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Article

Impact of Hydro-Climatic Changes on Coastal Dunes Landscape According to Normalized Difference Vegetation Index (The Case Study of Curonian Spit)

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Abstract: Coastal dunes are recognized as one of the most threatened ecosystems, the formation of which mainly depends on two opposite processes—sand dunes overgrowth and formation of open dunes. The application of cost-effective remote sensing methods permits monitoring the interaction of these two processes over a large area and long periods of time. Therefore in this study we assessed the links between hydro-meteorological parameters and the normalized difference vegetation index (NDVI) in Curonian spit coastal dunes landscape-a creation of human and nature integrity situated in the South eastern part of the Baltic Sea. Time series of NDVI (2000–2019) were obtained from the moderate resolution imaging spectro-radiometer and compared with hydro-meteorological parameters in three different ecosystems—forest, herbaceous and open sands. Moderate and strong positive correlation between NDVI and average wind speed was detected in non-forested ecosystems. Moderate positive correlation was detected between NDVI and the Baltic sea water level in all three analyzed ecosystems. Moderate positive correlation between NDVI and air temperature was found in forest ecosystem. This confirms that NDVI could be treated as an appropriate indicator, showing the interaction of coastal dunes overgrowth and formation of open dunes, and could be applied in its management that should be reconsidered under nowadays climate change.

Keywords: NDVI; coastal dunes; overgrowth; open dunes; hydro-climatic changes; wind speed

1. Introduction

The Curonian Spit is a sand-dune spit that separates the Curonian Lagoon from the Baltic Sea coast. It was formed by the sea and sand supply, affected by wind, vegetation, human activity and continues to be shaped by them. This outstanding creation was inscribed on the World Heritage List during the 24th session of the World Heritage Committee [1]. However, during a realization of WHC commitments a question about what nature and human interaction result should be protected in this territory appears: what part of sandy dunes should be covered by forest, herbaceous and open sand ecosystems.

In the past, a natural evolution of Curonian spit dunes landscape did not meet human expectations, therefore applied management of landscape and its protection strategy were controversial to natural processes. Irrational human activity started the processes influencing natural development of dunes landscape in the opposite direction. For example, on the one hand, the clear cuts encouraged eolian activity in dune systems. On the other hand, the excessive shrub and forest planting (*Salix, Pinus sylvestris, Pinus Mugo*) stopped eolian processes and influenced the overgrow of dunes.

Up to 16th c. the bigger part of Curonian Spit was covered by forests and herbaceous vegetation. Significant human impacts on the Curonian Spit began in the middle of the 16th century and followed up to 18th century. Deforestation of the Curonian Spit due to overgrazing and timber harvesting, destroyed the vide natural vegetation areas and open sandy dunes started to prevail–an aeolian activity was very high. Up to 16th c. the summary of forest cover was about 80%. It declined up to <10% in 19th c., whereas it recovered up to 80% at the end of the 20th c. [2]. Consequently, one of the most sensitive problems at the end of the 18th c. in Curonian Spit was buried buildings and roads beneath the sandy dunes. Therefore, starting from the beginning of the 19th c. the main direction of sandy dunes management in Curonian Spit reflected the main tendencies in North-Western Europe and other coastal dune areas worldwide—open sandy dunes were recognized as a threat and the significant part of the Curonian Spit dunes experienced deliberate afforestation by plantations of *Mugo* pine [3]. At the same time, the artificial foredune acting as a barrier from the seashore sand drift was formed along the entire length of the marine coast of the Curonian Spit. These management tools stopped the invasion of sand towards the urbanized territories. That was the main factor leading to the prevalence of herbaceous vegetation and forested landscape with some stretches of uncovered natural aeolian massifs.

Nowadays the change of Curonian Spit landscape is observed. Many researchers agree about decreasing sand dunes [4,5]. However, the two opposite processes-formation of open dunes and sandy dunes overgrowth are under heavy debate. The first one includes vegetation cover extinction influenced by climatic changes, natural or human induced fires, clear cuts, grazing and agriculture. The second group of processes combine natural overgrowth of dunes by forest and herbaceous vegetation, plantations, and urbanization. Some researchers report about the gradually deteriorating conditions for vegetation survival on the Curonian Spit coastal sand dunes during the last years (1982–2009) [6]. The others state about favorable conditions for forest cover expansion in Curonian Spit: there was a decrease in forest cover during 1989–2008 period, however 1% annual increase of forest cover is observed since 2009 [7]. These local processes forming dunes landscape may induce equilibrium between areas with active eolian processes and areas covered by herbaceous vegetation or artificial cover. However, climate change and anthropogenic activity may disturb this equilibrium and decrease the diversity of coastal landscape. Therefore, to maintain greater diversity of the landscape, it is important to understand how separate factors [8–11] influence the main processes of landscape formation. However, often these factors are simultaneous and strengthens or suppress each other and have positive or negative feedback. Therefore, it is hard or sometime impossible to distinguish the only one decisive cause of landscape change. The studies investigating a synergy of landscape forming factors have become more common in recent years [12–14]. To sum up, an increased natural tree establishment assumes the need for more detailed investigations in Curonian spit coastal zone.

Coastal dunes, containing a wide range of sensitive habitats, are important complex ecosystems, that require reporting about their condition regularly to take necessary measures in time. Remote sensing approaches provide cost-effective, rapid, and repeatable data across temporal and spatial scales that can be used for identifying and monitoring sparse canopies of highly mixed populations in coastal dunes [15]. Optical satellite data is often used for analysis of vegetation cover, manifesting as long-term changes in a vegetation index, for example, the normalized difference vegetation index (NDVI) [16,17]. NDVI is widely used to assess vegetation health in coastal habitats [18] and to provide phenological profiles to identify different vegetation types along coastal zone [16]. Time series of NDVI often becomes a proxy for seasonal vegetation productivity [16] and provide information about seasonal and interannual responses of vegetation to climate change in coastal dunes ecosystems [3]. Most studies reporting about the linear relationship between rainfall events and NDVI have been performed in arid or semi-arid areas [19–21]. However, a successful application of NDVI-based indices in Poland [22] confirms the suitability of NDVI usage in the areas with sufficient water supply.

There are few research studies related to NDVI responses to hydrological factors. Relationships between NDVI and hydrological values are used to assess the forest ecosystem response to changes in the groundwater lens [23] as well as groundwater flow discharge in wetland ecosystem [24] and raised bog ecosystem degradation patterns [25]. Promising opportunities for identifying potential groundwater dependent vegetation using NDVI [26] as well as riparian vegetation NDVI relationship with climate, surface water and groundwater [17] have been reported.

