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Assessment of Damages from Recreational Activities on Coastal Dunes of the Southern Baltic Sea

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ABSTRACT

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A study of the changes in natural phytodiversity that can be linked to recreational activities on tertiary dunes (grey dunes) is presented. Ten neighboring areas on the Islands of Wolin (Poland) and Usedom (Germany), representing all major disturbance factors (holiday resorts, campgrounds, parking), were chosen with two appropriate reference areas from Usedom and Wolin Island (Poland) that are situated in remote parts of the coast and showed no permanent signs of human disturbance. The results of recreational activities, especially trampling, eutrophication, and the neighboring effects of nearby gardens, parks, or fallow land, were assumed to be the main factors influencing natural dunal phytodiversity. Mechanical stress from trampling could result in a decrease in phytodiversity, whereas rising nutrient levels (*e.g.,* fecal deposits), as well as neighboring effects from urban development and a growing species pool, could lead to an increase in diversity, including the occurrence of generalist or ruderal species not typical of unmodified dunes. Hence, changes within natural dunal phytodiversity depend on character and intensity of recreational activities. Results show that the location of the beach largely influences visitor numbers and hence the level of disturbance. At holiday resorts, damage to dunes can be low, even though tourist numbers on the beach are very high, if the dunes can be overlooked from the main promenade. Visitors are reluctant to trespass onto the dunes if they are being watched by many people. Nevertheless, areas without major signs of human disturbance were mostly found on remote dunes that were only accessible by foot or bicycle. Application of established phytodiversity indices (*e.g.,* H') showed drawbacks in detecting the different types of disturbance; however, sensitivity is improved by a modified index (H'_{dune}).

ADDITIONAL INDEX WORDS: *Trampling, plant diversity, diversity index, eutrophication, Pomeranian bight, Baltic Sea, Wolin, Usedom.*

INTRODUCTION

Several studies have evaluated the effects of anthropogenic activities on coastal ecosystem diversity (*e.g.,* BOGAERT and LEMEUR, 1995; BUNDESAMT FÜR NATURSCHUTZ, 1997; HYLGAARD and LIDDLE, 1981; ISERMANN, 1995; JESCHKE, 1985; LEMAUVIEL and ROZÉ, 2003; LIDDLE, 1975; LIDDLE and GREIGH-SMITH, 1975; PETERS and POTT, 1999; RODGERS and PARKER, 2003).

The aim of this study is to evaluate disturbances linked to diffuse activities, *i.e.,* recreational activities on coastal dunes. The hypothesis was that natural plant diversity could be used as an indicator of human disturbance. Disturbance is defined in this study as any change in plant cover or species composition that can be linked to human (recreational) activities. This definition is much broader than that used by GRIME (2002), who restricts disturbance to "mechanisms which limit the plant biomass by causing its partial or total destruction." Instead, a different definition by PICKETT and WHITE (1985) seems more useful because more subtle changes in nutrient availability or neighboring effects from disturbances nearby might lead to significant changes in species composition and community structure, as was also described by GRIME (2002) or in the "intermediate disturbance hypothesis" (CONNELL, 1978). PICKETT and WHITE (1985) define disturbance as "any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability, or the physical environment."

Generally, coastal ecosystems and their associated biodiversity are described as especially sensitive to human disturbance such as trampling and eutrophication (JESCHKE, 1985; KNAPP, 1996; KUTIEL, ZHEVELEV, and HARRISON, 1999; LIDDLE, 1975; LIDDLE and GREIGH-SMITH, 1975; MCDONNELL, 1981; VON NORDHEIM and BOEDEKER, 1998). However, irrespective of more general descriptions, only a few studies deal with quantification of diffuse disturbances like trampling or eutrophication and the methods used differ largely.

Nevertheless, some general conclusions on the effects of human disturbance on the phytodiversity of dunes can be drawn. Commonly, a decrease of diversity (both species richness and evenness; see, *e.g.,* BAUR and EHRHARDT, 1995; VAN DER MAAREL, 1971) is believed to be the result of any sub-

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stantial anthropogenic action. A study on coastal dunes in Finland (Hellemaa, 1998) showed a degradation of flora by comparing white dunes (secondary dunes) influenced by human activities (mostly trampling). McDonnell (1981) also showed that all studied levels of trampling intensity will reduce species diversity, mostly plant cover. On the other hand, studies by Piotrowska (1979, 1989) or Piotrowska and Stasiak (1982) revealed an increase in species richness, especially in the older dune formations (grey and brown dunes, *i.e.,* tertiary dunes), which was *inter alia* explained by effects from eutrophication and a more intensive land use adjacent to the dunes (neighboring effects). Investigations by Rodgers (2002) on Atlantic barrier Islands in the US state of Georgia also showed the effect human disturbance can have on species richness and increasing occurrences of generalists and alien species. Rogers (2002) and Rodgers and Parker (2003) did not find a generally increased species richness of alien species with respect to human disturbance (they did find higher coverage values for alien species in disturbed sites) but also did not investigate dunes in the vicinity of holiday resorts. In those areas, neighboring effects from holiday resorts or harbor installations might also influence species diversity because the species pool of these sites is larger than at isolated sites (species pool hypothesis, Pärtel *et al.,* 1996). Finally, the intermediate disturbance hypothesis might explain a rise in diversity (Connell, 1978) as well. So character and intensity of disturbance (trampling or eutrophication) are important for the effect caused. Because all studies have shown that natural phytodiversity is affected by human activity, the use of biodiversity indices seemed a reasonable approach for quantification, and their use should be tested in this study. Thus, in this study, I try to define a measure on the basis of phytodiversity for quantification of the different types of human activity on tertiary dunes.

