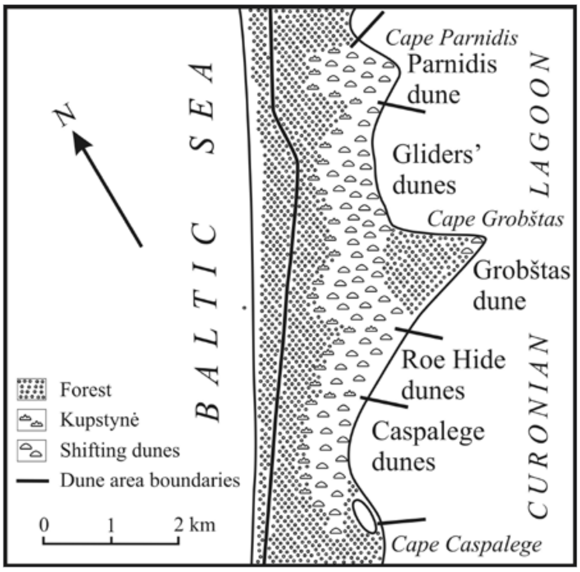

Fig. 5. The Glider‘s Dunes of the Grand Curonian Dune Ridge.

For example, although the height of the crest of the shifting dune ridge declined continuously at Cape Skilvit, the annual eastward advance of these dunes reached 4 m (Gudelis, Kazakevičius 1988), whereas the acreage of the shifting sand increased by 5.58% during the entire analyzed period of 1910–2000 (Table 3). Similar trends were noted on other shifting dune strips of the Grand Curonian Dune Ridge.

The entire 32.6 km–long ridge can be divided into 14 different shifting dune areas according to a local pattern of the modern geomorphologic processes, human impact and the succession of vegetation:

Table 3. Parameters of the geomorphologic processes of the greater shifting dune areas of the Grand Curonian Dune Ridge in 1910-2000.

Shifting dune area	Deflation, million m^3	Relative change of sand volume, %	Relative change of shifting sand acreage, %
Fringilla Dunes (sensu stricto)	3.4	-7.0%	+16.29%
Skilvit Dunes (sensu stricto)	6.3	-7.4%	+5.58%
Caspalege Dunes	9.1	-20.2%	-15.89%
Roe Hide Dunes	12.8	-18.9%	-6.21%
Glider‘s Dunes (sensu stricto)	7.2	-11.6%	-25.94%
Nagliai Dunes	18.2	-15.9%	-15.58%
Agila – Cape Avių Dunes	6.9	-17.8%	-18.73%

I. The strip of White Dunes comprises three shifting dune areas: White Dunes (sensu stricto), Cape Tern Dunes, and Round Hill Dune (Fig. 3);

II. The strip of Fringilla Dunes comprises two shifting dune areas: Fringilla Dunes (sensu stricto) and Kunčia Dune (Fig. 3);

III. The strip of Skilvit Dunes comprises two shifting dune areas: Priedin Dune and Skilvit Dunes (sensu stricto) (Fig. 4);

IV. The strip of Glider‘s Dunes comprises five shifting dune areas: Caspalege Dunes, Roe Hide Dunes, Grobštas Dune, Glider‘s Dunes (sensu stricto), and Parnidis Dune (Fig. 5);

V. The strip of Grey Dunes comprises two shifting dune areas: Nagliai Dunes and Agila–Cape Avių Dunes (Fig. 6).

We have divided all 14 shifting dune areas of the Grand Curonian Dune Ridge into two distinct groups according to their geomorphologic trends:

A. Greater shifting dune areas, which are featured by the greatest length, width and the largest volumes of sand.

B. Isolated shifting dunes, which contain small volumes of sand and lack supply sources as they are surrounded by the forest, forested palvė or degrading dune hummocks (*kupstynė*. Lith.).

A. Greater shifting dune areas

The greater shifting dune areas are characterised by relatively large and stable volumes of sand, both in the dune ridge itself and in the adjacent open palvė and *kupstynė*. Therefore these shifting dune areas

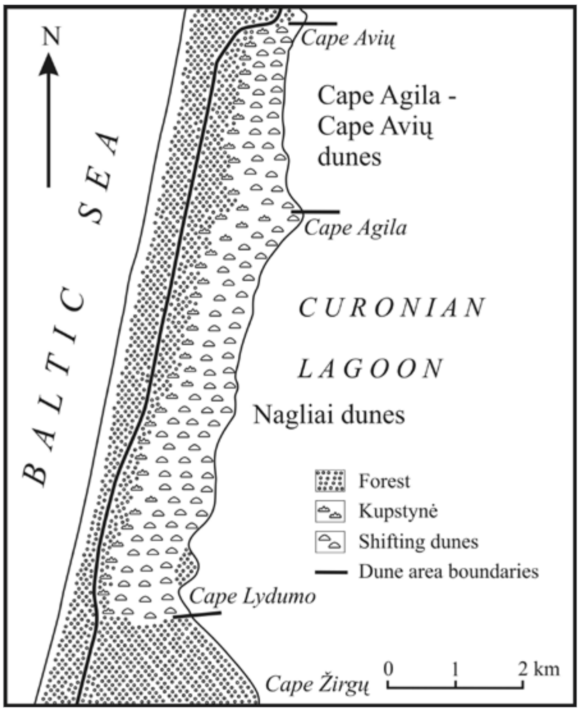

Fig. 6. The Grey Dunes of the Grand Curonian Dune Ridge.