However, there is little literature that investigates the synergetic influence of changing hydroclimatic conditions on NDVI for coastal dunes ecosystems. Moreover, the major challenge reported in the application of optical remote sensing in coastal zone studies [27] is to find a routine tool in assessment of change in the coastal zone.

Until now, investigations of Lithuanian coastal dunes have mostly been based on the integration of visual interpretation (e.g., photointerpretation of aerial imagery), floristic and fieldwork data [4,9,28–37], with some episodic attempts to analyze this unique area applying remote sensing techniques [38–40]. Therefore, the analysis of coastal dunes succession trends in different ecosystems represented by NDVI variation could provide valuable information for reconsideration of the existing nature protection and nature management tools applied in Curonian spit dunes.

The main aim of this study is to show that development of coastal dunes ecosystems would result in vegetation cover changes (forestation/herbaceous vegetation encroachment or formation of open dunes) that would be reflected by NDVI values and that changes in NDVI would reflect the synergetic influence of changing hydro-climatological conditions. Therefore, the main objectives of this study were (a) to evaluate the overgrowth tendencies in Curonian spit ecosystems according to NDVI index; (b) to analyze the influence of hydrological conditions towards the NDVI values; (c) to analyze the influence of meteorological conditions towards the NDVI values; (d) to evaluate the future perspectives of natural landscape in Curonian spit.

2. Materials and Methods

2.1. Study Area

The Curonian Spit (55°30′ N, 21°00′ E), is a 98 km long peninsula of South eastern part of the Baltic Sea, situated between the Baltic Sea and the Curonian Lagoon (Figure 1). The northern part of Curonian spit (52 km) belongs to Lithuania, while the rest is part of the Kaliningrad Oblast of Russian Federation. The width of the spit varies between 0.4–3.8 km, surface elevation reaches up to 67.2 m above sea level (Dune Vecekrugas).

It is protected as a strict nature reserve within the Kuršių nerija national park on the Lithuanian part (est. 1991) and the Kurshskaya kosa national park on the Russian part of the spit (est. 1987). The whole Curonian Spit was included into the UNESCO World Heritage List as a single cultural landscape of outstanding international importance in 2000.

According to CORINE (Coordination of information on the environment) Land Cover inventory 2018 data (https://land.copernicus.eu/pan-european/corine-land-cover) forest ecosystem (311 Broad-leaved forest, 312 Coniferous forest, 313 Mixed forest, 324 Transitional woodland-shrub) covers 64%, herbaceous ecosystem (322 Moors and heathland, 333 Sparsely vegetated areas)—17%, open sand ecosystem (331 Beaches, dunes, sands,)—16% of Lithuanian part of Curonian spit. Remaining 3% belongs to urban and agriculture areas.

Average annual temperature is 8.0 °C in this region. Average monthly temperature fluctuates from −1.5 °C in February up to 18.4 °C in August. Average annual rainfall is 769 mm, snow cover remains about 61 days (Nida WS meteorological data, 1981–2010).

The Quaternary deposits in Curonian spit area are approximately up to 100 m thick from the surface. Infiltration recharges >250 mm/year is dominant in this territory. Shallow groundwater is stored in marine varigrained sand with intercalated peat deposits. Its thickness in the territory reach up to 20 m, and its hydraulic conductivity ranges from 5 to 30 m/day. The shallow groundwater depth is 2–10 m below the surface. Below shallow aquifer lies the Pleistocene limnoglacial (varigrained sand) and low permeable glacial (loam, loamy sand) deposits.

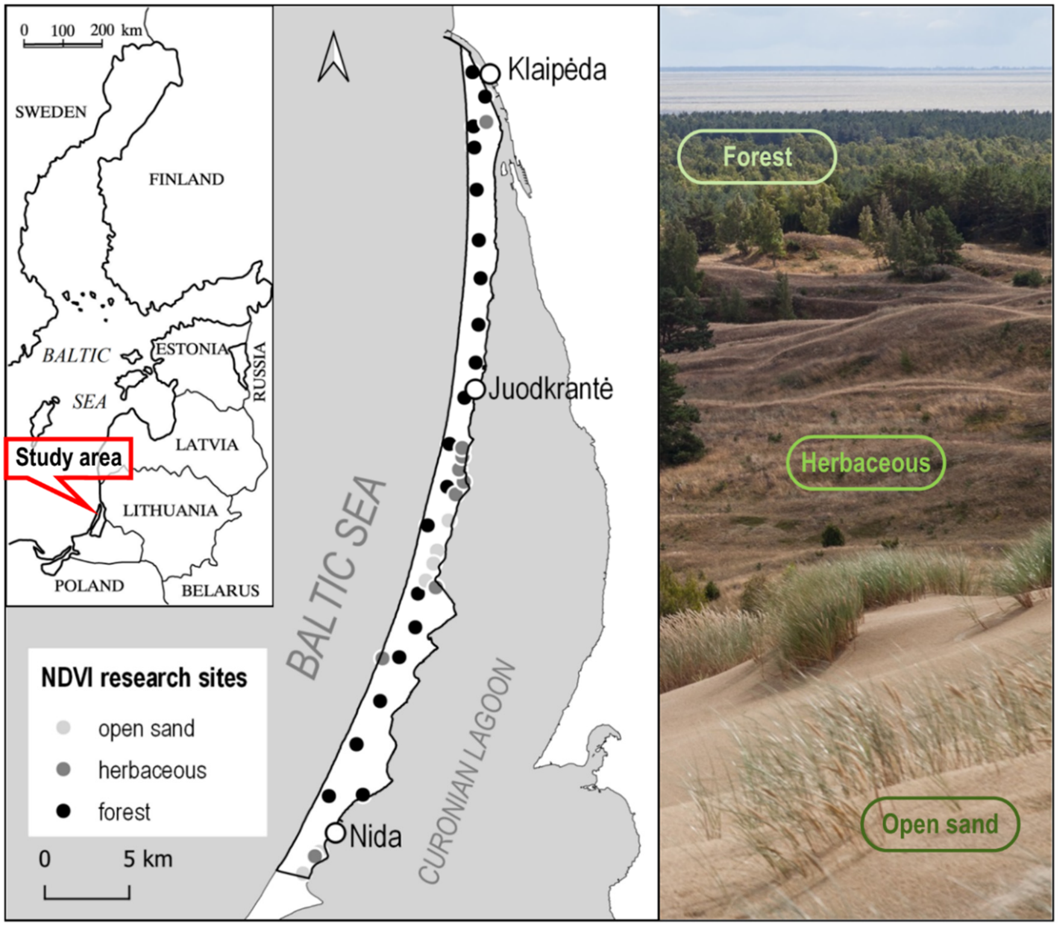

Figure 1. Location of research sites and typical view of studied ecosystem from sea to lagoon.