Along the southern Baltic Sea coast, urban development in combination with recreational activities and coastal defense measures has changed and altered the shape and plant species composition of most low-lying beaches with dunes (Isermann, 1997; Jeschke, 1985). However, along prograding coastlines, new dunes are constantly being formed, and the dynamic beach and dune ecosystem could be seen as one of the few primary habitats still remaining in Central Europe (Landesamt für Forsten und Grossschutzgebiete Mecklenburg-Vorpommern and Nationalparkamt Vorpommersche Boddenlandschaft, 2002). Figure 1 shows one transect through an almost undisturbed dune system and one through a typically altered dune system along the German Baltic Coast. The definition of the different dune types is based on the classification used in the Red List of biotopes and biotope complexes of the Baltic Sea, Belt Sea, and Kattegat (Von Nordheim and Boedeker, 1998), which differs from other definitions (*e.g.,* Hesp, 1991).

Because constantly blowing winds, moving sand (sand blasting), salt, and heavy storms inflict either continuous or abrupt changes, only specialized plants are able to survive within the beach and primary or secondary dune habitats (Hesp, 1991). This study focuses on tertiary dunes, which provide some shelter from sand blasting and in which salt water influence is minimal (Hesp, 1991). The vegetation succession, together with pedogenic processes (*e.g.,* leaching of calcium or the accumulation of organic matter from white dunes over grey dunes to brown dunes), will slowly dampen the conditions by building up a humus layer, accumulating nutrients, and storing water (Ellenberg, 1996; Hesp, 1991). However, with respect to daily temperature amplitude, water availability, and nutrient levels, tertiary dunes are still extreme habitats. Plant species show a number of different adaptations to cope with these conditions and can be regarded as specialized dune species forming typical dune communities (Hesp, 1991). Among others are many drought-resistant species of mosses and lichens, many of which are especially sensitive to trampling (Isermann, 1997).

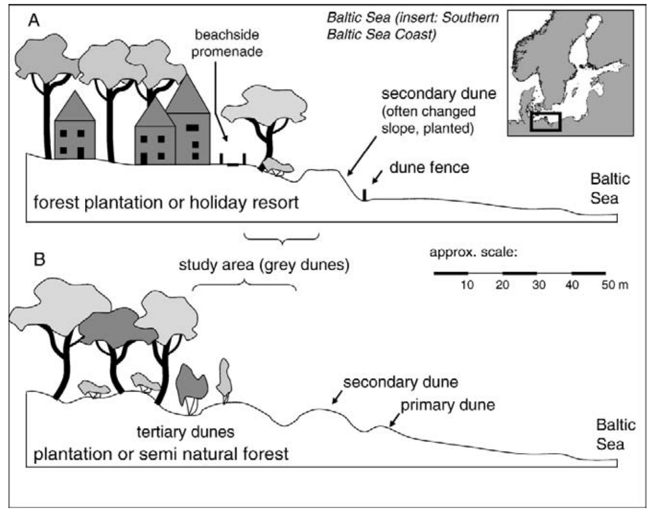


Figure 1. (A) Typical transect through a heavily changed beach and dune system along the German coast of the southern Baltic Sea. (B) Transect through an almost unchanged beach and dune system (except for forest plantation) with a succession of dunal ridges and depressions of different height and age (figure adapted and taken from Grunewald and Schubert (2005).

MATERIAL AND METHODS

The data used in this study were gathered in 2002 and 2003 on tertiary dunes along the coasts of Usedom (Germany) and Wolin Island (Poland) (Figure 2). Both islands were selected because they share the same abiotic and biotic conditions along the southern Baltic Sea, so that any changes in plant composition or community structure are most likely not linked to differences in habitat conditions. The coast is characterized by alternating Pleistocene moraine cores (under abrasion) and Holocene marine sediments (sand accumulation), which form sandy spits or barrier islands or enclose lagoons. Material from the moraine sediments is abraded, sorted, transported by the sea, and finally accumulated along low-lying, prograding coastlines where sand, wind, and vegetation interact to form beaches and dunes. The dunes studied are approximately only a few up to a hundred years old (Janke, 1971; Kliewe and Rast, 1979). The temperate climatic conditions are very similar (yearly mean ~7.5°C, year-

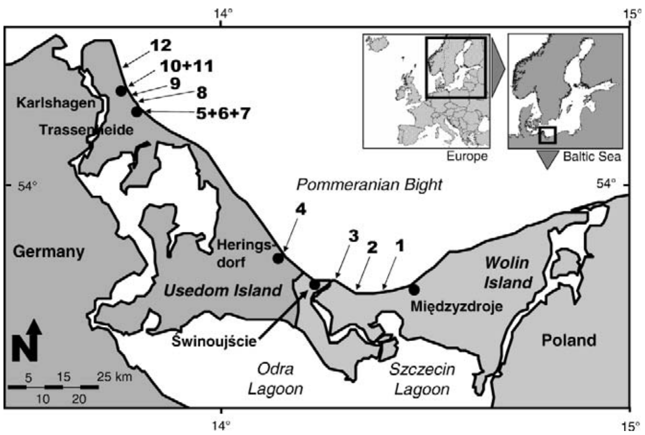


Figure 2. The Pomeranian Bight with study sites around Karlshagen, Trassenheide, and Heringsdorf on Usedom Island (see description in Table 2) and on the Swina Gate Barrier (Wolin Island, Poland).

ly precipitation 575 mm; MÜLLER, 2004; REINHARD, 1951, 1962). The two islands are characterized by sub-Atlantic climate because both are strongly influenced by their position between the two waterbodies of the Baltic Sea and the Szczecin and Odra Lagoons. Coastal exposition changes only little between the sites (*i.e.,* tertiary dunes), and westerly winds prevail during most of the year. Storm surges with peak wind speeds mostly come from northeasterly directions from November to February (HURTIG, 1957). The type of sand of which the dunes consist is also very similar in mineral composition, as well as grain size (ISERMANN, 2001). All study sites should therefore share the same potential for dune vegetation.

Usedom and Wolin Islands are located in the Polish-German transborder region (Figure 2), and tourism is one of the few thriving industries (SEIDEL, 2001). Growing numbers of visitors are expected in Poland, whereas numbers are already high in Germany. Because large stretches along the Wolin coast are only accessible by foot or bicycle, these areas so far remain in a fairly undisturbed ecological state, and coastal recreation in northwestern Poland is concentrated mostly around holiday resorts.

