Shifting Dune Types of the Curonian Spit and Factors of Their Development

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Abstract

This paper analyzes the main natural and human factors that affect a current morphodynamic and ecological development of the Grand Curonian Dune Ridge. All shifting dune areas of the Grand Curonian Dune Ridge are classified into four different types: 1) Equilibrium and various degradation risk areas. 2) Negative disequilibrium and high degradation risk areas. 3) Positive disequilibrium and high degradation risk areas. 3) Positive disequilibrium and low degradation risk areas. To ensure the long-term dune management sustainability, the linear functional zoning approach must replace the current perpendicular one in the management of the national parks of *Kurshskaya kosa* and *Kuršių nerija*. The shifting dune management should be based on the interpretation of the Curonian Spit as an interrelated system of linear littoral habitats. This interrelated system of the linear littoral habitats comprises the ridge of shifting barchans together with the adjacent windward strips of *kupstynė* and *palvė*. The management should focus on facilitating the dynamism of palvė by promoting responsible tourism there.

Key words: shifting dunes, Curonian Spit, forest proliferation, linear littoral habitats

Introduction

The anthropocentric paradigm of nature management that prevailed till the middle of the 20th century interpreted wild nature or wilderness as the major source of disorder, which must be ordered by purposeful nature management measures. Meanwhile, according to Moore and McLaran (1991, p. 224): "over the past 60 to 70 years, wilderness has been increasingly ordered in terms of the emerging science of ecology. Whereas recreation and aesthetics initially framed discussions about wilderness, scientists and managers now speak of energy flows, gene pools, fire regimes, endangered species and biological diversity". Biocentrism, thus, can be seen as competing and, possibly, replacing anthropocentrism as the prevailing nature management paradigm (Povilanskas 2004).

Such an inversion of the nature ordering and the shift in nature management principles are evident from the evolution of the dune management approaches. Forestation was the main dune management strategy along the coast of the North Sea and the Baltic Sea throughout the 19th century and the better part of the 20th century (Bučas 2001, Povilanskas 2004). These forests in most places were, and to a large extent, still are carefully managed, protected and replanted in the case of damage, e.g., from accidental fire.

Yet, the highest shifting dunes of the Curonian Spit were designated as a nature reserve as early as 1928 (Mager 1938). This was one of the first protected dune areas in Europe that heralded a new approach in the dune management – from the need to overcome and tame the sand drift towards the preservation of the shifting dunes as attractive natural landscapes.

Nowadays, with the development of dune ecology and an increasing aesthetic appeal of the shifting dune landscapes the dune management approach is further changing. Now shifting dunes are valued as diverse and variable habitats and as 'multifunctional systems with great importance for our society' (van der Meulen et al. 1989). Forests and other human interventions into dunes are labeled as aliens to the intrinsic natural order of the dynamic shifting dune areas (Rabski 1995). As dynamic systems, shifting dunes are considered to be highly fragile, and their natural ordering vulnerable.

A radical shift in the dune management approach – from forestation to removal of mugo pine plantations and revival of dune dynamism is currently taking place in the European Union (Doody 2001). In the early 1990s, coastal scientists and managers had developed a radically new understanding of the evolution of dune habitats, their role in maintenance of the biological and habitat diversity, and, thence, their management regime. European seminars on dune management in Denmark (1997), the Netherlands (1998) and England (1999) reflected greater appreciation of the importance of the revival of landscape dynamism for the dune management policy (Doody 1998, 2001, 2005, Dučinskas and Povilanskas 2000, Povilanskas 2004, Povilanskas and Taminskas 2004, Armaitienė et al. 2007, Povilanskas et al. 2006, 2009).

On the Curonian Spit, the main dune management problem is the clash between the two different nature management approaches – whether the priority should be given to the continued cultivation of Scots' pine plantations and a stringent management regime (antropocentric approach), or to the enhancement of the shifting sand drift (biocentric approach). While the authorities waver between the two management options the worst scenario comes true: a fast natural proliferation of Scots' pine to the low-lying open sand areas and, as a result, the depletion of sand supply to the shifting dunes.

Therefore, the main aims of this study are: a) classify different shifting dune areas of the Curonian Spit regarding their vulnerability to a natural or human stress, b) analyze different human and natural factors that affect modern development of the shifting dunes, and c) recommend optimization of the shifting dune management principles for the cross-border Curonian Spit.

Material and methods

The Grand Curonian Dune Ridge, i.e., the part of the Curonian Spit that comprises the shifting barchans, is the third highest and the second longest shifting coastal dune ridge in Europe (Povilanskas 2004). It is protected as a strict nature reserve within the *Kurshskaya kosa* national park on the Russian part, and the *Kuršių nerija* national park on the Lithuanian part of the spit. The shifting dune landscape forms the most distinctive natural heritage value of the spit, with the highest shifting dunes exceeding 50 meters in height (Povilanskas 2009).

On the European scale, shifting dunes are characterized by morphological diversity. Doody (2005) distinguishes seven different morphogenetic types of shifting dune habitats. 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 defense. Dunes also serve as geoecological indicators (Povilanskas et al. 2009) and as ecotourism areas (Vaitekūnas et al. 2001, Povilanskas 2004, Armaitienė et al. 2007). The Grand Curonian Dune Ridge also delivers important conservation functions: as series of the NATURA 2000 habitats of European importance (Rašomavičius et al. 2001) and as a specific complex blend of archaeological, cultural and natural heritage (Rimantienė 1999).

There are five strips of shifting barchans currently 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 linear structure (Povilanskas 2009). Many other dune areas present a mosaic of white and grey dunes, dune slacks and heath areas on a coastal accumulative plain. They have preserved their original parabolic form till modern times (Doody 1991, Korneyevets and Volkova 1995, Fisher 2004, Jungerius 2008). Meanwhile, the sand drift, which took place from the 1600s to the 1800s on the Curonian Spit, had destroyed the landscape mosaic of ancient parabolic dunes. It had created a chain of shifting 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, Povilanskas 2004).