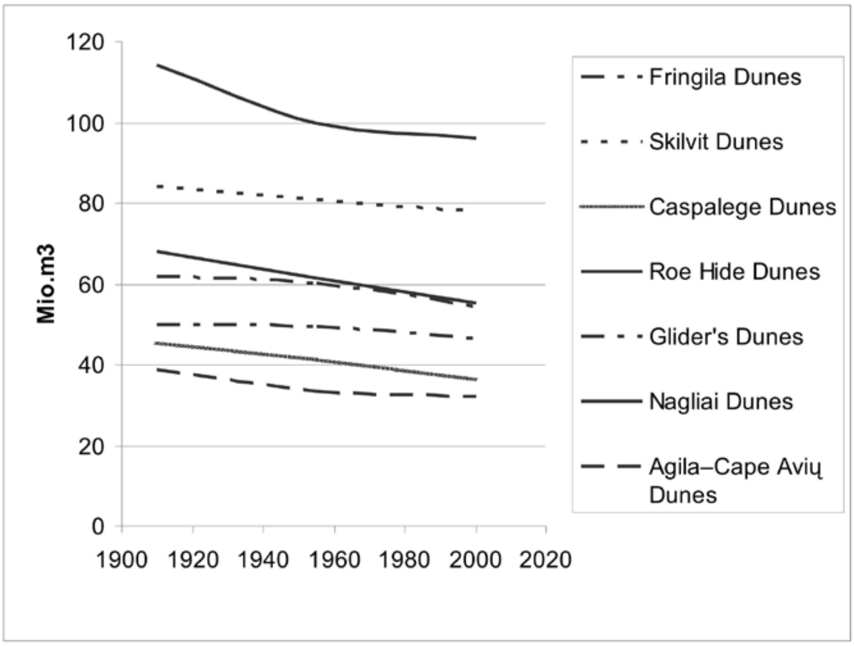

Fig. 7. Change of the sand volume of the greater shifting dune areas of the Grand Curonian Dune Ridge in the period 1910–2000. The resulting regression equation of the sand volume change is: y = –0.001 x + 65.83

enjoy a relative geomorphologic stability (Table 3, Fig. 7). Yet, various greater shifting dune areas experienced different geomorphologic processes, caused by different natural and human impacts, which resulted in specific local evolution patterns throughout the 20th century.

The Fringilla Dunes (sensu stricto) – the longest integral shifting dune strip on the Curonian Spit experienced a relatively robust development throughout the 20th century. The first half of the 20th century witnessed a further accumulation of sand in the shifting barchans, and the dunes were still in the growing phase: Dune Vyshka peak experienced a 5–m increase, from 50 m in 1910 to 55 m in 1955 (Povilanskas 2004). The total sand volume remained relatively stable and the area covered by the shifting sand increased at the expense of the coastal sand plain, which became ever narrower as waves and ice–drift eroded the sandy lagoon coast there. In the second half of the 20th century, a slow degradation of the Fringilla Dunes started, as the dunes had not received any additional sand input. In the period 1955–2000 the Fringilla Dunes lost 7% of their total sand volume, which was rather a big amount in absolute terms: the total loss was 3.1 million m^3 of sand (or 9000 m^3 of annual sand loss per 1 km of the dune front, Povilanskas *et al.* 2009).

The height of Dune Vyshka – the highest shifting dune in the Fringilla Dunes area – declined from 55 m in 1955 to 53 m in 1994 (a very small decline compared with all other shifting dune peaks on the Curonian Spit in the second half of the 20th century; Povilanskas 2004).

In the meantime the foresters established vast Mugo pine and Scots pine plantations in the adjacent dune areas (particularly the White Dunes to the south), but the acreage of the shifting sand remained relatively stable in the Fringilla Dunes, and the proliferation of psammophilic forbs, herbs, bushes, and trees in this area was minimal during 1955 to 2000. Where the sediment input from the shifting dunes is high, the dune coasts are rapidly advancing into the lagoon (up to 3.5 m annually). There, the onshore, the foreshore, and the nearshore are covered with bare sand. However, in the meantime the old sandy capes became destroyed by waves and ice. Yet huge sand supplies and a rapid advance of the Fringilla Dunes toward the lagoon caused not only a very fast advance of the lagoon shoreline, but also created new promontories there.

The Skilvit Dunes (sensu stricto) enjoyed a relative robustness throughout the 20th century. During the entire measurement period of 1910 to 2000, Skilvit Dunes lost 7.44% of the initial volume of drifting sand, which in absolute terms is a relatively huge amount: 6.5 million m^3 of sand, or 16'300 m^3 annually per 1 km of the dune ridge length (Povilanskas *et al.* 2009).

The height of Morskaya Dune, the highest dune in that area, had not changed between 1910 and 1955 and remained 60 m. Then within another 45 years, until 2000, the area experienced a rapid flattening of the shifting dune surface (probably due to increasing frequency of the westerly storms). The height of Morskaya Dune decreased to a mere 38.4 m already in 1990, whereas the area covered by the shifting sand increased by 50 hectares during the period 1955–2000. Also, the dune ridge experienced erosion and fragmentation of its surface, with numerous valleys and remnants of eroded dunes appearing on the surface of the windward side of the dune crest.

Because of a rapid eastward advance of the shifting dune ridge toward the lagoon (up to 4.4 m annually) and equally rapid shoreline erosion by waves and ice drift, the coastal accumulative plain along the lagoon shoreline completely disappeared until 1955, together with Cape Skilvit. Thence, already in 1955 the entire dune front of the Skilvit Dunes was in direct contact with the lagoon, forming a steep dune coast.