Altogether 12 different sites along the coast were selected for this study (Figure 2 and Table 1). The level of accessibility and control was used to choose sites because this can be seen as one indication of the intensity of recreational use. In addition, tourist counts were carried out along the northern part of Usedom Island to verify the assumption that remote areas are being visited by fewer people than easily accessible sites, as was also shown by KAMMLER (2003) for other sites along the southern Baltic Sea coast. Site 1 (Figure 3) is situated on the central part of Wolin (Swina Gate Barrier) between Międzyzdroje and Świnoujście, Poland, and is visited by very few people (for a detailed description, see ŁABUZ and GRUNEWALD, 2007). Sites 2 and 3 are closer to Świnoujście, and tourists regularly use the area because parking lots are close to the beach. In addition, site 3 is also close to the harbor of Świnoujście (possible neighboring effects). Site 4 on Usedom Island is situated in Heringsdorf; many tourists use the area, but for daytime visitors, the beach is not easily accessible. Furthermore, public toilets are available and rescue swimmers regularly control beach and dunes. Sites 5, 6, and

Table 1. *Study sites and associated recreational activities.*

Study Site		
No.	Name	Recreational Activity
1	Wolin, central Barrier	Central part of Wolin Island (Swina Gate Barrier): very few visitors, isolated, no parking, no public transportation (see also: Łabuz and Grunewald, 2004)
2	Wolin, near Świnoujście	Western part of Wolin Island (Swina Gate Barrier): high numbers of visitors, but a nearby bar overlooking the dunes "controls" number of visitors on the dunes
3	Wolin, Harbor	Westernmost part of Wolin Island (Swina Gate Barrier): high numbers of visitors, but the tower of Świnoujście harbor "controls" number of visitors on the dunes
4	Heringsdorf	Eastern part of Usedom Island. Very popular holiday resort, but no parking facilities for day tourists; public toilets available, lifeguards control beach and dunes
5	Trassenheide I	Northern part of Usedom Island: small holiday resort; open dunes can be easily observed from beach and official dune crossings
6	Trassenheide II	Northern part of Usedom Island: small holiday resort; open dunes can be easily observed from beach and official dune crossings
7	Trassenheide, center	Northern part of Usedom Island: small holiday resort; open dunes can be easily observed from beach and official dune crossings as well as a beachside promenade
8	Between Trassenheide and Karlshagen	Northern part of Usedom Island: very few visitors, isolated, no parking, no public transportation
9	Campground	Northern part of Usedom Island: adjacent to a large very popular campground south of Karlshagen, but no public parking available, so mostly campers use the beach
10	Karlshagen, center	Northern part of Usedom Island next to the main square in the holiday resort of Karlshagen: very high numbers of tourists; dunes can be overlooked from the beach and official dune crossings
11	Karlshagen-North	Northern part of Usedom Island just north of the site 10: trees, bushes, and shrubs block the view
12	Parking	Northern part of Usedom Island adjacent to a large parking lot north of Karlshagen: very popular; dune system is not as wide and complex as the other sites (fewer plots)

Figure 3. Study site 11: dunes within the holiday resort of Karlshagen showing clear signs of heavy disturbance from trampling. **For color version of this figure, see page 1173.**

7 are near or within the small holiday resort of Trassenheide, and public toilets are available. The number of tourists is high, but the open dunes can be easily observed and controlled from the beach or the official dune crossings (lifeguards). Site 8 is a remote beach and dune area between the holiday resorts of Karlshagen and Trassenheide. Like site 1, it is only accessible by foot or bicycle (>2 km from the nearest parking area or hotel). Site 9 is adjacent to a large campground south of Karlshagen; mostly campers use the beach, and public toilets are available. Sites 10 and 11 are used by many holidaymakers and day tourists who use the nearby parking areas. Public toilets are available, and site 10 is also easily observable by rescue swimmers or people on the promenade. This is not the case for site 11, which is only about 100 m north of site 10. At site 11, bushes and trees block the view from the beachside promenade and from the beach (Figure 4). Site 12 is north of the resort and adjacent to a large parking lot. Many day tourists and overnight campers (also illegal campers in the forested dunes) use the beach.

The method of BARKMAN, DOING, and SEGAL (1964) and BRAUN-BLANQUET (1964) was chosen to document plant species presence and coverage (%) at 249 individual plots from 12 sites on Usedom and Wolin Islands. The minimum area was determined, and a constant plot size of 16 m^2 was chosen for the study. For each plot, all species were listed, and the individual cover for each species was estimated according to the adapted scale from Braun-Blanquet (adapted by BARKMAN, DOING, and SEGAL, 1964). According to BRAUN-BLANQUET (1964) only homogeneous plots were studied, so that any effects on diversity from changing habitat conditions within one plot should be minimal (increasing habitat diversity = increasing species diversity). Even though epiphytic lichens and mosses were not included, pedogenic lichens and mosses were included in the study. Because both are on the same trophic level as vascular plants and make up a fair amount of plant diversity, they were included in the diversity studies. PIOTROWSKA (1979) found that more than 50% of phytodiversity on coastal dunes are cryptogams, which are known to be especially sensible to mechanical stress (ISERMANN, 1997) and should therefore be valuable indicators for changes in diversity. During summer drought situations, lichens and many mosses almost completely dry out and become fragile or brittle. Thus, any trampling on warm sunny days will result in heavy damage to the plants (ISERMANN, 1997).