Due to its spectacular's geomorphological features the territory of Curonian spit is characterized by a great variety of humidity conditions. Sandy soils (arenosols, fluvisols, gleysols) varies from dry to humid ones (with exceptional cases of histosols).

According to humidity conditions all soils are being categorized to dry soils (a surplus of humidity appears up to 200 cm depth); quite humid soils (a surplus of humidity appears from 100 to 200 cm depth), humid soils (a surplus of humidity appears from 50 to 100 cm depth), wet soils (a surplus of humidity appears from 0 to 50 cm depth) and very wet soils (a surplus of humidity appears in all soil profile or groundwater table is up to 50 cm depth). This classification is based on Lithuanian soil classification (in lithuanian *Lietuvos Dirvožemių Klasifikacija* LTDK-99) [41] which is harmonized with WRB2014 (World Reference Base for Soil Resources, update 2015) classification [42]. Humidity surplus in soil is significant for ecosystems when its features appear up to 100 cm depth. Such humidity surplus has influence upon the variety of forest and herbaceous vegetation species.

This research was carried out in Lithuanian part of Curonian spit, where areas of forest, herbaceous and open sand ecosystems were distinguished (Figure 1).

Open sand ecosystems. Sands with small patches of *Ammophiletea* and *Corynephoretea* prevail. The requirements of these communities for soil humidity are different (Table 1). Dry soils prevail in sand dunes (with *Ammophiletea* and *Corynephoretea* inserts), whereas surplus of humidity in 0–50 cm depth are observed in beach sands. The root depth of *Ammophila arenaria* is about 60 cm, however single roots may reach 90 cm depth [43].

Table 1. Relations between humidity conditions and plant communities.

Humidity Conditions	**Depth of Surplus Humidity Layer, cm**	**Plant Communities**
Dry	>200	*Vaccinio-myrtillo Pinetum, Corynephoretea*
Quite humid	100–200	
Humid	50–100	*Nyrtillo-Pinetum, Myrtilo-oxalido-Pinetum/Betuletum, Nardetea*
Wet	<50	*Urtico-Alnetum, Caric-irido-Alnetum, Calamagrostido-Betuletum pubescentis/Piceetum*
Very wet	groundwater table < 50 cm	

Herbaceous ecosystems. A dominant vegetation class in this ecosystem is *Corynephoretea*, however some stretches of *Nardetea* appear in lower areas with higher humidity. The requirements of these communities for soil humidity are different: *Corynephoretea canescentis* vegetation prevail on dry soils (a surplus of humidity is up to 200 cm), whereas those of the *Nardetea* are dominant communities in blown, nutrient poor sand plain with humid soils (a surplus of humidity appears in 50–100 cm depth). In lower places of seaside or lagoon side blown sand plain as well as in interdune meadows shrubs prevail. They are indicator of humid soils with a surplus of humidity appearing between 50–100 cm depth. In this case communities like the *Myrtillo-Pinetum* and *Myrtillo-oxalido-Piceetum* with *Betula pendula* are being formed. Average root depth of *Corynephorus canescens* and *Nardus stricta* prevailing in herbaceous ecosystems reaches 10–15 cm [44–46]. *Rosa rugosa* and *Salix daphnoides* dominating as shrubs in herbaceous ecosystems have their roots in 0.5–1 m depth. Single roots may reach up to 2 m depth [47]. *Salix daphnoides* have superficial root system with roots concentrated in 0–50 cm depth [48].

Forest ecosystems. Curonian spit forest ecosystems have a wide spectrum of humidity conditions and vary from very dry *Cladonio-Pinetum* and *Vaccinio-Pinetum* to very wet *Urtico-Alnetum* communities. Forest communities are mainly represented by normal humidity *Vaccinio-myrtillo Pinetum.* In this community humidity surplus traits are observed in 200 cm and deeper. Dry and normal humidity forest communities are common to dunes, whereas *Myrtillo-Pinetum* and *Myrtilo-oxalido-Pinetum/Betuletum* prevail in seaside blown sand plain. In these communities the surplus humidity traits are observed in 50–100 cm depth. There are wet and very wet bog forests (*Calamagrostido-Betuletum pubescentis/Piceetum, Caric-irido-Alnetum, Urtico-Alnetum*) found in lagoon side blown sand plain. Humidity surplus traits are observed in 0–50 cm depth and groundwater table is up to 50 cm depth in some cases. Normal humidity forest communities (surplus of humidity is >100 cm) are characterized by homogeneous vegetation cover, whereas wet and humid communities (surplus of humidity is <100 cm) form heterogenic territorial complexes. Due to different soil humidity forest ecosystems vary greatly in Curonian spit and are characterized mainly by *Alnus glutinosa, Betula spp., Picea abies* and *Pinus sylvestris*. According to P. Crow [48] *Pinus sylvestris* roots may reach up to 3 m depth in dry arenosols. Roots of *Betula* family individuals may reach up to 1 m in humid arenosols, however some soils may influence the concentration of roots systems up to 0.5 m depth. Roots *Alnus* and *Picea* are mainly concentrated up to 1 m depth.

2.2. Data and Methods

Succession patterns were analyzed during 2000–2019 period in three ecosystem types: forest, herbaceous and open sand. Each of them was represented by certain number (20 territories for forest, 9 for herbaceous and 6 territories for open sand ecosystems) of homogeneous vegetation squares (250 × 250 m) according to orthophotos of 1995, 2005, 2013 and 2017. Each square was also calibrated according to MODIS (Moderate Resolution Imaging Spectroradiometer) product pixels (250 × 250 m). Territories affected by fires in 2006 and 2014 were not included in the investigation area.

Normalized difference vegetation index (NDVI) was used for evaluation of the succession trends in those ecosystems. This index is widely used for the estimation of vegetation's response towards changes in hydroclimatic conditions [49].

The NDVI was calculated from the reflectance data using visible red (RED; at 620–670 nm from MODIS,) and near-infrared (NIR; at 841–876 nm from MODIS,) regions of the electromagnetic spectrum according to (1):

$$\text{NDVI} = (\text{NIR} - \text{RED})/(\text{NIR} + \text{RED}) \quad (1)$$

NDVI ranges from −1.0 to + 1.0 with increasing values related to photosynthetically active healthy vegetation, that is characterized by low reflectance in the visible portion of the electromagnetic spectrum and has high reflectance in the NIR [49].