The southern flank of the Caspalege Dunes (Lepu Kalns) reached the Curonian Lagoon in the 1920s and supplied the northbound longshore sediment drift in the lagoon with sand, which separated the picturesque Lakelet Caspalege from the lagoon as a result (Paul 1944–1951). Unfortunately, the policy of dune forestation that prevailed on the Curonian Spit after World

War II, and, particularly, in the 1970s and the 1980s, speeded up the degradation, fragmentation and sylvanization of the Caspalege Dunes (Fig. 8).

Fig. 8. Senseless efforts to stabilize one of the highest shifting dunes – Caspalege Dune in the 1980s (after Povilanskas 2004).

These processes resulted in the loss of 18% of its sand volume in the period 1955–2000. Another reason for the last drive of afforestation by the Russian foresters in the 1980s was their aim to prevent a rapid flattening of the Caspalege Dunes and their fast eastward advance towards the Lakelet Caspalege which could result in the disappearance of the latter. Unfortunately, the Caspalege Dunes, a unique landmark of the Grand Curonian Dune Ridge, was irreversibly lost as a result of the forestation urge. In 1955–2000, the acreage of the shifting sand on the Caspalege Dunes declined by 16%. Currently, the degradation and overgrowth of the Caspalege Dunes is moderate.

The shifting dunes of the Roe Hide Dunes area are rapidly flattening, particularly their northern strip at Cape Grobštas. In 1955–2000, Roe Hide Dune, which is the highest shifting dune in the area, experienced a dramatic inversion of the geomorphologic processes – from a rapid growth to an equally rapid decline. The entire Roe Hide shifting dune area lost 17.2% acreage of the white dune landscape in the same period. A fast eastward advance of the shifting dunes in this area leaves the landscape of dune relicts and hummocks (kupstynė) behind the dune ridge. Yet, the dunes themselves still contain a rather stable volume of sand and present a relatively robust white dunes landscape.

The central and the highest cross–border area of the shifting dunes (Gliders' Dunes) experienced a dramatic change in the dune development trend during the last quarter of the 20th century. The latest history of the Gliders' Dunes (sensu stricto) was completely different from the neighboring shifting dune areas. In the first two–thirds of the 20th century, these highest dunes of the Grand Curonian Dune Ridge were steadily growing and rapidly advancing eastward. The southern peak of Gliders' Dune reached 68.3 m in height in 1967 (Gudelis 1998), which made it the highest contemporary coastal dune in the Baltic Sea region. A rapid advance of the Gliders' Dunes left a wide belt of hummocks behind on the windward slope of the shifting barchans.

Then, suddenly, the height of the highest peak of Gliders' Dunes rapidly declined, from 68.3 m in 1967 to 53.1 m in 1983 (Mardosienė, Vainauskas 1984). In 1955–2000, the Gliders' Dunes lost 141.8 ha (16.66%) of their original acreage of shifting sand to vegetation. However, currently this strip of some of the highest shifting coastal dunes in Europe is protected as a strict nature reserve and as frontier zone, and therefore suffers no more from any human impact.

The Nagliai shifting dune area of Grey Dunes is characterized by intensive geomorphologic processes (Fig. 9). It is especially heavily influenced by aeolian processes (Česnulevičius *et al.*, 2006). Most of the deflation basins of Grey Dunes are concentrated there (Morkūnaitė, Česnulevičius 2005). Between 1910 and 2000, the average annual eastward advance rate of Nagliai Dunes was 1.6 m (Česnulevičius *et al.* 2006), and the volume of sand decreased by 18.2 million m3, or 40.4 thousand m^3 per 1 km length of the dune strip, according to our estimates.

In 1955–2000, the Nagliai Dunes lost 12% of the white dune landscape, which was afforested (at Cape Būdos) or gradually turned into the grey dune landscape. In 2003, the height of Vingkopė shifting dune reached 57 m above sea level (Morkūnaitė, Česnulevičius 2005), thus becoming the highest contemporary coastal dune in the Baltic Sea region and the third highest shifting coastal dune in Europe. Slow migration of the crest of the slope eastwards (0.4–1.0 m annually) is the main trend of the western (windward) slope dynamics. A study suggests a strong wind aerodynamic effect, which results in the shore–normal aeolian depressions intersecting the shifting dune ridge (Česnulevičius *et al.* 2006). The advance of the Nagliai Dunes into the lagoon currently leads to the formation of new capes along the lagoon coast in front of the deflation ravines (Cape Vingkopės and Cape Senųjų Naglių), according to the results of our long–term field surveys (Povilanskas *et al.* 2009).

The Agila–Cape Avių Dunes are characterised by a very distinct structure and peculiar patterns of the geomorphologic development trends (Česnulevičius, Morkūnaitė 1997, 1998; Morkūnaitė 2000; Morkūnaitė, Česnulevičius 2005; Česnulevičius *et al.* 2006).