Heavy mechanical damages to the vegetation through trampling, like large illegal footpaths or areas of bare sand with footprints, are clearly visible on tertiary dunes. There-

Figure 4. Study site 1: dunes on Wolin Island showing no major signs of human disturbance. **For color version of this figure, see page 1174.**

fore, the following protocol to choose the individual plots at each study site was used. A minimum of three transects (from young grey dunes to the older nonforested dunes; Figure 1) were investigated at each of the 12 study sites: one covered the areas exhibiting the highest degree of damage within this site (*e.g.,* large illegal footpaths with bare sand, if present), one had a representative level of damage within this site, and one had the lowest level of damage for this study site. If some trees or shrubs were present, these sites were included, but the study mainly focused on the open dunes. For each study site, all plots from the three transects were pooled and the groups were then used for analyzing and comparing the different sites with each other. The number of plots per study site can vary because the width of the dunes varies between the different sites.

Because two main factors affecting diversity can be identified (eutrophication and trampling), but both have adverse effects on the natural plant community (either increase or decrease of species diversity and plant cover), both factors must be dealt with separately. Growing levels of diffuse human influence often correspond with increasing numbers of generalist, alien, or both types of species (*e.g.,* CORNELL, 1999, species pool hypothesis; HILL, ROY, and THOMPSON, 2002; PÄRTEL *et al.,* 1996). Therefore, one approach analyzes qualitative changes in species diversity and plant cover and a second approach focuses on quantitative changes that clearly can be linked to mechanical stress from trampling. Although different diversity indices were initially calculated, an index (H'_{dune}; GRUNEWALD, 2004; GRUNEWALD and SCHUBERT, 2006) adapted from the Shannon and Wiener Index of entropy (H', as described by HAEUPLER, 1982; MAGURRAN, 1988) was used to indicate the main differences in diversity between the dunes (Figure 5). The use of H' revealed some major drawbacks for this study because it strongly depends on evenness and thus only measures the difference between the potential maximum and actual diversity regardless of the area covered by the species (Figure 6). HOBOHM and PETERSEN (1999) and HAEUPLER (1982) already stated the strong weight H' puts on evenness. This makes a direct comparison of different plots at the same time or even monitoring the same plot over time difficult. Mechanical damages will lead to a decrease in coverage (destruction on biomass), which could result in an increase in evenness (*e.g.,* Figure 6: from C2 to C1 or further to C3), which will lead to higher H' values even though many species might be less abundant or even become extinct.

The difference between H' and H'_{dune} is the definition of the sample size (Figures 5 and 6; GRUNEWALD and SCHUBERT, 2005). As shown in GRUNEWALD and SCHUBERT (2005), the sample size for H' is not determined by the plot size only.

$H'_{dune} = -\Sigma p_{i\text{-}dune} * \ln(p_{i\text{-}dune})$

$p_{i\text{-}dune}$ = coverage percentage of the i^{th} species (relative to the plot size)

Note:
In calculating H', p_i is normalized and "defined" as:

$(p_{i\text{-}dune}) * (\Sigma p_{i\text{-}dune})^{-1}$

$H'_{dune\text{-}max} = -s * [((\Sigma p_{i\text{-}dune})/s) * \ln((\Sigma p_{i\text{-}dune})/s)]$

$(\Sigma p_{i\text{-}dune})/s$ = average coverage percentage

s = number of species

$E = H'_{dune}/H'_{dune\text{-}max}$

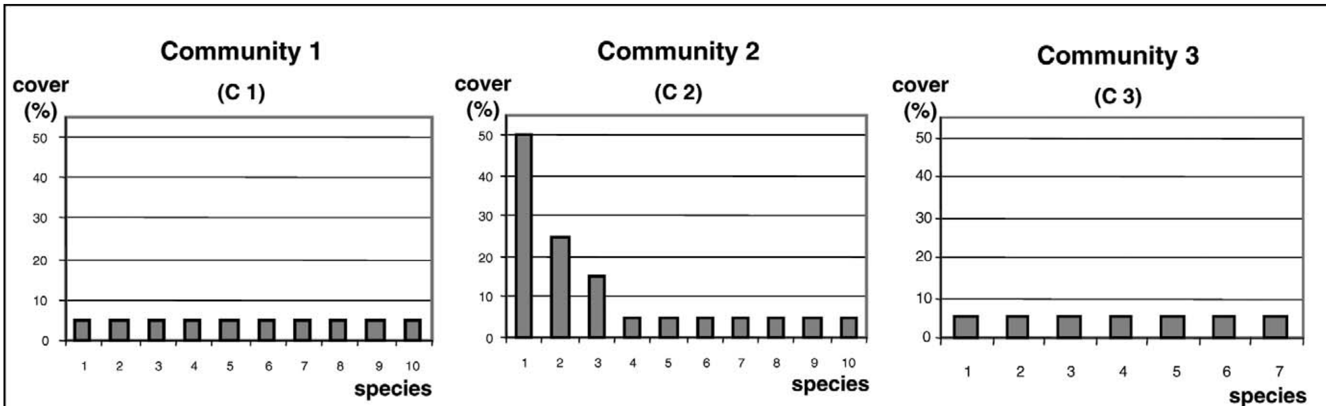
E = Evenness

Figure 5. The definition of H'_{dune} and differences to the index H' (Shannon and Weaver, 1949). Figure adapted and taken from Grunewald and Schubert (2005).

Because the total number of individuals sampled is always set to 100%, the total number of individuals must be regarded as a second dimension of sample size, which is not kept constant with the use of H'. It is an important difference whether plants cover 80% or only 30% of the constant sample area; nevertheless, H' will lose the information through normalization, and the index will then be dominated by evenness. This second normalization is omitted with the use of the adapted index H'_{dune}. In other words, the individual percent coverage, $P_{i\text{-}dune}$, is used to calculate the adapted H'_{dune}, and sample size is only determined by unified plot size, which was kept constant at 16 m^2 throughout the study. Because the second normalization of abundance relative to the total plant cover is not made with H'_{dune}, effects from a reduced plant cover as a possible result of trampling are incorporated into H'_{dune}. Furthermore, the strong weight H' puts on the factor evenness is balanced by the factor coverage in H'_{dune}. Evenness is now mainly used to differentiate between communities sharing roughly the same number of species and similar total coverage.