Table 1. Shifting dune strips of the Grand Curonian Dune Ridge

Dune strip	White Dunes	Fringilla Dunes	Skilvit Dunes	Glider's Dunes	Grey Dunes
Length, km	5.9	7.5	6.1	5.7	7.4
Max. height, m	15.0	53.0	38.4	53.1	57.0
Shift of the lagoon coastline, m/year	0 – +3	-1 – +3.5	-1 – +4.4	-2 – 0	-1 – +1

From the coast of the Baltic Sea to the coast of the Curonian Lagoon, the landscape of the Curonian Spit is featured by the sequence of the following key linear littoral habitats:

• seaside beach,

- artificially created foredune with Burnet Rose (*Rosa pimpinellifolia*),
- strip of accumulative sand plain (*palvė*) covered by Scots' pine (*Pinus silvestris*) stands with natural patches of deciduous trees (*Betula pendula* and *Alnus incana*),
- strip of recent dune relics (*kupstynė*),
- chains of shifting barchans interspersed by dune strips fixed with Mugo pine (*Pinus mugo*),
- reed beds (*Phragmites australis*) along the lagoon coast.

The barchans of the Grand Curonian Dune Ridge together with the parallel strips of *kupstynė* and *palvė* on the windward hinterland (i.e., to the west from the shifting dune ridge) comprise an interrelated system of linear littoral habitats. Due to the linearity 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 mitigating degraded shifting dunes or dune slacks elsewhere on the coastal plain (Grootjans et al. 2002).

Material for this study was collected in three ways: from the cartometric analysis of topographic maps and satellite images, from the field mapping of the five shifting dune strips on both, the Lithuanian and the Russian sides of the border (except a narrow inaccessible border strip), which took place from June to August 2007, and from the state archives in Lithuania and Russia.

For the aims of our study, we have adapted a checklist method to evaluate coastal dunes' vulnerability (Table 2). It was developed within an EU-sponsored ELOISE-Dunes Project that defined coastal dune vulnerability as the degree of coastal dune system's susceptibility to experience change and irreversible degradation (Williams and Bennett 1996, Williams et al. 1998, Laranjeira et al. 1999, Williams and Davies 2001).

At 155 rather evenly distributed transect strips of the shifting dunes and hinterland *palvė* and *kupstynė* areas (100 m x 1000 m, perpendicular to the lagoon coastline) we have assessed 21 different variables that characterize seven parameters, according to the slightly modified checklist (Table 2):

Table 2. Morphodynamic parameters and variables of the dune vulnerability checklist (adapted from Laranjeira et al. 1999)

Parameters	Variables (values from 0 to 4)
1. Dune morphology	1.1. Length of a shifting dune strip: **0** – >20 km, **1** –10–20 km, **2** – 5–10 km, **3** – 1–5 km, **4** – <1 km
	1.2. Average width of a shifting dune strip: **0** – >5 km, **1** – 2–5 km, **2** – 1–2 km, **3** – 0.1–1 km, **4** – <0.1 km
	1.3. Maximum height of dunes: **0** – >40 m, **1** – 30–40 m, **2** – 20–30 m, **3** – 10–20 m, **4** – <10 m
2. Sand input into the shifting dunes from 1955 to 2003 (% of the total dune sand volume)	2.1. Sand input from the sea: **0** – >25%, **1** – 10–25%, **2** –5–10%, **3** – 1–5%, **4** – <1%
	2.2. Sand input from the hinterland: **0** – >25%, **1** – 10–25%, **2** –5–10%, **3** – 1–5%, **4** – <1%
	2.3. Sand input from the adjacent dune areas: **0** – >25%, **1** – 10–25%, **2** –5–10%, **3** – 1–5%, **4** – <1%
3. Sand retention by vegetation	3.1. Percentage of open sand area in the dune hinterland: **0** – >80%, **1** – 60–80%, **2** – 40–60%, **3** – 20–40%, **4** – <20%
	3.2. Hinterland area covered by grasses: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
	3.3. Forest cover increase in the hinterland since 1955: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
4. Pressure of recreational use	4.1. Number of visitors in the shifting dunes per hour on summer weekends at noon: **0** – <10, **1** – 10–25, **2** – 25–50, **3** – 50–100, **4** – >100
	4.2. Path network density (length of paths in meters per hectare of dune area): **0** – no paths, **1** – 0–100 m/ha, **2** – 100–200 m/ha, **3** – 200–300 m/ha, **4** – >300 m/ha
	4.3. Number of tourists sliding down or climbing up the dunes per hour on summer weekends at noon: **0** – 0, **1** – 1–3, **2** – 4–6, **3** – 7–9, **4** – ?10
5. Dune management and conservation regime	5.1. Percentage of area with restricted access: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
	5.2. Percentage of area protected by strict conservation regime: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
	5.3. Percentage of open sand areas artificially fixed since 1955: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
6. Obstacles to sand transgression (% of a dune strip barred by inpermeable obstacles)	6.1. Barred by brushwood and/or forest: **0** – <20%, **1** – 20–40%, 2 – 40–60%, **3** – 60–80%, **4** – >80%
	6.2. Barred by roads and/or bike paths: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
	6.3. Barred by urban and/or recreational areas: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
7. Morphodynamic peculiarities	7.1. Percentage of shifting dune areas eroded by blowouts and gullies: **0** – <20%, **1** – 20–40%, **2** – 40–60%, **3** – 60–80%, **4** – >80%
	7.2. Change of shifting dune volume since 1955: **0** – < -2.5%, **1** – from -2.5% to -5%, **2** – from -5% to -25%, **3** – from -25% to -50%, **4** – > -50%
	7.3. Change of the dune crest height since 1955: **0** – < -2.5%, **1** – from -2.5% to -5%, **2** – from -5% to -25%, **3** – from -25% to -50%, **4** – > -50%

1) Dune morphology.