MODIS data were downloaded from NASA's LAADS–DAAC (https://ladsweb.modaps.eosdis.nasa.gov). NDVI was derived from MOD09Q1 (8-day composite product, 250 m resolution). Phenological behavior of the three investigated ecosystems in every annual growing season (May–September) were calculated according to cloud-free images from 2000 to 2019. May-September is an active vegetation growing season in Lithuania (when average day temperature is >10 °C) characterized by the sufficient data sets of cloud free MODIS images.

The analysis of the Baltic sea and the Curonian lagoon hydrological conditions were carried out according to Klaipėda GS and Nida GS monthly water level data during 2000–2019 period. The data (average monthly temperature, monthly precipitation, average monthly air humidity and average monthly wind speed data) of the same period of Nida WS were used for climatic research. We obtained quality-controlled gauging station and water station datasets from Lithuanian Hydrometeorological Service (www.meteo.lt). Groundwater table research was carried out according to two wells (Nida GW and Juodkrantė GW, Figure 1) monthly water level data during 2000–2019 period. Groundwater table dataset were obtained from Lithuanian Geological Survey (www.lgt.lt).

Vegetation and soil data were taken from field expeditions during 2015–2020 period [50–53]. Predominant vegetation root depth was determined, according to woody vegetation species in forest ecosystems; dominating herbs species in herbaceous and open sand ecosystems. Humidity conditions and soil texture were also considered.

In this analysis, NDVI variance is evaluated on a temporal scale. For each MODIS image (8-day composite) in each type of ecosystem, the average NDVI values were determined and analyzed during the growing season and interannual period.

MOD09Q1 is an 8-day composite product; however, due to regular cloud cover, the use of suitable images is limited. As a result, a different collection of data sets (6–15 images) was used for analysis of different year-growing seasons (Table 2). In addition, the dates of the relevant images used to determine the average values were unevenly distributed during the growing season. Therefore, the linear interpolation approach was used to fill the data set gaps for missing dates to decide if such data sets had a major effect on the subsequent growing season study. This approach was used to fill the NDVI data set gaps, and a data set of 20 values was obtained for each year (this number of values is obtained when the entire May–September season is divided into 8-day periods).

Table 2. Number of available satellite images per year, used for statistics.

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Forests	10	9	13	6	9	15	10	10	10	12	6	11	11	9	12	15	12	12	13	7
Herbaceous	11	9	13	7	8	13	11	13	10	12	6	11	10	9	12	15	12	12	13	7
Open sands	10	9	12	6	9	14	10	14	10	12	6	11	11	9	12	15	12	12	13	7

Pearson correlation coefficient was used to analyze the relationships between separate ecosystems NDVI and hydrometeorological data. Correlation was calculated between NDVI and the following hydrometeorological parameters: (1) average data of each month during the growing season, (2) average data of the whole growing season; (3) NDVI average of the growing season and average values of hydrometeorological parameters of previous period (spring, winter and annual). The following hydrological parameters were chosen for the analysis: water level of the Baltic sea, water level of the Curonian lagoon, groundwater depth and the following meteorological parameters—average air temperature, precipitation, potential evapotranspiration (PET) [54] and average wind speed.

Mann–Kendall trend test using Real Statistics Resource Pack XREALSTATS (https://www.real-statistics.com/)software was performed to detect the statistical significance of the analyzed trends.

3. Results

3.1. NDVI Variation in Different Ecosystems

Three ecosystem types—forest, herbaceous and open sand, dominating in Curonian spit are characterized by different NDVI values. However, some disparities manifest among NDVI trends of the growing season in these ecosystems during 2000–2019.

Forest ecosystem is characterized by highest NDVI values: average–0.807, average maximum of the growing season–0.867, average minimum–0.691. However, in some years the latter may decrease below 0.6. Average NDVI value in herbaceous ecosystem is 0.557, but amplitude of the growing season is bigger than in forest ecosystems (0.192) and changes from 0.451 average minimum up to 0.643 average maximum value. Open sand ecosystems are characterized by the lowest NDVI values (average value–0.264) and the lowest amplitude during the whole growing season (0.112, average minimum–0.208, average maximum–0.321).

Average NDVI values of the growing season increased in all ecosystem types during the whole study period (20 years). The most rapid increase appeared in herbaceous ecosystem and slightly less in open sand ecosystem. Increase trends are statistically significant ($p < 0.0001$), Sen's slope values reach respectively 0.0069 and 0.0038. However, NDVI increase trend of the growing season in forest ecosystem are less significant ($p < 0.1$) and Sen's slope value is 0.0016.

According to the analysis of average NDVI values variation trends in different months the differences among ecosystems become more apparent. There are no NDVI variation trends during July–August in forest ecosystem. Conversely, statistically significant NDVI increase trends were detected during July–August in herbaceous and open sand ecosystems. The most obvious increase (according to Sen's slope) is observed in September (Table 3).

Table 3. Indexes of NDVI trends variation during growing season (May–September), Mann-Kendall Test, $\alpha = 0.05$.

Index	Ecosystem	May	June	July	August	September
p-value	forest	0.03496	0.02125	0.72118	0.87113	0.04780
	herbaceous	0.00041	0.00255	0.00007	0.00032	0.00165
	open sand	0.00009	0.00132	0.00025	0.00066	0.00165
Sen's slope	forest	0.00220	0.00290	−0.00033	0.00027	0.00272
	herbaceous	0.00686	0.00530	0.00684	0.00724	0.00922
	open sand	0.00386	0.00371	0.00387	0.00371	0.00479

Annual variation of NDVI in all ecosystems is quite similar but appears in different intervals (Figure 2). NDVI values increase or remains in the same level from July up to September. There is no decrease in NDVI values in August–September period, like it is observed in the other Lithuanian regions [25]. The maritime climate influences the longer growing season in the Curonian spit.