Figure 5 indicates the different formula for $H'_{dune\text{-}max}$ (compared with the calculation on H'_{max}) that is needed for the calculation of evenness. Evenness with H'_{dune} remains independent from both cover and species richness and can be used to analyze community structure in the same way evenness with H' is used. This is also shown in Figure 6 and GRUNEWALD and SCHUBERT (2005).

As already described by PIOTROWSKA (1979) or RODGERS (2002), the number of species can also rise on tertiary dunes as a result of eutrophication caused by tourism or general development. Because other studies also showed that increasing levels of human influence will result in increasing numbers of alien species (*e.g.,* CORNELL, 1999, species pool hypothesis; GRIME, 2002; HILL, ROY, and THOMPSON, 2002; PÄRTEL *et al.,* 1996), qualitative changes within the species composition must be studied as well. GRIME (2002) states that "phosphorus and nitrogen are often the limiting resources in natural vegetation and several recent studies have shown that soil nutrient levels may play an important role in determining a community's invasibility." In some areas on the studied dunes, many ruderal species were observed that were assumed to be a result of eutrophication; hence, the presented study tried to use the level of natural diversity (typical native dune species) as an additional indicator aiming at qualitative changes. To measure the level of natural diversity, H'_{dune} was calculated twice: first with all species included and then a second time excluding alien and ruderal species. This second calculation could be interpreted as a measure-



	C 1	C 2	C 3
H'	2,3026	1,8441	1,9459
H'_{dune}	1,4979	2,0262	1,0485
H_{max}	2,3026	2,3026	1,9459
$H_{max\text{-}dune}$	1,4979	2,5993	1,0485
Evenness	1	0,8009	1
Evenness-dune	1	0,7795	1

Figure 6. Community models and diversity parameters for testing and comparing H' and H'_{dune}.

ment of natural diversity of the different sites ($H'_{dune\text{-}nat}$). The ratio between the two values ($H'_{dune\text{-}nat}/H'_{dune}$) could be seen as the degree or level of natural diversity in the communities. This indicator will be independent of species richness and coverage, and a maximum value of one will only be reached if no alien or atypical species are found. Therefore, the species found on all study sites were classified into typical native dune species or species atypical for dunes or alien. Most of the atypical species are also alien species to Poland or Germany, but also, some native species alien to the dunal habitat were excluded from the calculation of $H'_{dune\text{-}nat}$. The following species were seen as being either atypical or alien to the southern Baltic Sea dunes: *Acer platanoides, Acer pseudoplatanus, Aira praecox, Artemisia vulgaris, Campylopos introflexus, Conyza canadensis, Crataegus* sp., *Elaeagnus angustifolia, Elaeagnus commutata, Prunus serotina, Rosa rugosa, Sambucus nigra, Sedum sempervivum, Solidago virgaurea, Symphoricarpos albus,* and *Tortula ruraliformis.* The classification was based on habitat requirements taken from the literature (Ellenberg *et al.,* 1992; Haeupler and Muer, 2000). Classification of the moss *T. ruraliformis* is based on personal experience, as well as on a study by Berg, Schramm, and Dieminger (unpublished study).

In addition to the analysis of species diversity, so-called "ecological indicator values" (Ellenberg *et al.,* 1992) were calculated as well. On the basis of decades of field studies and vegetation analysis, Ellenberg developed a method to use typical habitat conditions of plant species to assign ecological indicator values for different parameters to the species. These were developed for the parameters light (L), moisture (F), continentality/climate (K), temperature (T), nitrogen (N), chemical reaction or soil acidity (R), and salinity (S). In this study, the parameter N for nutrient conditions was calculated and used for the analysis of possible effects from eutrophication. The maximum value of 9 will only be reached "in extremely rich situation, such as cattle resting places or near polluted rivers," and a value of 1 will only be reached in "sites extremely poor in available nitrogen" (Ellenberg *et al.,* 1992, p. 251). Even though the ecological indicator values cannot be used as substitutes for exact measurements, they do have the advantage of providing information on habitat conditions for longer time periods because mostly perennials are used for their calculation. For the nitrogen parameter, the indicator will only reflect the presence of available nitrogen, which is one advantage compared with some chemical methods. The information is also integrated over the complete study area because average values are calculated on the basis of all species present in a plot, and results have shown significant correlations to measured data (Ellenberg *et al.,* 1992). Abundance of species was not used to weight the calculation because Ellenberg *et al.* (1992) cited several studies that have shown that the more simple qualitative method often yields better estimates of habitat conditions. This is explained *inter alia* by the low abundances that important indicator plants with a high level of specialization on specific habitat conditions show in their preferred habitats.

For classification of the level of human-induced changes, a system of five classes was used, defined according to both deviation from the natural state as well as potential for regeneration. Having two different main effects types—mechanical damage and eutrophication—classification should reflect both adequately. Therefore, classification was done following the rationale that any disturbance so low in frequency, amplitude, or both that does not change the system within the time of observation must be ignored, and the system still is considered to be "undisturbed" irrespective of no longer being pristine. This rationale can be applied for both mechanical action as well as eutrophication. If frequency or amplitude of the disturbance increases to an extent leading to a significant reaction of the system, this reaction might be interpreted as a setback of the dunal succession from white dunes over grey to brown dunes (*e.g.,* Ellenberg, 1996; Grime, 2002). This setback can be complete (*i.e.,* back to bare sand) or incomplete to a pioneer stage or an intermediate stage of succession. However, in both cases, the potential for regeneration would be quite high. Restoration would take place after switching off the effect and would follow a typical dunal primary succession line, as might be expected for most mechanical actions. So for all but the most severe mechanical damage (heavy eutrophication or remobilization of the dune because of large areas of bare sand), such disturbances could be regarded as an intermediate effect: the system would be regarded as good (minor disturbances) or disturbed (moderately disturbed) depending on the disturbance intensity. The next higher level of disturbance would be an irreversible distortion leading to an environment changed so that succession would follow another line. Such changes would be regarded as "heavily disturbed" (*e.g.,* heavy eutrophication, leading to a ruderalization of the vegetation; heavy trampling could lead to a remobilization of the sand and parts of the dune). The worst case would be complete destruction and annihilated restoration ability for either line of succession for a substantial time period. Such changes would then be rated "very heavy damages and irreversibly substantially disturbed." Table 2 gives an overview of the classification system.