Aeolian processes and a high groundwater level caused a rapid succession and great landscape diversity within this dune area. It had reached maturity and started to degrade in the first half of the 20th century

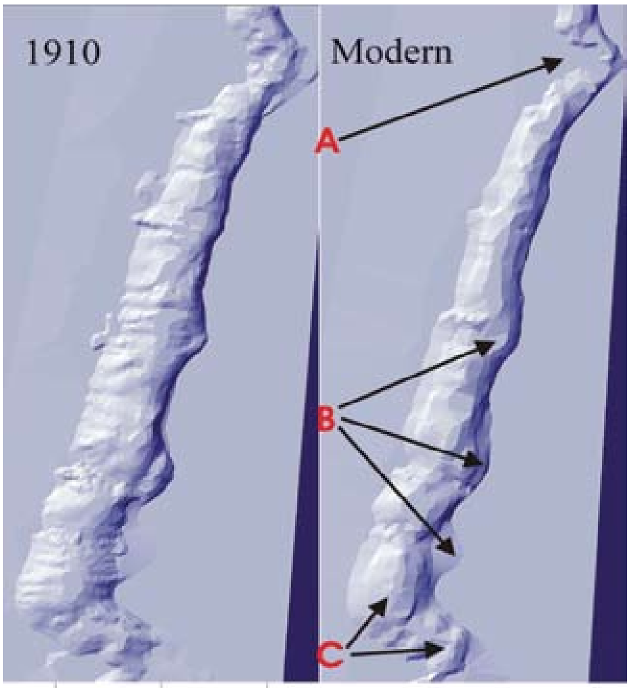

Fig. 9. 3D digital model of the Grey Dunes in 1910 and 2000 (after Povilanskas, 2004): A) degradation of the Avių Hill shifting dune on the northern flank of Grey Dunes south of Juodkrantė; B) grading of the lagoon coast of the Curonian Spit caused by wave action and ice–drift, and the advance of the shifting dunes; C) relative stability of the southern flank of the Grey Dunes.

Fig. 10. Day–trippers on the Avių Hill shifting dune south of Juodkrantė in the early 1900s (Povilanskas 2004).

already. Its surface is least fragmented with relatively large distances between depressions (Morkūnaitė, Česnulevičius 2005).

The sand volume of the Agila – Cape Avių Dunes had declined by 6.9 million m^3 or 30.7 thousand m^3 per 1 km length of the dune strip in the entire surveyed period 1910–2000. Avių Hill was still a shifting dune throughout the first half of the 20th century (Fig. 10 and Fig. 11). Now its relicts are nearly completely degraded (see Fig. 9) and overgrown by natural forest. In 2007–2008, efforts were taken by the administration of the Kuršių nerija national park to remove the natural forest and to increase the acreage of the grey dune landscape as part of a EU–supported LIFE NATURE project.

B. Isolated shifting dunes

Since the 1950s, the isolated shifting dunes of the Grand Curonian Dune Ridge, which contain small volumes of sand, have experienced a disastrous degradation. They lack fresh sand supply sources as they are surrounded by forest, forested palvė or degrading kupstynė areas (Povilanskas 2004; Cherednichenko *et al.* 2007). An integral shifting dune strip of White Dunes became fragmented in the second half of the 20th century, and currently comprise isolated shifting dune areas, which are separated by forest wedges – White Dunes (sensu stricto), Round Hill Dune and Cape Tern Dunes. All other isolated shifting dunes of the Grand Curonian Dune Ridge – Kunčia Dune, Priedin Dune, Grobštas Dune and Parnidis Dune suffered a similar fate in the same period (Table 4, Fig. 12).

The White Dunes (sensu stricto) in the southernmost part of the Curonian Spit experienced moderate degradation already in the first half of the 20th century. This dune area faced particularly disastrous degradation from the 1950s to the 1980s, as a result of the senseless afforestation of the adjacent palvė and the recreational development of the Dyuny bungalow site.

The White Dunes (by name) have gradually turned into grey dunes (by landscape definition) and kupstynė (hummock) landscape replacing the shifting barchans with psammophilic herbal plants covering the surface. The sprawl of the Dyuny bungalow site still causes a rather great stress on the integrity of White Dunes (Povilanskas 2009).

In 1910–1955, the White Dunes (sensu stricto) lost 13% of the sand volume, and ca. 18% of their area became covered by the naturally proliferating birch forest. The degradation of the White Dunes reached dramatic dimensions between 1955 and 2000: the dunes lost 53% of the sand volume and about half of the area became covered by Mugo pine and Scots pine plantations as well as by the naturally proliferating bush vegetation. The barchans became very much fragmented and turned into a mixture of the grey dune and forested dune landscapes. The altitude of the White Dune peak declined from 35 m in 1910 and 1955 to a mere 15 m in 1990.

The shifting dunes of the Tern Cape Dunes area remained relatively robust in 1910–1955 due to a steady supply of sand from the adjacent palvė plain. Yet, these shifting dunes have almost completely disappeared as a result of an intensive drive for afforestation of the remaining shifting dunes in the Russian part of

Table 4. Parameters of the geomorphologic processes of the isolated shifting dunes of the Grand Curonian Dune Ridge in 1910-2000.

Shifting dune area	Deflation, million m^3	Relative change of sand volume, %	Relative change of shifting sand acreage, %
White Dunes	0.5	-63.4%	-60.50%
Cape Tern Dunes	0.1	-70.2%	-63.15%
Round Hill Dune	0.1	-39.8%	-47.24%
Kunčia Dune	0.1	-50.0%	-55.02%
Priedin Dune	0.1	-71.4%	-54.31%
Grobštas Dune	0.6	-72.0%	-43.72%
Parnidis Dune	0.5	-67.9%	-32.68%