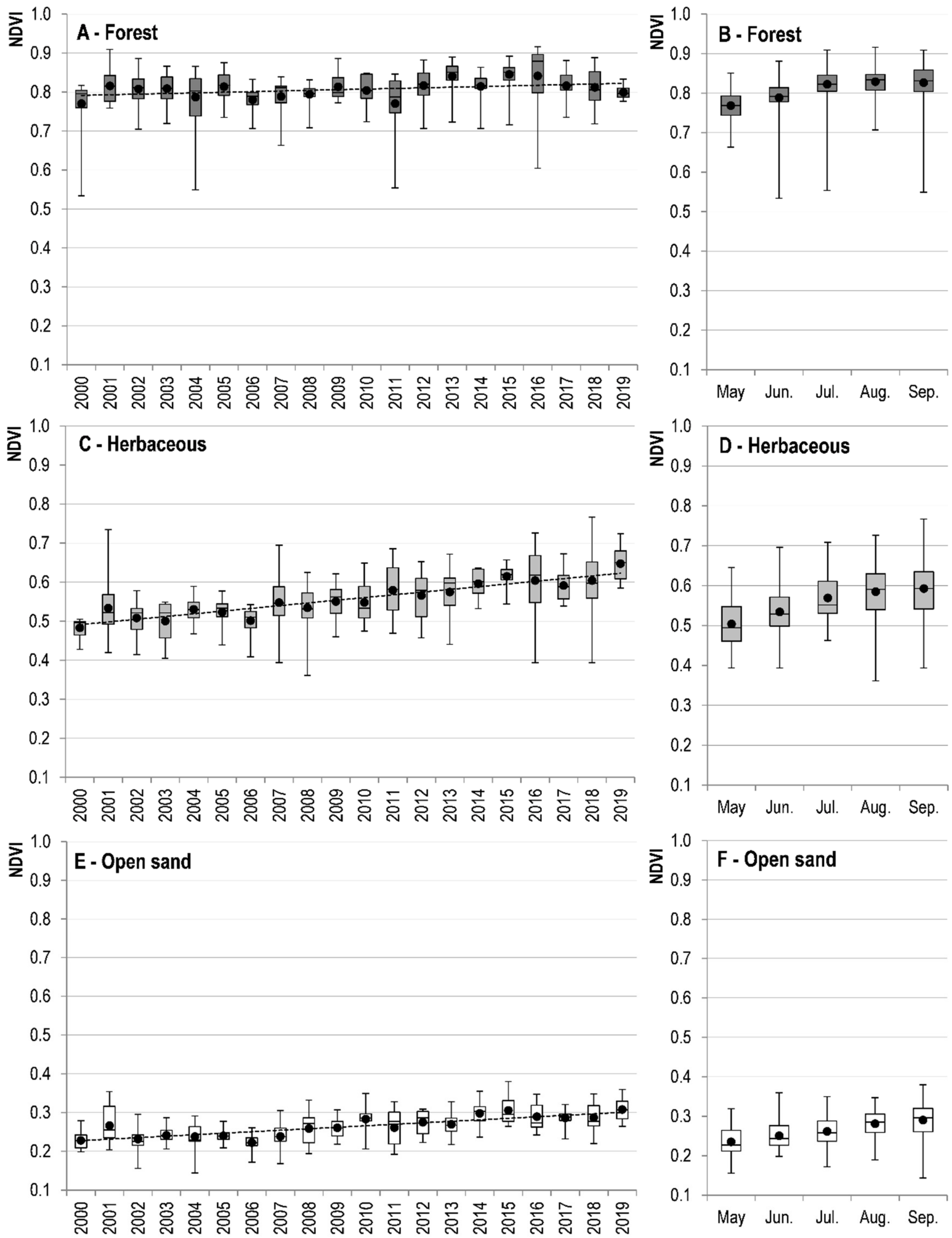

Figure 2. Average annual (**A**,**C**,**E**) and average monthly (**B**,**D**,**F**) NDVI box plots during growing seasons (May–September) in 2000–2019. The lower and upper hinges correspond to the first and the third quartiles, upper and lower whiskers correspond to maximum and minimum values.

3.2. Trends of Hydrological Parameters Variation and Their Relationship with NDVI

Water level in the Baltic sea and the Curonian lagoon increased less than 0.1 cm annually during 2000–2019 period, however this trend is not statistically significant ($p > 0.1$). The variations of groundwater depth are characterized by statistically significant decrease trend ($p < 0.01$), which reached about 0.8 cm annually (Figure 3). During the recent 20 years period the level of the Baltic sea and the Curonian lagoon raised about 1.6 cm, and groundwater depth decreased even in 16 cm. The highest level of the Baltic sea, the Curonian lagoon and the groundwater is observed in winter, the lowest one–at the very end of spring. Annual water level amplitude in the Baltic sea and the Curonian lagoon exceeded even 1 m, while in groundwater–0.6 m during 2000–2019 period.

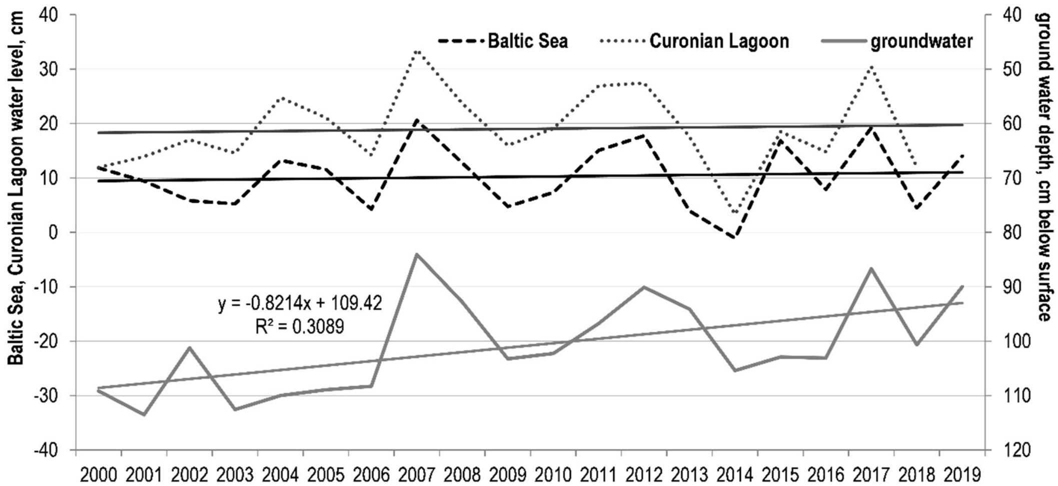

Figure 3. Variation and trends of average annual water level of the Baltic sea and the Curonian lagoon as well as the groundwater depth.

According to the analysis of the growing season NDVI dependence on the Baltic sea, the Curonian lagoon and groundwater table (monthly averages) the statistically significant relationship was determined between: (a) NDVI values in all studied ecosystems and the Baltic sea water level, (b) NDVI values in forest and herbaceous ecosystems and the Curonian lagoon water level, (c) NDVI values in forest and herbaceous ecosystems and groundwater depth (Table 4). The most statistically significant ($p < 0.0001$) relationship is determined between NDVI values in herbaceous ecosystem and the Baltic sea level, the less statistically significant ($p < 0.05$) relationship is between NDVI values in forest and herbaceous ecosystems and groundwater depth. The relationships between NDVI values of open sand ecosystems and groundwater depth statistically is less significant ($0.05 < p < 0.1$). However, even a statistically significant correlation indicates weak or moderate relation between analyzing indexes.