The method was tested along a gradient of different forms and levels of recreational activities. Nine different study sites on Usedom Island and three sites on Wolin Island were used to conduct a dune survey of tertiary dunes with presumably different levels of disturbance (Figure 2 and Table 1). Along Usedom Island, only one site was found that was remote and thus not visited by many people. Because no signs of permanent human influence were found, this site was used together with the site on the central Wolin coast, which also did not show any clear signs of permanent human influence, as reference areas or the reference status representing the class "undisturbed." Because it is not possible to completely prove that these areas have not changed from human activities and because minimal changes will remain unnoticed, the classification system must be seen as subjective to a certain degree.

In a first test, all plots were analyzed by nonparametric multidimensional scaling (MDS). Therefore, Bray-Curtis dissimilarity was applied on all plots with species and species abundance as variables. In a second step, the different plots were grouped into the 12 study sites and then analyzed and compared with a Kruskal-Wallis one-way analysis performed on ranks and a following pairwise multiple comparison test

Table 2. *A classification and evaluation system for coastal tertiary dunes.*

Ecological State	Verbal Description
Undisturbed	No signs of permanent human-induced changes
Only minor disturbances	Few typical species are missing, some signs of eutrophication, moderate signs of trampling, which could be restored within a few years if disturbance is stopped
Medium disturbances	A number of alien and generalist species, obvious signs of trampling and eutrophication (some atypical dune species present), but no large areas without vegetation
Heavy disturbances	Many alien and generalist species, heavy eutrophication and/or heavy trampling, with large areas without vegetation; neighboring effects from nearby disturbances
Very heavy damages and irreversibly substantially disturbed	Housing, construction, remobilization of the dune, covering dune sands with nutrient-rich top soil for gardening purposes

for all parameters. A study site was rated as heavily disturbed when significant differences were detected between itself and the reference areas (sites 1 and 8) with the use at least of the parameters H'_{dune} (diversity including coverage) and N (degree of natural diversity). If only one parameter showed significant differences, this site was classified as only moderately disturbed. If no significant changes could be detected, but mean values for both parameters are clearly different, the site was classified as having only minor levels of disturbance. The classification of the study sites into this last group is the most subjective and is also based on observations in the field (*e.g.,* presence of small pathways, garbage, footprints, some ruderals, *etc.*).

RESULTS

Figure 7 shows the MDS plot and dissimilarities between all 249 plots (B) and two selected sites (A). Even though the