2) Sand input into the shifting dunes from 1955 to 2003.

3) Sand retention by vegetation.

4) Pressure of recreational use.

5) Dune management and conservation regime.

6) Obstacles to sand transgression.

7) Morphodynamic peculiarities.

The cartometric analysis was applied to elicit the values of the key morphometric variables according to a well-established methodology that has a long history on the Curonian Spit (Berendt 1869, Hess von Wichdorf 1919, Michaliukaitė 1967, Povilanskas 2004):

1.1. Length of a shifting dune strip. 1.2. Average width of a shifting dune strip. 2.1. Sand input from the sea. 2.2. Sand input from the hinterland. 2.3. Sand input from the adjacent dune areas. 3.1. Percentage of open sand area. 3.3. Forest-cover increase between 1955 and 2003. 5.1. Percentage of area with restricted access. 5.2. Percentage of area protected by strict conservation regime. 5.3. Percentage of open sand areas artificially fixed between 1955 and 2003. 7.2. Change of shifting dune volume since 1955. 7.3. Change of the dune crest height between 1955 and 2003.

Digital cartometric analysis was carried out using the program Surfer 7, which enables computing of various planimetric parameters. The minimum accuracy of the digital cartometric analysis δx was limited by the accuracy of the original topographic maps of the Curonian Spit from 1955 on scale 1:25'000 (δx = 2.5 m) and a 3D satellite image of the Curonian Spit from 2003 (δx = 1.0 m).

The field mapping was applied to elicit the values of the following variables:

1.3. Maximum height of dunes. 3.2. Percentage of open sand area covered by grasses. 4.1. Number of visitors in the shifting dunes. 4.2. Path network density. 4.3. Number of tourists sliding down or climbing up the dunes. 6.1. Percentage of a dune strip barred by brushwood and/or forest. 6.2. Percentage of a dune strip barred by roads and/or bike paths. 6.3. Percentage of a dune strip barred by urban and/or recreational areas. 7.1. Percentage of mobile dune areas eroded by blowouts and gullies.

The mapping was done using a GPS GAR MIN 60CX. The measurement accuracy was äx = 1 m. Field data were gathered at a particular time, so the resulting vulnerability checklist only makes it possible to characterise a particular state of the dune system (Laranjeira et al. 1999).

Materials deemed necessary to assess the impact of human and natural factors on the long-term dynamics of the shifting dunes had been quarried from the state archives. Data on monthly precipitation and temperature in Nida between 1947 and 2007 were quarried from the archive of the Lithuanian Hydrometeorological Service. The data on the percentage of free-grazing cattle and number of elk on both, Lithuanian and Russian parts of the Curonian Spit were quarried from the state archives of Lithuania and Russia. Data on the percentage of the open sand areas on both, Lithuanian and Russian parts of the Curonian Spit in different years were derived from the forest management plans and monitoring reports, topographic maps and from satellite images.

According to the ELOISE-Dunes Project methodology, the first four parameters (dune morphology, sand input into the shifting dunes between 1955 and 2003, sand retention by vegetation, pressure of recreational use) were assembled to calculate a vulnerability index (VI).The fifth parameter assesses dune management and conservation measures and gives a management index (MI). The balance between vulnerability and management and conservation measures for the shifting dune system was calculated by the VI/MI ratio (Φ).

According to Davies et al. (1995), Williams and Bennett (1996), Williams et al. (1998), Laranjeira et al. (1999), Williams and Davies (2001), the European coastal dune areas could be classified into four categories. The point of equilibrium occurs when Φ is between 0.8 and 1.3 (Laranjeira et al. 1999). Values lower than 0.8 indicate positive disequilibrium ('over-protected' areas of mobile sand dune forms), whereas values higher than 1.3 indicate negative disequilibrium (later degrading dune forms that are more stable, yet 'under-protected' according to the functional zoning) (Davies et al. 1995, Williams and Bennett 1996). The average of the parameters 6 to 7 indicates the level of degradation risk of dune area (Ђ). The dune area experiences low or high degradation risk, if Ђ is below 1.8 or over 2.2 respectively.This dichotomy that is derived from the ELOISE-Dunes Project methodology also refers to a more common dichotomy of "Stabilised/Overstable" and "Dynamic/Mobile/eroding" dune forms.

For the analysis of the resilience of the Grand Curonian Dune Ridge to withstand identified risks (obstacles to sand transgression and a negative morphodynamic trend) we have applied morphological integrity index (б) (Povilanskas et al. 2011). For the calculation of the morphological integrity index we have applied the following equation:

$$б = (\bar{h} / h_{\max} * l_{tot} / l) / \sqrt{n} \quad (1)$$

where: б – morphological integrity index (0 – no integrity, *l* – full integrity); $\bar{h}$ – average width of the shifting dunes' strips of the Grand Curonian Dune Ridge, m; h_{max} – maximum width of the shifting dunes' strips of the Grand Curonian Dune Ridge, m;

l_{tot} – total length of all shifting dunes' strips of the Grand Curonian Dune Ridge, m;

l – length of the entire Curonian Spit, m;

n – number of the shifting dunes' strips of the Grand Curonian Dune Ridge.