Table 4. Pearson correlation coefficients (R) and statistical significance (p), comparing different ecosystems NDVI values and hydrological parameters average monthly values during the growing season (May–September).

Hydrological Index	Forests		Herbaceous		Open Sands	
	R	p	R	p	R	p
The Baltic seas water level	0.303	<0.01	0.466	<0.0001	0.314	<0.01
The Curonian lagoon water level	0.272	<0.01	0.360	<0.001	0.196	<0.1
The Curonian spit groundwater depth	−0.201	<0.05	−0.252	<0.05	−0.166	<0.1

The relationships of the growing season average NDVI values and average water level and water depth values are statistically unsignificant. The comparison of the growing season average NDVI values with preceding period hydrological parameters showed that statistically significant relationship ($p > 0.05$) was detected between herbaceous ecosystems NDVI values and average annual groundwater depth (R = −0.492) and average December-February groundwater depth (R = −0.540).

3.3. Variation Trends of Meteorological Parameters and Their Relationship with NDVI

There are no real tendencies in variation trends of average (annual and growing season) precipitation, air temperature and potential evapotranspiration (PET) during the last twenty years. However the values of some parameters vary in quite wide interval: for example, annual values of precipitation vary from 528 up to 1151 mm, whereas the values of the growing season vary form 174 up to 617 mm. Statistically significant trend was detected during the analysis of average annual ($p < 0.01$) and growing season ($p < 0.001$) wind speed data (Figure 4). Starting from 2000 an average wind speed increased about 0.6–0.7 m/s (Sen's slope–0.035 annual value; 0.031 the growing season value).

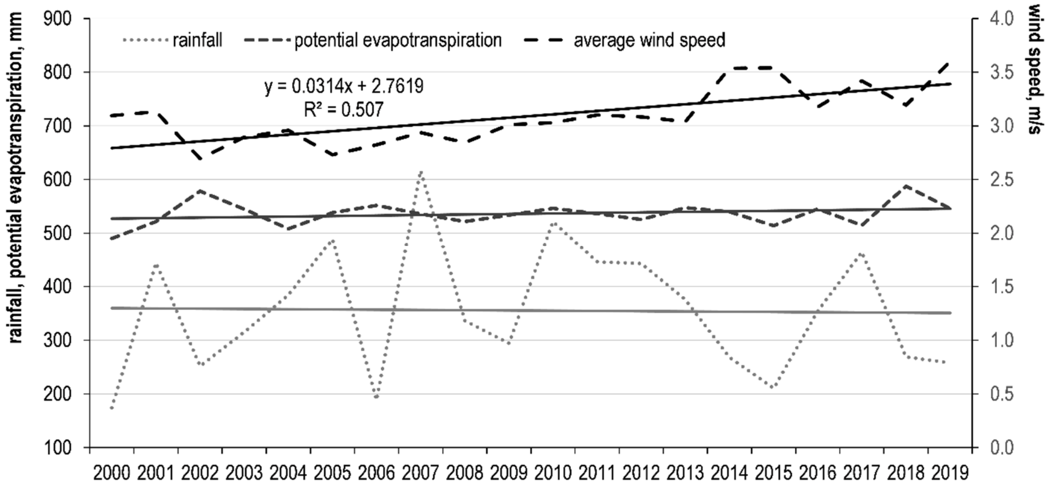

Figure 4. Trends and variation of meteorological parameters average values during the growing season (May–September).

Statistically significant correlation ($p > 0.05$) between average monthly NDVI and average monthly temperature and precipitation was determined in all ecosystems during the growing season. Comparing the average monthly values in growing season between forest and herbaceous ecosystems, statistically significant correlation was detected between NDVI and potential evapotranspiration, whereas in herbaceous and open sand ecosystems–between NDVI and average wind speed (Table 5).

Analysis of the whole growing season average NDVI values and some periods meteorological parameters showed the statistically significant correlation with only one parameter–average wind speed: in forest ecosystem—with average wind speed in winter; in herbaceous ecosystem–with average annual, the growing season and spring wind speed; in open sand ecosystem–with wind speed during all periods (Table 5).

Table 5. Pearson correlation coefficients (R) and statistical significance (p) comparing different ecosystems NDVI and meteorological parameters values during the growing season (May–September).

Meteorological Parameter	Forest		Herbaceous		Open Sand	
	R	p	R	p	R	p
	NDVI monthly average					
Average monthly air temperature	0.409	<0.0001	0.296	<0.01	0.242	<0.05
Monthly precipitation	0.318	<0.01	0.292	<0.01	0.259	<0.01
Monthly PET	0.207	<0.05	0.253	<0.05		
Average monthly wind speed			0.468	<0.00001	0.476	<0.00001
	NDVI growing season average					
Average wind speed in the growing season			0.808	<0.0001	0.847	<0.00001
Average annual wind speed	0.379	<0.1	0.767	<0.0001	0.846	<0.00001
Average spring wind speed	0.409	<0.1	0.709	<0.001	0.759	<0.001
Average winter wind speed	0.465	<0.05	0.416	<0.1	0.507	<0.05

Analysis of NDVI relationship with air temperature (monthly averages) showed the statistically significant moderate positive correlation in forest ecosystem (Figure 5), while the weakest correlation was found in open sand ecosystems. However, the dependence between NDVI and average temperature is uneven in different growing season temperature intervals. When temperature is higher than 17–18 °C the NDVI values remain the same if the temperature increases and the relationship of these two parameters becomes weaker.

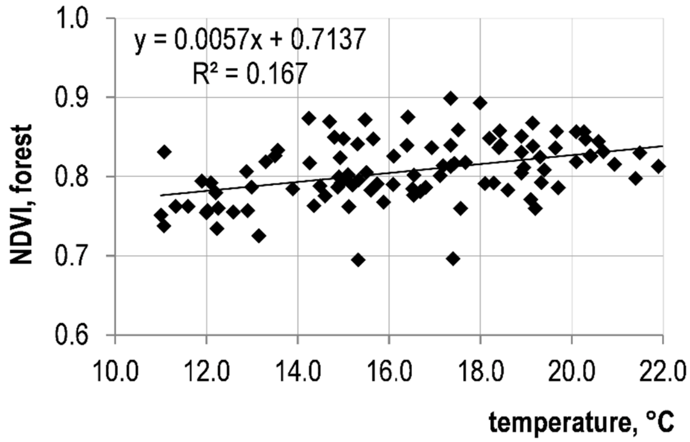

Figure 5. Relationship between NDVI and air temperature average monthly values in the growing season (May–September).