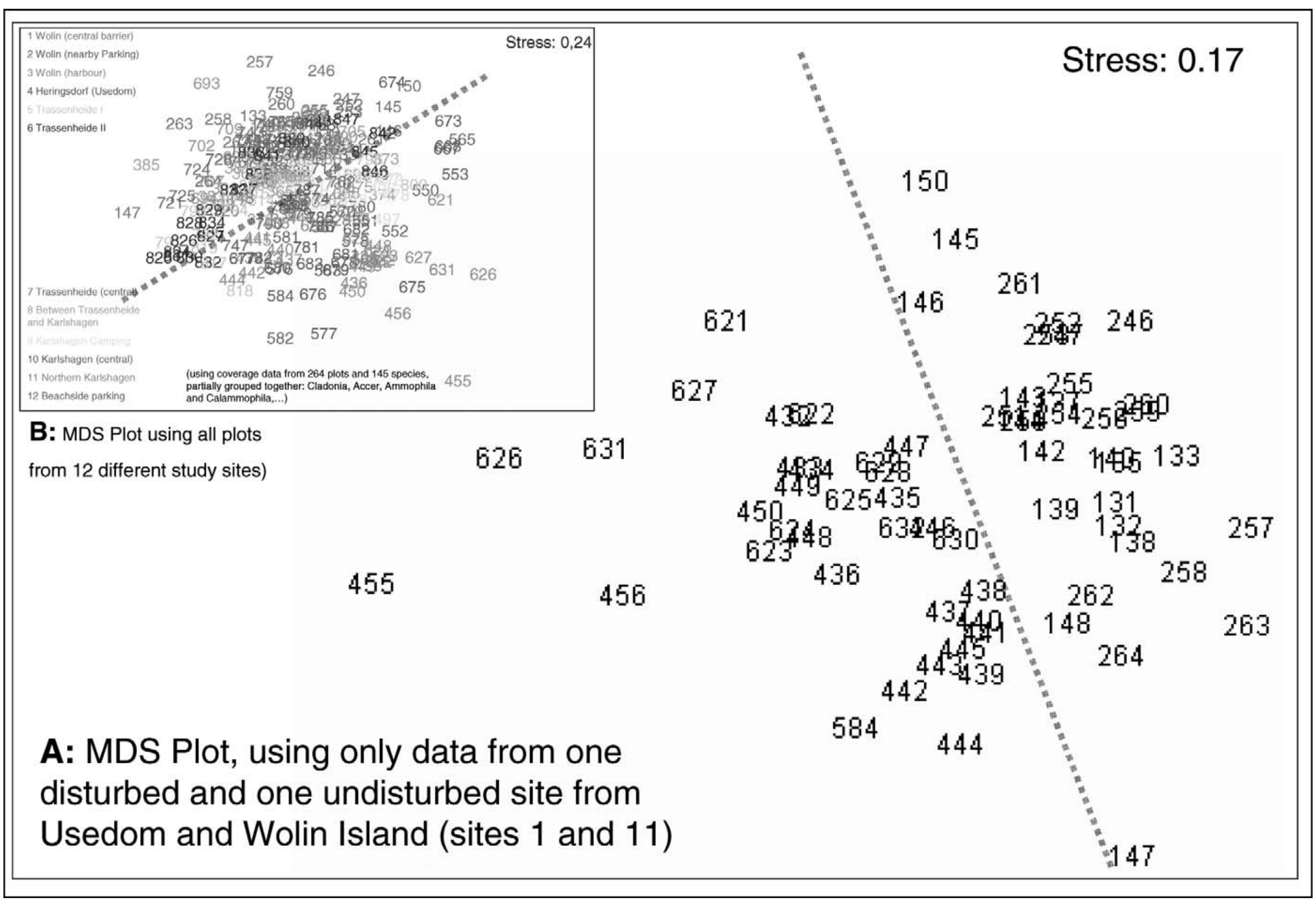


Figure 7. Biplot with multidimensional scaling (MDS) and Bray-Curtis Dissimilarity based on species abundance data with the use of (A) only data from site 1 (Wolin, undisturbed), which groups on the upper right, and site 11 (Karlshagen, heavily disturbed), which groups in the lower left and (B) data from all 12 study sites (264 plots and 145 different species). **For color version of this figure, see page 1175.**

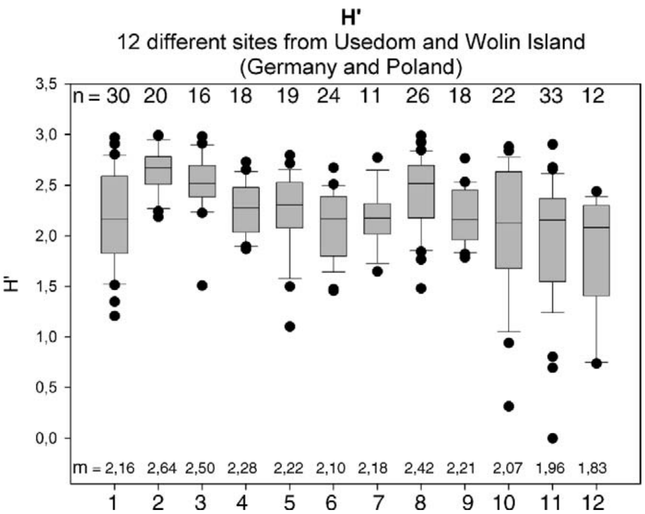


Figure 8. Comparison of tertiary dunes with different levels of recreational activities with H'. Boxes represent the second and third quartiles, the bar within the boxes indicates the median, and whiskers show the standard deviation. Small dots indicate extreme values (n = number of plots, m = mean). 1 = Wolin, undisturbed; 2 = Wolin, near harbor; 3 = Wolin, harbor; 4 = Heringsdorf, resort; 5 = near Trassenheide; 6 = near Trassenheide; 7 = Trassenheide, resort; 8 = between Trassenheide and Karlshagen, undisturbed; 9 = Karlshagen, camping; 10 = Karlshagen, resort center; 11 = Karlshagen, northern resort; 12 = parking, north of Karlshagen.

plots from each of the study sites mostly group together, groups of the study sites strongly overlap, and the stress value is quite high (stress = 0.24). However, when only the plots from reference site 1 (undisturbed) and disturbed site 11 are being looked at (stress is still high at 0.14), these form distinct clouds. Major overlapping occurs when all plots are looked at and the "gap" between the undisturbed and urban sites is filled. This overlapping is also observed in Figures 8 to 11, which show the box and whisker plots for the old diversity index H', the two new diversity parameters H'_{dune} (quantitative diversity) and N (degree of natural diversity = qualitative diversity) and for the ecological indicator value (ELLENBERG *et al.,* 1992) for each of the study sites. The number of plots for each site (n) differs because the width of the dune area also varies. Generally all parameters show differences between the sites, and the different types of action (physical and chemical) are reflected in the results.

The Kruskal-Wallis one-way analysis of variance of ranks shows significant differences ($p < 0.01$) for all tested diversity parameters, and a following pairwise multiple comparison procedure (Tukey test) revealed significant differences ($p < 0.05$) between the site Parking and the remote sites Wolin and Trassenheide for H'_{dune} (Table 3). The analysis for the traditional index H' did not reveal as many significant differences as for H'_{dune}. For the degree of natural diversity within vegetation (N), the Kruskal-Wallis one-way analysis performed on ranks and a following pairwise multiple comparison test (Dunn's method, Table 3) revealed significant differ-

Table 3. *Significant differences according to Kruskal-Wallis one-way analysis performed on ranks and a following pairwise multiple comparison test for all parameters. Upper right half shows split cells for the diversity parameters* H′ *and* H'_{dune}*. Lower left shows split cells for the level of natural diversity and the ecological indicator value for nitrogen (significant differences are indicated with "yes").*

H' and H'dune / Nat. Div. Nitrogen	1 Wolin Undist.	2 Wolin near harbour	3 Wolin Harbour	4 Herings-dorf Resort	5 Near Trassen-heide I	6 Near Trassen-heide II	7 Trassen-heide – Resort	8 Trassen-heide – undisturbe d	9 Karls-hagen Camping	10 Karls-hagen, resort center	11 Karls-hagen, norhern resort	12 Parking	H'dune / H'
Wolin Undisturbed		No	No	No	No	No	No	No	yes / no	yes / no	yes / no	yes / no	1
Wolin Near harbour	No		No	No	No	No / yes	No	No	yes / no	yes / yes	yes / yes	yes / yes	2
Wolin Harbour	No	No		No	No	No	No	No	No	No	no / yes	no / yes	3
Heringsdorf Resort	No	No	No		No	No	No	No	No	No	No	No	4
Near Trassenheide I	No	No	No	No		No	No	No	No	No	no	No	5
Near Trassenheide II	No	No	No	No	No		No	No	No	No	No	No	6
Trassenheide – Resort	No	No	No	No	No	No		No	No	No	No	No	7
Trassenheide – undisturbed	No	No	No	No	No	No	No		No	yes / no	Yes / no	No	8
Karlshagen Camping	yes / no	yes / no	No	No	No	No	No	yes / no		No	No	No	9
Karlshagen, resort center	yes / yes	yes / no	No	No	No	No	No	yes / no	No		No	No	10
Karlshagen, norhern resort	yes / no	yes / no	No	yes / no	yes / no	No	yes / no	yes / no	No	No		No	11
Parking	yes / yes	yes / no	No	No	no / yes	No	No	yes / yes	no / yes	No	No		12
Deg. of nat. diversity / Nitrogen	Wolin Undist-urbed 1	Wolin Near harbour 2	Wolin Harbour 3	Herings-dorf Resort 4	Near Trassen-heide I 5	Near Trassen-heide II 6	Trassen-heide – Resort 7	Trassen-heide – undisturbe d 8	Karls-hagen Camping 9	Karls-hagen, resort center 10	Karls-hagen, norhern resort 11	Parking 12	H' and H'dune / Nat. Diversity Nitrogen