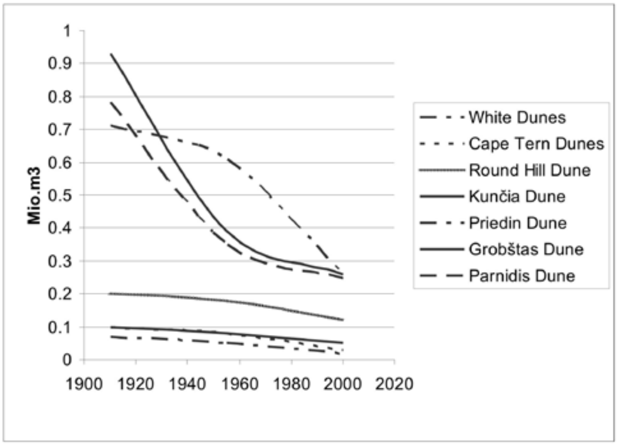

Fig. 12. Change of the sand volume of the isolated shifting dunes of the Grand Curonian Dune Ridge from 1910 to 2000. The resulting regression equation of the sand volume change is: $y = -0.003\ x + 0.40$.

the Curonian Spit in the second half of the 20th century. As a result of such long–term dynamics of these shifting dunes, they became very much fragmented and turned into the kupstynė landscape, with many aeolian blowouts and deflation ravines intersecting the dune surface. Particularly notable for nature conservation is the largest southeast Baltic population of sea holly (Eryngium maritimum), which is found in the deflation ravines of the Tern Cape Dunes (Ėringis, Pancekauskienė 1995).

Fig. 11. Aerial photo of the yet active dunes in the Agila – Cape Avių shifting dune area in the early 1960s. Note that Avių Hill – the last shifting dune in the vicinity of Juodkrantė (upper right corner of the picture) is still void of any vegetation; photo by V. Boldyrev, 1961.

Round Hill Dune remained an open shifting dune till the 1950s. Yet, in 1955–2000, it lost nearly half of its sand volume and half of its height (decreasing from 25 m to 13 m in 2000). Round Hill Dune is a typical example of the coastal squeeze caused by natural causes (Nicholls, Mimura 1998; Doody 2004; Vermaat *et al.* 2005; Wolters *et al.* 2005). Its western slope is gradually becoming covered by a natural mixed forest, and its eastern slope, which is adjacent to the Curonian Lagoon, is destroyed by ice–drift and wave action (Povilanskas 1998a, b).

The area south of Cape Rybachy experienced a significant degradation, fragmentation and flattening of the shifting dunes in the course of the 20th century, which was caused by the lack of sand supply and by the senseless forestation drive of the 1950s to the 1980s on the Curonian Spit. Most of the area became covered by pine plantations, except of Kunčia Dune. It nevertheless became isolated and lost its aeolian integrity with the Fringilla Dunes as a result of the last forestation drive of the 1980s. This process caused a 50% loss of its sand volume and nearly total degradation of the shifting dune area. Kunčia Dune can be distinguished from other isolated dunes by its gradual flattening. Its surface is least fragmented by deflation ravines, but its leeward slope, which is adjacent to the Curonian Lagoon, is destroyed by ice–drift and wave action (Fig. 13). Hence, Kunčia Dune is also a very good example of the natural coastal squeeze.

Like many other isolated shifting dunes of the Grand Curonian Dune Ridge, Priedin Dune remained stable till the 1950s. Yet, it had nearly completely disappeared by the turn of the century. It was cut from the southern flank of the Skilvit Dunes as a result of the aforementioned forestation of the 1950s to the 1980s. Its relicts suffer further degradation due to the natural coastal squeeze. Grasses and forbs and bush vegetation spreads on the windward western slope of the remaining dune relicts, while the leeward eastern slope adjacent to the lagoon is destroyed by ice–drift and wave action (Povilanskas 1998a, b).

Grobštas Dune is the oldest modern shifting dune on the Curonian Spit (Mager 1938). It features a specific geomorphologic structure and a rapid evolution. This compound barchan (Gudelis, Karužaitė 1962, 1993; Gudelis 1998) had reached its maturity and started to degrade in the early 1900s already. Between 1910 and 1955, the sand volume of Grobštas Dune declined by 58%, and between 1955 and 2000 another 14%.

Grobštas Dune is currently devoid of any human impact, being located within a strict nature reserve and the frontier zone. Yet, intensive degradation processes of the shifting dune relicts are currently taking place. The situation is even more aggravated by the natural coastal squeeze. The dune is at the very tip of Cape Grobštas and therefore it is destroyed by the ice–drift and wave action (Povilanskas 1998a, b; 2004).