For the analysis of the impact of climate change on the development of the shifting dunes we have calculated humidity index (HI) for the vegetation seasons of 1950–2007:

$$HI = P / P_{ET} \quad (2)$$

where: HI – humidity index; P – 5-year shifting average of annual precipitation during vegetation season, mm; P_{ET} – 5-year shifting average of annual potential evapotranspiration during vegetation season, mm.

We applied statistical analysis to identify which factors have the strongest impact on the long-term morphological changes in the Grand Curonian Dune Ridge. The factor analysis for identification of the dominant factors was done by applying principal component's method with normalized varimax rotation. For this aim, the elicited values of 12 out of 21 variables in the 155 transsects of the Grand Curonian Dune Ridge describing the shifting dune vulnerabilty parameters have been used as a database. For verification of the interrelationship between different dune vulnerability variables a correlation matrix was calculated. To verify the dependence of various variables of the morphodynamic impact on different factors, communalities among these factors were estimated.

Results

The entire 32.6 km–long Grand Curonian Dune Ridge comprises 14 different shifting dune areas. All these areas can be classified into four different types according to the dynamic equilibrium and degradation risk conditions (Fig. 1, Table 3).

Dynamic equilibrium and various degradation risk areas (13.7 km length): The areas of this prevailing shifting dune type currently enjoy the dynamic equilibrium betweeen the human and/or natural stress and management measures. Yet, Skilvit Dunes and Fringilla Dunes, although being robust in their morphology and ecology, experience erosion and fragmentation of the surface. Numerous valleys and remnants of eroded dunes (*kupstynė*) appear on the surface of the windward side of the dune crest there.

Parnidis Dune is an integral part and the dominant landmark of the Parnidis Bight coastscape. It is one of the most picturesque coastcapes of Europe (Povilanskas, 2004). After an intensive forestation program, the dune became void of any local sand supply sources and degraded in the 1980s. Yet, currently, the degradation has slowed down.

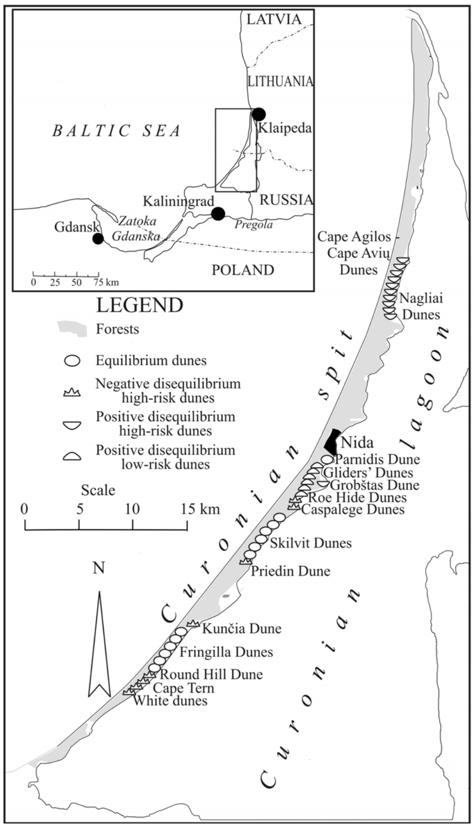

Figure 1. The Curonian Spit with shifting dune strips

Table 3. Indices of dynamic equilibrium (Φ), degradation risk (Ђ) and key human and natural impact factors for different types of shifting dune areas of the Grand Curonian Dune Ridge: A – Sand retention by vegetation (4 – complete); B – Pressure of recreational use (4 – very high); C – Dune management and conservation regime (4 – absolutely strict); D – Obstacles to sand transgression (4 – completely impermeable)

Shifting dune types and areas	Φ	Ђ	Key human and natural impact factors			
			A	B	C	D
Equilibrium and various risk areas						
Round Hill	1.2	3.1	2.7	2.0	2.3	3.3
Parnidis Dune	0.8	2.3	2.3	1.7	3.3	2.7
Fringilla Dunes (*sensu stricto*)	0.8	2.2	2.1	1.7	2.7	2.7
Skilvit Dunes (*sensu stricto*)	0.8	1.7	2.1	1.7	2.7	2.7
Negative disequilibrium and High-risk areas						
White Dunes (*sensu stricto*)	3.4	3.0	3.3	3.0	1.0	3.0
Cape Tern	3.3	3.0	3.3	2.7	1.0	3.0
Kunčia Dune	2.6	3.0	3.0	3.0	1.3	3.0
Priedin Dune	2.6	3.0	3.0	3.0	1.3	3.0
Caspalege dunes	2.2	2.3	3.0	2.0	1.3	2.7
Positive disequilibrium and High-risk areas						
Grobštas Dune	0.5	3.0	3.0	0.0	4.0	2.7
Naglių Dunes	0.7	2.3	1.9	0.6	3.0	2.7
Agila – Cape Avių Dunes	0.7	2.3	1.9	0.4	2.7	2.7
Positive disequilibrium and Low-risk areas						
Gliders' Dunes (*sensu stricto*)	0.5	0.8	1.3	0.4	3.3	1.7
Roe Hide Dunes	0.5	0.8	1.3	0.4	3.0	1.7

Negative disequilibrium and high-risk areas (6.9 km length): An essential loss of the main ecological features of the shifting dune habitat in these areas was caused by indiscriminate forestation in the second half of the 20th century. Void of any sand supply, these small dune areas experienced a dramatic evolution between 1955 and 2003. About 80% of open sand acreage became lost to Mugo pine and Scots' pine plantations and to a naturally proliferating vegetation of hawthorns, junipers, Scots' pine and birch trees. Dune areas of this type also suffer from tourism and recreation, ice drift and wave activity along the Curonian Lagoon coast. The *kupstynė* habitat replaced the shifting barchans with psammophilic herbal plants and the Scots' pine covering the surface there. The sprawl of the Dyuny bungalow site causes a rather big stress on the integrity of White Dunes. They become ever more isolated from the rest of the shifting dune ridge, flatter and less fragmented as a result of their current morphodynamic evolution.