The relationship between NDVI and precipitation monthly averages are also statistically significant ($p < 0.01$), but weak in all analyzed ecosystems. The relationship between NDVI and potential evapotranspiration monthly averages are statistically significant, but weak in forest and herbaceous ecosystems. Furthermore, there are no statistically significant relation detected between these variables in open sand ecosystems (Table 5).

Average wind speed values represent the best relationship ($p < 0.001$) with the monthly and growing season average NDVI values in the Curonian spit herbaceous and open sand ecosystems. Moderate positive correlation was determined between average wind speed and NDVI monthly averages. Strong and very strong positive correlation was determined between annual, the growing season and spring average wind speed with NDVI average values of growing season (Figure 6). Analysis of forest ecosystem NDVI showed the statistically significant ($p < 0.05$) moderate correlation with only one element—average wind speed in winter.

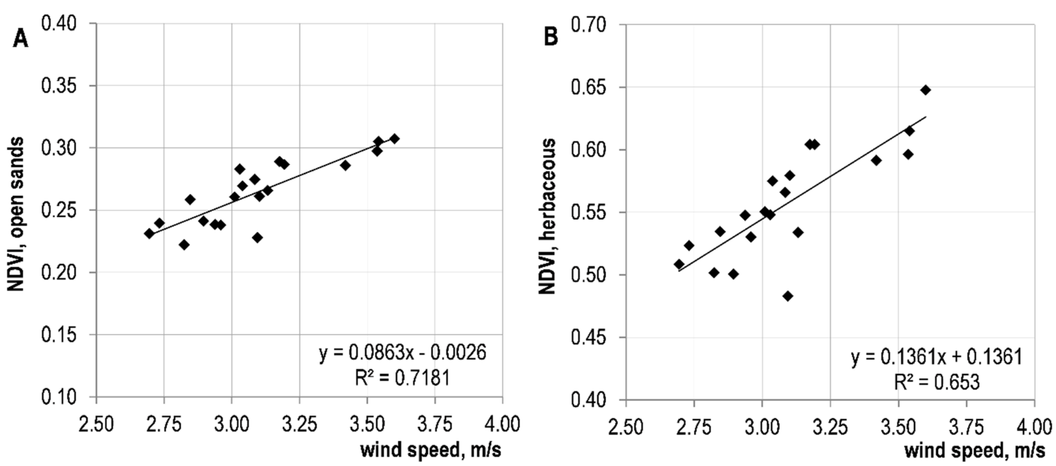

Figure 6. The relationship between average values of NDVI and wind speed in open sands (**A**) and herbaceous (**B**) ecosystems during the growing season (May–September).

4. Discussion

Curonian spit coastal dunes landscape is a unique creation of human and nature integrity in Northern Europe and the Baltic region. Eight habitats of European importance are identified here, including embryonic shifting dunes, white dunes, grey dunes etc. [32,55]. The formation of these sensitive habitats mainly depends on two contrary processes-sand dunes overgrowth and formation of open dunes. The interaction of these two processes is clearly reflected in the interannual NDVI variation in our study, revealing the dependence of NDVI values on various hydro-meteorological parameters in three different ecosystems—forest, herbaceous and open sands.

The results of our study reflect the ongoing worldwide trend of dune stabilization [56] as well as the main tendencies reported in several local and regional analyses of European coastal dune activity—most European coastal dunes have undergone a progressive stabilization as vegetation cover expanded [57–63]. Interannual NDVI variation trends reflect improving condition of vegetation in all Curonian Spit ecosystems. However, this trend is less significant in the old succession stages of the dune series, like forest: a stable vegetation condition is observed in July–August during the whole 20 years period. Statistically significant increasing trend ($p < 0.05$) is observed at the first part and at the end of growing season in forest ecosystem. Meanwhile, statistically significant NDVI increasing trend during the whole growing season as well as in separate months of it is observed in both open sand and herbaceous ecosystems. Therefore, assessing the overgrowth processes and formation of open dunes in the Curonian spit, it can be stated that due to changes in natural conditions overgrowth trends have prevailed in the recent decades and they are related to succession in non-forested ecosystems.

Some previous studies demonstrate the strong relationship between NDVI and hydrological variables in vulnerable coastal ecosystems [23]. In our study, herbaceous ecosystems are characterized by the most sensitive response to changes in hydrological conditions: statistically significant moderate correlation was determined with Baltic sea water level of the same period and with the groundwater table of the preceding period. Relationships of forest ecosystem NDVI and hydrological parameters are weaker but statistically significant, whereas relationships of open sand ecosystems NDVI and hydrological parameters are weak and statistically unsignificant in the most cases. Thus, the condition of herbaceous plants has the best response to changes in hydrological conditions of a particular year, season, or even month. This may be influenced by the relatively shallow depth of the root system that determines the variation of groundwater table to be more significant for herbaceous plant condition. Statistically significant and the strongest correlation was detected between NDVI and the Baltic sea water level in all three analyzed ecosystems. The sea water level reflects the more integrated effects of regional hydro-climatic conditions. However, the strong and statistically significant correlation between average annual water level in the Baltic sea, the Curonian lagoon and groundwater table in the Curonian spit shows the close relationship of water resources between separate parts of the unified water system of the region. Hydrological parameters trends that have been observed in the southeastern part of the Baltic sea [64] suggest that due to the impact of these changes in the Curonian Spit, conditions for vegetation will improve and overgrowth processes will exceed the formation of open dunes.

Relationship of NDVI with climatic variables such as temperature, evapotranspiration or rainfall are well documented in previous studies [20,65–69]. In our study, the relationship between the growing season month temperature and average NDVI is statistically significant and positive in all three ecosystems. However, only in forest ecosystem this relationship is moderate, whereas in the other ecosystems it remains weak. Therefore, forest ecosystem condition is obviously improving when average temperature increases. Such dependence may also be related to cyclical changes in temperature during the growing season: the highest average temperature is in July–August, when plant growing reaches a seasonal chlorophyl extremes [70], whereas, lower average temperatures at the beginning and the end of the growing season correspond to the initial and final stages of annual growing of plants characterized by lower NDVI values. However, in other ecosystems such relationship between NDVI and temperature (maybe cyclical fluctuation) is disturbed by the other factors (ex. lack of moisture) that influence herbaceous vegetation condition and is weaker. Another important remark is the weakening of the relationship between NDVI and the average monthly temperature in the higher temperature range (preliminary > 18 °C). Thus, when the temperature exceeds the average temperatures of the warmest months, the growing conditions of the vegetation and its' state naturally worsens.