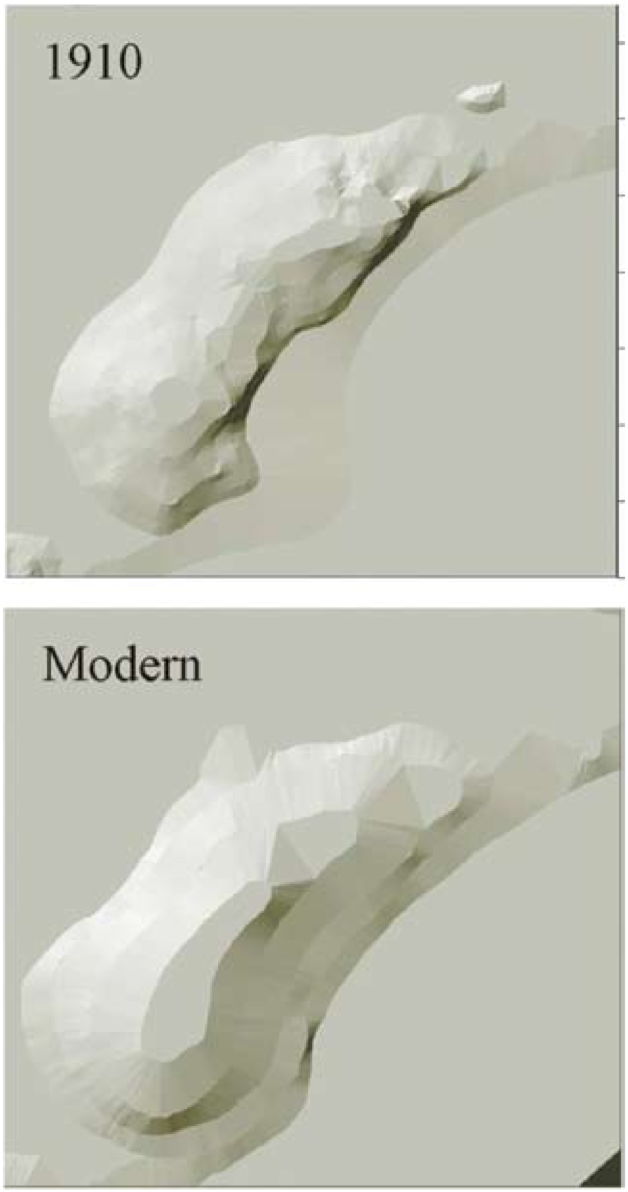

Fig. 13. 3D digital model of the evolution of Kunčia Dune. Note the flattened surface of the shifting dune and the eroded lagoon coast (Povilanskas 2004).

Disastrous shifting dune degradation in the second half of the 20th century also occurred at Parnidis Dune and Parnidis Cape, which lost 89.1 hectares (24.39%) of its original acreage of shifting sand to vegetation, mainly to Mugo pine and Scots pine plantations. Parnidis Dune is an integral part and the dominant landmark of the Parnidis Bight coastscape, which is one of the most picturesque coastcapes in Europe. It was a source of inspiration to Thomas Mann, a Nobel Prize–winning author in the 1930s (Povilanskas 2004). After an intensive forestation program, the dune became void of any local sand supply sources and rapidly degraded. From 1955 to 2000, the height of the shifting part of Parnidis Dune declined from 55 m to 43 m (Povilanskas *et al.* 2009).

CONCLUSIONS

The main resulting modern geomorphologic development trend of the Grand Curonian Dune Ridge is relative stability and robustness of the greater shifting dune areas and disastrous degradation of the isolated shifting dunes. The average annual deflation rate of the greater shifting dune areas does not exceed 0.1% of their volume.

However, all the isolated shifting dunes of the Grand Curonian Dune Ridge have suffered rapid deflation and fragmentation due to the senseless forestation drive of the 1950s to the 1980s and the resulting lack of sand supply from palvė. The average annual deflation rate of the isolated shifting dunes is ca 0.3% of their volume.

The overall acreage of the shifting sand (the 'white dune' landscape) of the Grand Curonian Dune Ridge is relatively stable. The average annual decrease of the acreage of the shifting sand did not exceed 0.1% during the second half of the 20th century.

The major modern geomorphologic development problems of the Grand Curonian Dune Ridge are: flattening and fragmentation of the shifting dunes, development of aeolian depressions and the decline of the main visual qualities – some of the highest shifting coastal dunes in Europe.

Acknowledgements

The above study was conducted with support from Small Project Fund under TACIS Cross–Border Cooperation Programme (project number TSPF /0302/0101). Engineer Eugenijus Žikulinas digitized the archive maps for the comparative cartometric survey, which is gratefully acknowledged. Author kindly appreciate input to the article made by reviewers Prof. Peter D. Jungerius (The Netherlands) and Prof. Algimantas Česnulevičius (Lithuania). The corrections and comments have improved the quality of the publication.

REFERENCES

Armaitienė, A., Boldyrev, V.L., Povilanskas, R., Taminskas, J., 2007. Integrated shoreline management and tourism development on the cross–border World Heritage Site: A case study from the Curonian spit (Lithuania/Russia). *Journal of Coastal Conservation 11(1),* 13–22.

Arens, B., Geelen, L., Slings, R., Wondergem, H., 2005. Restoration of dune mobility in the Netherlands. *In* Herrier, J.–L., Mees, J., Salman, A., Seys, J., Van Nieuwenhuyse, H., Dobbelaere, I. (eds.), *Proceedings 'Dunes and Estuaries 2005', International conference on nature restoration practices in European coastal habitats*. VLIZ Special Publication No. 19, Oostende. 129–138.

Berendt, G., 1869. *Geologie des Kurisches Haffes und seiner Umgebung*. W. Koch Commission, Koenigsberg, 110 + vi pp.

Bessa Junior, O.D., Angulo, R.J., 2003. Volumetric Variations on the Beaches of the South Seashore of Parana State in Brazil. *Journal of Coastal Research, Special Issue 35 (Proceedings of the Brazilian Symposium on Sandy Beaches),* 209–215.

Brivio, P.A; Zilioli, E., 1996. Assessing wetland changes in the Venice lagoon by means of satellite remote sensing data. *Journal of Coastal Conservation 2(1),* 23–32.

Česnulevičius, A., Morkūnaitė, R., 1997. Morphometrical, lithological and mineralogical traits of eolian formations in the Lithuanian coastal zone of the Baltic Sea. *Baltica 10*, 52–58.

Česnulevičius, A., Morkūnaitė, R., 1998. Some aspects of comparative characteristics of the old and new generation dunes in the Curonian Spit. *Geographical Yearbook 31*, 200–211. [In Lithuanian].

Česnulevičius, A., Izmaiłov, B., Morkūnaitė, R., 2006. Dynamics of deflation hollows of the main ridge in the Curonian Spit. *Geography 42 (2),* 21–28. [In Lithuanian].