Positive disequilibrium and high-risk areas (8.1 km length): The dunes of this type do not suffer from any direct human impact as all of them are protected within strict nature reserves. Grobštas Dune features a specific morphological structure and experiences a rapid evolution. This barchan reached its maturity and started to degrade in the early 1950s (Gudelis 1998). Although being in the border zone and, hence, void of any direct human impact, the dune is at the tip of Cape Grobštas and therefore is destroyed by the ice drift and wave activity along the coast of the Curonian Lagoon.

The Nagliai and Agila-Cape Avių Dunes are characterized by intensive morphodynamic processes. These dunes are heavily influenced by aeolian processes. In 1955-2003, the Nagliai Dunes lost over 27 % of the white dune habitat that was forested or gradually evolved into eroded dune relics (*kupstynė*) partly covered with the Scots' pine.

Nagliai and Agila-Cape Avių Dunes could be already classified as either forested or grey dunes in habitat terms. Only 31 % of this area comprises still open bare sand areas. Yet, in 2003, the height of Vingkopė, the highest shifting dune of this area reached 57 m above the sea level (Morkūnaitė and Česnulevičius 2005). It became the highest contemporary coastal dune in the Baltic Sea region and the third highest shifting coastal dune in Europe. The advance of the Nagliai Dunes into the Curonian 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).

Positive disequilibrium and low-risk areas (3.9 km length): These are the two central shifting dune areas. They are within the Lithuanian – Russian border zone and, therefore, are 'over-protected' from any direct human impact.These areas are still characterized by a relative habitat stability and large supplies of sand in *palvė*. Gliders' Dunes are characterized by a relative robustness of the shifting dune habitat, large acreage (over 50 %) of the bare sand areas and relatively large sand supplies on the windward side.

Factors of the Modern Development of the Grand Curonian Dune Ridge

The results of the factor analysis show that there are three components (complex factors) having the strongest impact on the shifting dune vulnerability and development on the Curonian Spit (Table 4 and Table 5). They capture 83.73 % of the variance. Judging from the set of variables they impact, these complex factors are: a) tourism; b) processes causing the proliferation of vegetation and declining sand supply; c) forestation. As shown in Table 6, it is clear that most of the communalities are rather high and this indicates that substantial parts of the variance in the original variables are captured by the factor solution.

Tourism and recreation

Component 1 shows the role of the inter-relationship of different aspects of tourism and recreation with the development of the shifting dunes on the Curoni-

Table 4. Total explained variance of morphodynamic variables of the dune vulnerability

Component	Rotation sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	5.280	40.618	40.618
2	4.185	32.196	72.814
3	1.419	10.914	83.729

Table 5. Rotated component matrix of morphodynamic variables of the dune vulnerability

Morphodynamic variables of the dune vulnerability	Component 1	Component 2	Component 3
1. Percentage of open sand area in the dune hinterland in 2007	0.626	0.606	-0.128
2. Hinterland area covered by grasses in 2007	0.093	-0.826	-0.104
3. Forest cover increase in the hinterland since 1955	0.567	0.712	-0.098
4. Number of visitors in the shifting dunes in 2007	0.683	0.438	0.458
5. Path network density in 2007	0.685	0.314	0.393
6. Number of tourists sliding down or climbing up the dunes in 2007	0.911	0.221	0.201
7. Percentage of area with restricted access in 2007	-0.947	-0.152	-0.079
8. Percentage of area protected by strict conservation regime in 2007	-0.924	-0.188	-0.149
9. Percentage of open sand areas artificially fixed since 1955	0.146	-0.205	0.873
10. Physical obstacles to sand transgression in 2007	0.214	0.949	-0.090
11. Tourism facilities as obstacles to sand transgression in 2007	0.814	-0.377	-0.154
12. Morphodynamic decline of dunes since 1955	0.517	0.622	-0.383

Table 6. Estimated communalities among different factors

Morphodynamic variables of the dune vulnerability	Communalities (Extraction)
1. Percentage of open sand area in the dune hinterland in 2007	0.776
2. Hinterland area covered by grasses in 2007	0.701
3. Forest cover increase in the hinterland since 1955	0.838
4. Number of visitors in the shifting dunes in 2007	0.868
5. Path network density in 2007	0.722
6. Number of tourists sliding down or climbing up the dunes in 2007	0.919
7. Percentage of area with restricted access in 2007	0.925
8. Percentage of area protected by strict conservation regime in 2007	0.911
9. Percentage of open sand areas artificially fixed since 1955	0.826
10. Physical obstacles to sand transgression in 2007	0.955
11. Tourism facilities as obstacles to sand transgression in 2007	0.688
12. Morphodynamic decline of dunes since 1955	0.800

an Spit as the most significant factor statistically. It explains 40.6 % of the total variance (spatial variation) of the shifting dune morphodynamics and related processes between 1955 and 2003.

According to Česnulevičius et al. (2006), after the collapse of the Soviet planning system in the 1990s, unregulated flows of visitors became the main destabilizing factor of the shifting dunes, particularly in the dune areas adjacent to the recreational zone. Jungerius (2008) also emphasizes that many of threats to which dune habitats are exposed, result from their recreational function which is a continuous source of concern for dune managers. Olšauskas (1996) has shown how the trampled paths on the foredune within a year turn to 1.5-3.5 m wide gullies with drifting sand, and the places where holiday-makers had lain, change to hollows and pits 3-4 m wide in diameter.