The weak relationship between NDVI and precipitation/evapotranspiration shows that monthly precipitation has no significance towards the vegetation located on water-permeable soils. Analysis of the correlation between precipitation and NDVI showed a weakening of the relationship and even the appearance of a negative relationship in the range of higher precipitation values (>100–120 mm/month). This may be due to the elevated groundwater table and the consequent lack of oxygen in the root zone.

Our study confirmed increasing average wind speed values in the short-term temporal scale– the last 20 years. A medium and strong correlation was detected between NDVI and the average wind speed of the same and the preceding period in non-forested ecosystems. In both herbaceous and open sand dune ecosystems, this dependence is direct, i.e., increasing average wind speed also leads to the better vegetation condition. Such results seem somewhat unexpected, as the increasing wind speed usually activates aeolian processes, sand folding and deterioration of vegetation cover in open sand dunes. However, apparently, the increase in the average wind speed does not lead to a significant activation of aeolian processes, but to a higher moisture transfer from the Baltic Sea or the Curonian Lagoon. Condensation improves the water feeding and the condition of herbaceous plants growing in sandy soils. Woody vegetation in forest ecosystems has better access to groundwater resources due to the deeper root system. On the other hand, forests form a specific wind field, therefore there is no correlation between forest NDVI and average wind speed values as well as possible condensation moisture.

The relationship between relative humidity and NDVI was also analyzed, but no statistically significant correlation was found. This might be due to the data taken from a meteorological station used for this analysis: relative humidity is highly dependent on microclimatic conditions and the meteorological station measurements do not reflect the humidity parameters in the NDVI measurement pixels.

The only meteorological parameter investigated that has a statistically significant growth trend over the last twenty years is the wind speed. It also has a positive correlation with the NDVI values; therefore, it can be assumed that this change in the natural environment also leads to the better growing conditions in herbaceous and open sand ecosystems. As mentioned in previous studies [3,58,71] considering the long-term temporal scale (starting from the middle of the 20th century) a progressive expansion in vegetation cover in other European coastal sand dunes ecosystems, coincide with a gradually wind speed deceleration. This phenomenon was also confirmed in our study (Figure 7). However, wind speeds, recorded since 1985, hold sufficient kinetic energy for sand entrainment [3]. Therefore, the other factors (like raising sea level) must be considered to explain the overgrowth of sand dunes ecosystems.

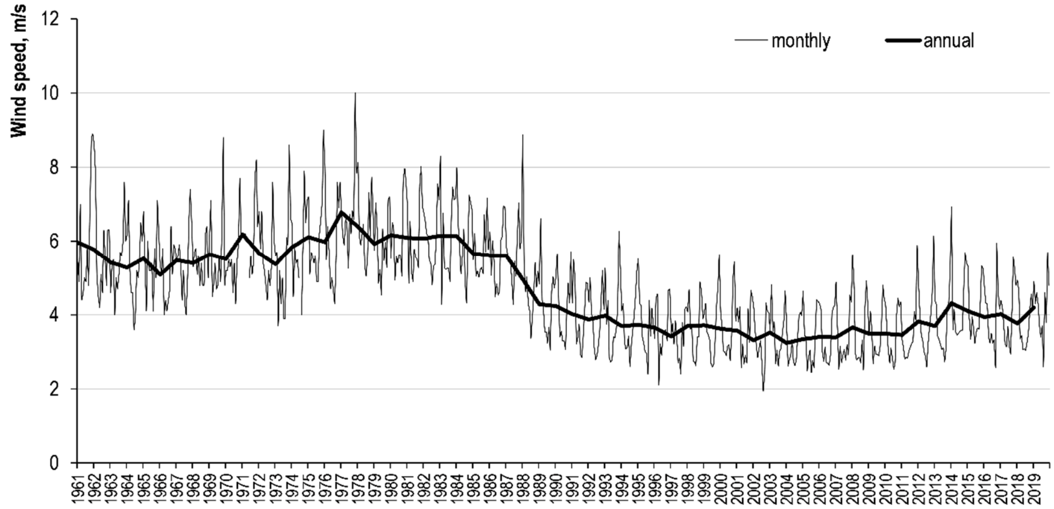

Figure 7. Interannual average wind speed variation during 1961–2019 (Nida WS).

NDVI is an optical property whose relation to biomass is empirical and species-specific [72]. Therefore, remote sensing methods can be used to assess relatively short-term changes in the vegetation condition and its correlations with hydroclimatic parameters. However, the high spatial and temporal resolution of these data and their availability open additional opportunities to examine changes in sensitive coastal dune ecosystems. For example, some previous studies applying remote sensing approaches have used NDVI to infer dune vegetation biomass from coarse resolution satellite imagery [73,74] as well as from fine resolution hyperspectral data [72].

The Curonian spit has a complex geological and human impact history and a strong need to reconcile a recreational pressure and a conservation of natural values. Therefore, a deeper understanding of changes in natural environment would also help in making management decisions.

Nowadays anti-succession management of sandy dunes are supported by EU Habitat directive–shifting (white) dunes and fixed (grey) dunes with herbaceous vegetation are priority habitats in EU [75]. Moreover, an artificial recovery of shifting dunes (cutting off Mugo pine plantations and grazing) is supported by EU LIFE Program (for example, Litcoast project (LIFE05 NAT/LT/000095) Despite this, the implication of anti-succession management becomes complicated for both—climate change, that accelerates natural succession; and the protection status of Curonian Spit that restricts visiting this area. Therefore, the existing nature protection and nature management tools applied in coastal dunes should be reconsidered under nowadays climate change.

Our research revealed the overgrowth trends in herbaceous ecosystems during the last two decades. The same tendencies are observed in the other European coastal dunes [3]. The same trends though less pronounced is observed in the open sand ecosystems. These changes are also supported by the growth trends of hydroclimatic parameters that correlates with the vegetation condition. Thus, due to the natural environment change, the areas of open sand dunes should decrease as they are occupied by herbaceous ecosystems.

5. Conclusions

1. The increase in NDVI in various ecosystems of the Curonian Spit has best relationship with the augmentation in average wind speed, water table (the Baltic sea, the Curonian Lagoon and groundwater) and air temperature.
2. According to the correlations of NDVI and hydroclimatic parameters in different ecosystems, it is probable that the most important source of water in forest ecosystems is precipitation and groundwater, in herbaceous ecosystems-precipitation and condensation, in open sand ecosystems-condensation.
3. Due to the changes in natural conditions the overgrowth trends prevailed in recent decades in the Curonian spit. They are mostly determined by processes in non-forested ecosystems. Thus,

the protection of sand dunes, covered with herbaceous vegetation is not anti-successive management tool, as is the aim of the EU dune management policy. On the contrary, it is a successive measure that encourages the overgrowth of shifting dunes in Curonian spit.

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