Cherednichenko, V.P., Doroshin, A.V., Solodov, A.A., 2007. Dynamics of the sand relief and dune–handling on the Curonian Spit. *Problems of desert development 40(1),* 15–22. [In Russian].

Doody, J.P., 2001. *Coastal Conservation and Management: An Ecological Perspective*. Springer Verlag, Berlin, Heidelberg, New York, 328 pp.

Doody, J.P., 2004. 'Coastal squeeze' – an historical perspective. *Journal of Coastal Conservation 10(1),* 129–138.

Doody, J.P., 2005. Sand dune inventory of Europe. *In* Herrier, J.–L., Mees, J., Salman, A., Seys, J., Van Nieuwenhuyse, H., Dobbelaere, I. (eds.), *Proceedings 'Dunes and Estuaries 2005' International conference on nature restoration practices in European coastal habitats*. VLIZ Special Publication No. 19, Oostende, 45–54.

Ėringis, K., Pancekauskienė, D., 1995. *Eryngium maritimum* L. population dynamics in the Kuršių nerija national park of Lithuania and total population inventory method. *In* Gudelis, V., Povilanskas, R., Roepstorff, A. (eds), *Coastal Conservation and Management in the Baltic Region. Proceedings of the EUCC–WWF Conference, 3–7 May, 1994, Rīga – Klaipėda – Kaliningrad*. University Publishers, Klaipėda, 223–234.

Fisher, E., 2004. Coastal Sand Dunes: An Evolutionary Inventory. *In* D. Green (ed.), *Delivering Sustainable Coasts: Connecting Science and Policy – 7th International Multi–Disciplinary Symposium on Coastal Zone Research, Management and Planning, Aberdeen, September 2004*; Cambridge Publications Ltd., vol. 1, 145–150.

Grootjans, A.P., Geelen, H.W.T., Jansen, A.J.M. Lammerts, E.J., 2002. Restoration of coastal dune slacks in the Netherlands. *Hydrobiologia 478*, 181–203.

Gudelis V., 1960. Geology and development history of the coastal dunes on the Curonian Spit. *Proceedings of the Estonian Academy of Sciences 5*, 305–316. [In Russian].

Gudelis, V., 1998. *Lithuanian coast and offshore.* Academia, Vilnius, 444 pp. [In Lithuanian].

Gudelis, V., Karužaitė, G., 1962. Cape Grobštas (a physical geographical and landscape description of one landscape locality on the Curonian Spit). *Geographical Yearbook 5*, 175–196. [In Lithuanian].

Gudelis, V., Karužaitė, G., 1993. Mapping and areal subdivision of geographical landscapes in the Curonian Spit. *Dynamics and paleogeography of the Baltic Sea coastline 2*, 94–98. [In Lithuanian].

Gudelis, V., Kazakevičius, S., 1988. Some regularities of the dune development on the Curonian Spit according to cartometric data. *Proceedings of the Lithuanian Academy of Sciences, Series B (2)*, 136–143. [In Russian].

Gudelis, V., Michaliukaitė, R., 1959. On the question of lithology and dynamic differentiation of the present aeolian sand in the Curonian Spit. *Geography 5*, 48–53. [In Lithuanian].

Hess von Wichdorf, H., 1919. *Geologie der Kurischen Nehrung*. Berlin, 198 pp.

Jungerius, P. D., 2008. Dune development and management, geomorphological and soil processes, responses to sea level rise and climate change. *Baltica 21 (1–2),* 13–23.

Kazakevičius, S., 1985. Cartometric analysis of the coastline change dynamics on the Curonian Spit. *Geodesy 13*, 133–138. [In Russian].

Korneyevets, L., Volkova, I., 1995. Natural Complexes of the South–eastern Baltic Dunes and Characteristics of Their Main Components. *In* Gudelis, V., Povilanskas, R., Roepstorff, A. (eds.), *Coastal Conservation and Management in the Baltic Region. Proceedings of the EUCC–WWF Conference, 3–7 May, 1994, Rīga–Klaipėda–Kaliningrad*. University Publishers, Klaipėda, 69–74.

Kuzminskaya, T.L., Shelestovskaya, Y.A., Kessel, D.S., 2003. Initial stages of the succession on the dunes of the Curonian and Vistula spits of the Baltic Sea (Kaliningrad Oblast). *Botanical Journal 1***,** 62–75. [In Russian].

Kudaba Č., Mardosienė D., 1986. Peculiarities of the Aeolian geodynamics on the leeward slopes of the shifting dunes of the Curonian Spit. *Geography 22*, 81–86. [In Russian].

Litvin, V., Balayan, B., Korneyevets, L., Volkova, I., 1995. Landscape map of Kaliningrad coast, South–East Baltic. *In* Gudelis, V., Povilanskas, R., Roepstorff, A. (eds.), *Coastal Conservation and Management in the Baltic Region. Proceedings of the EUCC–WWF Conference, 3–7 May, 1994, Rīga – Klaipėda – Kaliningrad*. University Publishers, Klaipėda, 75–80.

Lodovisi, A.; Torresani, S., 1996. Evaluating historical cartography as a tool for the study of coastal areas. *In* P.S. Jones, M.G. Healy, J.P. Doody (eds.), *Studies in European Coastal Management.* Samara Publishing Ltd., Cardigan, 111–120.

Mader, D., 1995. *Aeolian and Adhesion Morphodynamics and Phytoecology in Recent Coastal and Inland Sand and Snow Flats and Dunes from mainly North Sea and Baltic Sea to Mars and Venus,* Vol. 1–2. Peter Lang, Frankfurt/Main–Berlin–Berne–New York–Vienna, 2348 pp.