Yet, the results of our field survey in the summer of 2007 show that a negative impact of tourists on the shifting dunes development is relatively small in absolute terms, although being statistically well-correlated to spatial variation in the shifting dune morphodynamics. Except of five smallest negative disequilibrium and high-risk shifting dune areas that lie outside the strict nature reserves, the remaining shifting dune areas are characterized by a relatively low pressure of recreational use. These shifting dune areas are protected within strict nature reserves. Any access to these areas is prohibited to visitors, except three nature trails. The prohibition is respected to a large extent, particularly in the areas adjacent to the Lithuanian–Russian border (correlation between the number of visitors to the dune areas and their nature protection regime R = -0.82, see Table 7).

Table 7. Correlation matrix (R) of selected morphodynamic variables of the dune vulnerability

Morphodynamic variables of the dune vulnerability	1	3	4	8	10	12
1. Percentage of open sand area in the dune hinterland in 2007	(--)	0.76	0.61	-0.60	0.75	0.73
3. Forest cover increase in the hinterland between 1955 and 2003		(--)	0.61	-0.67	0.77	0.73
4. Number of visitors in the shifting dunes in 2007			(--)	-0.82	0.60	0.50
8. Percentage of area protected by strict conservation regime in 2007				(--)	-0.37	-0.50
10. Physical obstacles to sand transgression in 2007					(--)	0.72
12. Morphodynamic decline of dunes between 1955 and 2003						(--)

Processes causing the proliferation of vegetation and declining sand supply

Component 2 shows the inter-relationship of different processes that cause the encroachment of the shifting sand areas by proliferating vegetation as a second statistically most significant factor. It explains 32.2 % of the variance of the shifting dune morphodynamics.

The decline of the population of free-grazing animals, both, domestic and wild, had a significant impact on the long-term shifting dune morphodynamics on the Curonian Spit. The population of elk decreased from ca. 200 in 1938 to just 42 in 2003 on the spit. Large domestic herds of sheep, goats and cattle that once roamed *palvė* have completely disappeared. The overgrazing had often led to a disastrous deforestation and sand drift. Yet, the opposite extreme, i.e., a complete abandoning of grazing leads to the decline of shifting sand acreage on the spit. The direct impact of grazing in controlling vegetation on the Curonian Spit was confined to *palvė* and grey dunes, like elsewhere in Europe (Jungerius 2008). However, the decline of grazing as the means to control the vegetation on *palvė* resulted also in the degradation of both, the white and grey dunes. These dune strips are located leewards of *palvė*, and the sand supply to the shifting dunes declined resulting from a rapid natural proliferation of the unchecked Scots' pine forest.

According to Jungerius (2008), climate is the key factor of the natural processes of the dune habitat. In the periods of humid climate, the excess of precipitation over total evaporation is nourishing an upper groundwater table. As *palvė* and *kupstynė* become ever more deflated on the Curonian Spit, the upper groundwater table comes ever closer to the surface. Thence, every period of a more humid climate causes a rapid bogging-up of the terrain, a development of wet dune slacks in the deflation gullies and a faster proliferation of forest vegetation. Meanwhile, due to an ever increasing evapotranspiration in the vegetation season, the humidity of the upper sand layer is ever declining. This process results in the encroachment of the psammophilic grass habitats by the forest and by open sand areas (see a strong negative statistical relationship of the acreage of the psammophilic grass habitats with the forest proliferation and the acreage of the open sand, Table 5 and Table 7).

Forestation

Component 3 shows that the forestation is a third statistically most significant factor explaining 10.9 % of the spatial variation of the shifting dune development on the Curonian Spit. The forest cover increase in the hinterland since 1955 is the only variable that loads strongly on the third factor.

Since the middle of the 19th century, Scots' pine plantations completely prevented the transgression of sand from the seashore to the shifting dunes. Between the 1950s and the 2000s, the acreage of the shifting sand area on the Curonian Spit was steadily decreasing. The percentage of forested areas increased from 61 % in 1963, to 74 % in 2003 on the Lithuanian side of the spit, and from 43 % in 1953 to 65 % in 2003 on the Russian side causing both, the morphological and ecological decline of the shifting dune areas.

Integrated effect of different human and natural factors

As we can see from Figure 2, till the mid-1950s, the Curonian Spit enjoyed a rather moderate morphodynamic and ecological development. The natural proliferation of the forest was checked by abundant herds of free-grazing domestic and wild animals and a relatively dry climate. The percentage of the open sand and psammophilic grass habitats in the shifting dunes and their hinterland declined relatively slowly, mainly due to planting of forest plantations on *palvė*. Between 1955 and 2003, the Curonian Spit experienced three periods of rapid morphodynamic and ecological development. The system of the open sand and psammophilic grass plain (*palvė*) and shifting dunes reacted to a coincidental change of several human and natural factors (with a few years' delay) then.

Between 1961 and 1967, the percentage of the open sand and psammofilic grass area had decreased by 32 %. It occured after the decline of free-grazing domestic cattle herds on the spit by 60% between 1958 and 1962 and the increase in the humidity index by 10.6% between 1959 and 1965. Another similar dramatic decrease of the open sand and psammophilic grass area by 33 % occured between 1981 and 1987. Then the spit became almost void of the free-grazing domestic cattle herds, the number of elk became regulated on the spit and declined by 54% between 1975 and 1986, whereas the humidity index had increased by 32.2 % between 1976 and 1985.

The third and most recent dramatic decrease of the open sand and psammophilic grass area (by 31 %) took place between 1997 and 2003 due to an increase in the humidity index by 24.1 % between 1992 and 2003 as the free-grazing cattle herds became absent and the number of elk became stabilized. Since then the climate change is the only relevant factor determining the morphodynamic and ecological development of the Curonian Spit.

Resilience of the shifting dunes of the Curonian Spit

Considering the resilience of the shifting dunes of the Curonian Spit to the investigated factors and their capacity to withstand degradation risks (obstacles to sand transgression and a negative morphodynamic trend), the key criterion is the morphological integrity of the entire shifting dune ridge. The isolated smaller shifting dunes are rapidly declining, but the Grand Curonian Dune Ridge as a whole is relatively robust and integrated in morphological terms, although already void of any sand supply from the sea across the spit. It is much more integrated (morphological integrity index $б$ = 0.12) than, e.g., reed-beds stretching along the lagoon coast of the Curonian Spit ($б$= 0.02). A relatively high morphological integrity index of the Grand Curonian Dune Ridge is determined by a relatively homogenous width of the ridge ($/h_{max}$ = 0.55).

As we can see from Table 3, four different shifting dune types show different resilience patterns. From the management perspective, they face different risks and management challenges. Three first types of dune areas, except the lowest risk ones, risk a long-term depletion of sand supply (D > 2). Dune areas, which are in the situation of dynamic equilibrium, suffer from the encroachment by forest vegetation (A = 2.1-2.7). Paradoxically, the equilibrium of these areas is maintained by an actual violation of the strict conservation regime. This violation happens due to the marginal unregulated visits by tourists from Nida to Parnidis Dune and by anglers to Round Hill, Skilvit and Fringilla Dunes. These unregulated visits do not cause an excessive recreational pressure (B = 1.7-2.0). Negative disequilibrium high-risk areas suffer from the natural encroachment by vegetation (A = 3.0-3.7), the extreme pressure by recreational use (B = 2.0-3.0) and an insufficiently strict (or chronically abused) nature conservation regime (C = 1.0-1.3).

On the contrary, positive disequilibrium areas (both, high-risk and low-risk ones) enjoy a relatively slow natural encroachment by vegetation (A <2), a relatively low pressure by recreational use (B = 0.4-0.6) and, yet, a rather stringent nature management regime (C = 2.7-4.0). Table 7 shows an ambivalent role of the current nature management regime for the vulnerability, resilience and morphodynamic development of the Grand Curonian Dune Ridge. On the one hand, the lack of a stringent nature conservation regime predetermined the forest proliferation in the hinterland between 1955 and 2003 (R = -0.67). On the other hand, the stringent nature management regime determined the shrinkage of the open sand area in the dune hinterland (R = -0.60).

Discussion

Here we come to the key question of our study: is the excessively strict nature conservation regime indeed necessary to ensure the management sustainability of the shifting dunes and adjacent areas, except the most vulnerable ones? It is evident from the presented results that the main challenge in achieving the sustainability of the long-term management of the Grand Curonian Dune Ridge is to strike a balance between dynamism and stability. This means that the role of humans as destabilizing agents should not be overlooked, particularly in the absence of grazing and in the presence of increasing climate humidity during the vegetation season. Hence, the main debatable issues regarding the management of the shifting dunes and their hinterland on the Curonian Spit that stem from the results of our study are: a) potential role of overlooked natural factors and b) radical shift in the functional zoning principles of both national parks on the Curonian Spit.

Potential role of overlooked natural factors

The role of three natural factors that might play an important role in the long-term development of the Curonian Spit was not addressed in our study due to a limited possibility to apply more diverse investigation methods. These potentially important natural factors are: neotectonic movements, long-term changes in the wind regime and a geomorphologic role of precipitation.

The groundwater level fluctuation and its impact on the shifting dune dynamics might be controlled by secular neotectonic movements. Kunskas (1978) argues that in the 1600s, before the period of the dramatic landscape transformations of the Curonian Spit, a catastrophic lowering of the groundwater level occurred as a result of slight tectonic elevation. This process caused rapid formation and advance of the shifting barchans, as the old parabolic dune areas had dried and became eroded by wind and re-deposited easier.

Also, long-term changes in wind regime might cause changes in the morphodynamic processes of the shifting dune areas. The most important might be changes in the regime of strong westerly and southwesterly winds (Minkevičius 1969, Гудялис и Казакявичюс 1988). According to Česnulevičius et al. (2006), strong recurring winds of the same direction are the main driving force of deflation processes. Yet, the role of the wind as the key natural factor of the dune dynamics is controversial. Quoting Jungerius (2008, p. 16): 'A related theory which is equally misleading is that only wind is a prominent geomorphic factor in coastal dunes. This is true only as long as the sand contains no organic matter, for instance in the foredunes. It is difficult for wind to move the humic sand of the grey dunes further inland.'

Precipitation also reduces the aeolian impact of wind by 20-30% (Morkūnaitė 2001). Yet, it might play not only stabilizing, but also an enhancing role in the development of the shifting dunes. Jungerius (2008) argues that when dry, dune sand is water repellent and is subject to water erosion and slope wash. Splash drift might have large effect on the flattening of the grey dunes (Goossens et al. 2000, Jungerius 2008).

The role of these natural factors in the long-term development of the Curonian Spit requires further investigation.

Shift in the functional zoning principles

The results of our study prove that a wrong nature conservation regime and a flawed functional zoning could thwart the management sustainability of the shifting dune areas. Whatever paradoxical it may look, yet the restrictions for tourists (equally as animals) to roam *palvė* freely are not justified either from morphodynamic, or ecological point of view and facilitate further proliferation of vegetation and retention of sand supply. This assumption is supported by the British dune management experience of the recent decades (Doody 1998, 2001, 2005).

The overreaching strict nature conservation regime also contradicts the status of the Curonian Spit as a UNESCO World cultural heritage site (Bučas 2001). The solution of this complicated problem might be achieved by a more active facilitating of the responsible ecotourism on open *palvė* of the Curonian Spit (Armaitienė et al. 2007), as well as by radical changes in the principles of the functional zoning of *Kuršių nerija* and *Kuršskaja kosa* national parks.