Mager, F., 1938. *Die Landschaftsentwicklung auf der Kurischen Nehrung*. Graeffe und Unser, Koenigsberg. i. Pr., 140 pp.

Mardosienė, D., 1988. Analysis of the dynamics of the highest dunes on the Curonian Spit. *Geographical Yearbook 24*, 114–119. [In Lithuanian].

Mardosienė D., Vainauskas, V., 1984. Cartometric survey of the dune dynamics on the Curonian Spit. *Geographia Lituanica (Geographical Yearbook) 22*, 52–57. [In Russian].

Michailiukaitė, E., 1967. Dynamics of coasts and dunes on the Curonian Spit during the last 100 years. *Geographical Yearbook 8*, 97–111. [In Lithuanian].

Minkevičius V., 1968. Micro– and meso–forms of the shifting dunes on the Curonian Spit. *Geographical Yearbook. 9*, 97–102. [In Lithuanian].

Minkevičius V., 1969. Dependence of the sand transport on the meteorological conditions in the shifting dunes of the Curonian Spit. *Geographical Yearbook 10*, 187–195. [In Lithuanian].

Minkevičius V., 1972. On the issue of the sand dynamics of the shifting dunes of the Curonian Spit in the winter and spring period. *Proceedings of Lithuanian Academy of Sciences, Series B 4(71)*, 169–174. [In Russian].

Minkevičius V., 1982. Aeolian relief of the Baltic coast. *Geographical Yearbook 20*, 156–160. [In Lithuanian].

Morkūnaitė R., 2000. Consequences of the wind activity on the Juodkrantė—Pervalka dune strip of the Curonian Spit. *Geographical Yearbook* 33, 244–256. [In Lithuanian].

Morkūnaitė R., Česnulevičius A., 2005. Changes in blowout segments of the Main Ridge in the Curonian Spit in 1999–2003. *Acta Zoologica Lituanica 15(2)*, 145–150.

Nicholls, R. J., Mimura, N., 1998. Regional issues raised by sea–level rise and their policy implications. *Climate Research 11*, 5–18.

Paškauskas, S., 2006. Morphometric investigations of the main dune ridge on the Curonian Spit, Lithuania. *Baltica 19 (1),* 38–46.

Paul, K.H., 1944–1951. *Morphologie und Vegetation der Kurischen Nehrung. Gestaltung der Bodenformen und ihrer Abhangigkeit von Pflanzendecke*. Halle (Saale), 1944, Bd. 1, 1951, Bd. 2, 88 pp.

Povilanskas, R., 1998a. Ice impact on the lagoon shore of the Curonian spit, Southeast Baltic. *Geografija 34(1)*, 35–40.

Povilanskas, R., 1998b. Morphological changes of the Curonian Lagoon shoreline in 1955–1994. *Geographical Yearbook 31*, 224–235. [In Lithuanian].

Povilanskas, R., 1999. Outline of the integrated lagoon shoreline management programme for the Curonian Spit. *Geographical Yearbook 32*, 139–148. [In Lithuanian].

Povilanskas, R., 2004. *Landscape management on the Curonian Spit: A cross–border perspective*. EUCC, Klaipėda, 242 pp.

Povilanskas, R., 2009. *Management of littoral linear ecotones (Habilitation Thesis)*. University Publishers, Klaipėda, 36 pp. [In Lithuanian].

Povilanskas, R.; Chubarenko, B.V., 1998. Interaction between the migrating dunes of the Curonian barrier spit and the Curonian lagoon. *In* C.H. Ovesen, (ed.), *Coastal dunes – management, protection and research. Report from a European Seminar, Skagen, Denmark, August 1997*. The national Forest and Nature Agency / Geological Survey of Denmark and Greenland; 108–113.

Povilanskas, R.; Chubarenko, B.V., 2000. Interaction between the drifting dunes of the Curonian Barrier Spit and the Curonian Lagoon. *Baltica 13,* 8–14.

Povilanskas, R., Satkūnas, J., Taminskas, J., 2006. Results of cartometric investigations of dune morphodynamics on the Curonian Spit. *Geologija 53*, 22–27.

Povilanskas, R., Baghdasarian, H., Arakelyan, S., Satkūnas, J., Taminskas, J., 2009. Morphodynamic trends of the Holocene dune ridge on the Curonian Spit (Lithuania/Russia). *Journal of Coastal Research 25(1)*, 209–215.

UNESCO, 2001. *Report of the 24th Session of the UNESCO World Heritage Committee*, 27 November–2 December 2000, Cairns, Australia; Doc. Nr. WHC–2000/CONF.204/21; UNESCO, Paris, 144 pp.

Vermaat, J., Bouwer, L., Turner, K., Salomons, W. (eds.), 2005. *Managing European Coasts: Past, Present and Future.* Springer Verlag, Berlin, Heidelberg, New York. 387 pp.

Volkova, N.I., 1998. Landscape and ecological characteristics of the Curonian and Vistula spits. *Problems of nature survey and conservation on the Curonian Spit.* IORAN, Kaliningrad, 112–126. [In Russian].

Williams, A.T., Davies, P., 1987. Rates and mechanisms of coastal cliff erosion in Lower Lias rocks. *In* N.C. Kraus (ed.), *Coastal Sediments '87, Vol. 2*. American Society of Civil Engineers, New Orleans, 1855–1870.

Wolters, M., Bakker, J.P., Bertness, M.D., Jefferies, R.L. Möller, I., 2005. Salt–marsh erosion and restoration in south–east England: squeezing the evidence requires realignment. *Journal of Applied Ecology 42*, 844–851.