Currently existing 'nested' functional zoning principle of the Curonian Spit was developed in the 1950s. It treated the spit primarily as a seaside resort comprising several scattered settlements surrounded by a natural landscape. The promoters of such a functional zoning principle argue that it helps to protect the nature by establishing wide buffer zones of managed reserves on both sides of the settlements that transect the spit from the sea to the lagoon (Kavaliauskas 2010). These buffer zones separate the recreational areas from the strictly protected nature reserves.

Yet, the perpendicular functional zoning is incongruent with the linear structure of the landscape on the Curonian Spit. It fails to ensure the adequacy of management and conservation to actual nature protection needs and prevent the natural proliferation of the Scots' pine that takes place mainly on low-lying *palvė*. More seldom these processes take place on *kupstynė* and, sometimes, even on the shifting dune slopes adjacent to already forested areas (Репшас 1994).

Therefore, our proposal, which was first upheld in 1993 (Riepšas 1995), embraces the idea, that the longitudinal functional zones should be established instead of current perpendicular functional zones covering 'bits and pieces' of all habitat types. These longitudinal functional zones should provide an adequate management regime to every major habitat type corresponding to the linear structure of the Curonian Spit landscape.

The interpretation of the shifting barchans with the adjacent windward strips of *kupstynė* and *palvė* as an interrelated system of linear littoral habitats substantiates such a radical functional zoning change. The strictest conservation regime should be confined only to the shifting dune strips, whereas the strips of *kupstynė* and *palvė* should be turned into managed nature reserves. The clue to the management sustainability of the shifting dunes lies in enhancing the dynamism of *palvė* where a free access of tourists should be allowed and any existing forest vegetation should be removed. Increasing elk stocks and bringing back herds of free-grazing domestic animals on *palvė* should also have a positive effect in restoring the dynamism of the adjacent shifting dune strips (Boorman 2004).

Conclusions

1. All 14 shifting dune areas comprising the Grand Curonian Dune Ridge can be classified into four different types according to the dynamic equilibrium and degradation risk conditions. Currently, four shifting dune areas of the Grand Curonian Dune Ridge are in the dynamic equilibrium (0.8 < Φ < 1.3) and various degradation risk conditions (1.7 < Ђ < 3.1). These areas comprise 13.7 km (42 %) of the total length of the shifting dune ridge. Five shifting dune areas are classified as negative disequilibrium (Φ > 1.3) and high degradation risk areas (Ђ > 2.2). Three shifting dune areas are classified as positive disequilibrium (Φ < 1.3) and high degradation risk areas (Ђ > 2.2), whereas two central shifting dune areas that are adjacent to the Lithuanian – Russian border, are classified as positive disequilibrium (Φ < 1.3) and low degradation risk areas (Ђ < 1.8). An eventual fifth type of shifting dune areas, namely negative disequilibrium (Φ > 1.3) and low degradation risk (Ђ < 1.8) is absent on the Curonian Spit due to local dune evolution and management peculiarities.

2. Between 1955 and 2003, the Curonian Spit had experienced three periods of rapid morphodynamic and ecological development when the acreage of the open sand and psammofilic grass plain as well as the acreage of the shifting dunes declined by over 30 % during every period due to a coincidental change of several human and natural factors (with a few years' delay). The results of the factor analysis show that there are three components (complex factors) having the strongest impact on the shifting dune vulnerability and development patterns on the Curonian Spit. They are: a) tourism; b) processes causing the proliferation of vegetation and declining sand supply; c) forestation. The free-grazing cattle herds became absent and the number of elk became stabilized at the turn of the century. Hence, the climate change became the only relevant factor currently determining the morphodynamic and ecological development of the Curonian Spit.

3. To ensure the long-term dune management sustainability, the longitudinal functional zoning must replace the current perpendicular one in the management of the entire Curonian Spit on both sides of the border. The dune management should be based on the interpretation of the shifting barchans with the adjacent windward strips of *kupstynė* and *palvė* as an interrelated system of linear littoral habitats and, thence, on facilitating the dynamism of palvė as the main dune management priority.

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ТИПЫ ПЕРЕВЕВАЕМЫХ ДЮН КУРШСКОЙ КОСЫ И ФАКТОРЫ, ВЛИЯЮЩИЕ НА ИХ РАЗВИТИЕ

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Резюме

В настоящей статье анализируются основные природные и антропогенные факторы и принципы краеустройства, влияющие на современное морфодинамическое и экологическое развитие Большой гряды перевеваемых дюн Куршской косы. По отношению между морфодинамическим и экологическим стрессом и риском деградации, все отрезки Большой гряды перевеваемых дюн можно разделить на четыре различных типа: 1. Равновесия и разного риска деградации. 2. Отрицательного неравновесия и значительного риска деградации. 3. Положительного неравновесия и значительного риска деградации. 4. Положительного неравновесия и незначительного риска деградации. В целях обеспечения устойчивого долгосрочного краеустройства Куршской косы, настоящее перпендикулярное берегу функциональное зонирование национальных парков «Куршская коса» и «Куршю нярия» должно быть заменено на линейное, которое лучше соответствует морфологической и ландшафтной структуре Куршской косы. Интерпретируя Большую гряду перевеваемых дюн вместе с прилегающими полосами купстине и пальве как систему взаимосвязаных приморских ландшафтных полос, авторы статьи обосновывают предлагаемые радикальные изменения функционального зонирования национальных парков. Краеустройство Большой гряды перевеваемых дюн Куршской косы должно основываться на поощрении динамизма пальве через развитие ответственного туризма как основном приоритете.

Ключевые слова: перевеваемые дюны, Куршская коса, обрастание лесом, линейный приморский ландшафт.