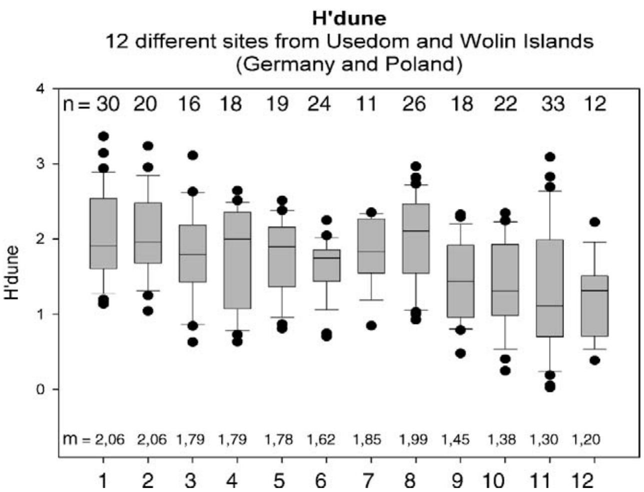


Figure 9. Comparison of tertiary dunes with different levels of recreational activities with H'_{dune}. Boxes represent the second and third quartiles, the bar within the boxes indicates the median, and whiskers show the standard deviation. Small dots indicate extreme values (n = number of plots, m = mean). 1 = Wolin, undisturbed; 2 = Wolin, near harbor; 3 = Wolin, harbor; 4 = Heringsdorf, resort; 5 = near Trassenheide; 6 = near Trassenheide; 7 = Trassenheide, resort; 8 = between Trassenheide and Karlshagen, undisturbed; 9 = Karlshagen, camping; 10 = Karlshagen, resort center; 11 = Karlshagen, northern resort; 12 = parking, north of Karlshagen.

ences between the rural sites 1 (Wolin), 8 (Trassenheide), and 12 (Parking) compared with the urban study sites 10 (Karlshagen-South), 11 (Karlshagen-North), and the adjacent site 9 (Campground). Figure 9 shows box and whisker plots for the ecological indicator value (Ellenberg *et al.,* 1992) for nitrogen. The Kruskal-Wallis one-way analysis (Dunn's method) revealed some, but not all, significant differences between study sites, which were also detected with the level of natural diversity.

According to the classification system, the sites can be grouped into the classes of ecological state shown in Table 4.

DISCUSSION

In the study presented here, no clear general trend with respect to species richness could be found when individual plots are compared with each other. The MDS with Bray-Curtis dissimilarity (Figures 7A and 7B) showed a high stress value, and only the presumably undisturbed and obviously heavily disturbed study sites form distinct clouds. Major overlapping of all other groups is observed. However, a gradient from the undisturbed sites over sites showing little or intermediate signs of disturbance toward the heavily disturbed sites seems clear (from the upper left to the lower right of Figure 7B). This overlapping was also observed in the box and whisker plots from the different study sites and parameters in Figures 8 to 11. At undisturbed as well as disturbed sites, plots with high (≤30 species) as well as with low diversity figures are found. This shows that disturbance is not evenly distributed on the dunes with respect to intensity, quality (type), or both. In this study, in which patches of influenced and uninfluenced plots occurred on a small spatial scale together, pooling of the results obtained from at least three transects per site was still required to allow for a reliable discrimination between disturbed and undisturbed sites. Only then were significant differences found between the study sites and a classification into different ecological states possible.

The alternative would be to evaluate the whole system and document study sites completely with numerous plots—which is time consuming and impracticable. The common practice, choosing representative sites by the investigator, is however quite subjective and therefore often critically debated (*e.g.,* Barkman, Doing, and Segal, 1964; Dierschke, 1994). By combining the results of the easily recognizable "extreme" transects—the most influenced and the best preserved—with those from the subjectively chosen representative transect, the effect of the subjective element can be minimized. As shown in Figures 8 to 10 and Table 3, a good discrimination between sites influenced by human activities in a different degree was achieved by this method.

High coverage values and high species numbers at undisturbed sites were observed, whereas disturbed sites exhibited significantly lower mean values, leading to high and low H'_{dune} values, respectively (Figure 9). This difference can be explained by the effect of physical disturbance, which in dune systems is not homogeneously distributed. Pure physical disturbance will lead to decreased coverage and a general decrease in species number, especially in those species that are more sensitive to trampling (*e.g.,* Andersen, 1995; Hylgaard and Liddle, 1981; Isermann, 1997; LeMauviel and Rozé, 2003; Liddle, 1975; McDonnell, 1981).

With respect to eutrophication, most of the nutrient input is likely to originate either from fecal pollution or coastal protection measures and gardening for aesthetic reasons in the vicinity of holiday resorts. Whereas the first effect shows a high degree of patchiness because it is restricted to places hidden from the beach, the later effect influences large areas almost homogeneously. Both effects led to increased nutrient availability, resulting in high coverage at plots predominant-

Table 4. *Classification of study sites into different classes of ecological state according to different levels of human disturbance.*

Study Sites	Ecological State	Explanation
1, 2, 8	Undisturbed	No visible signs of permanent human disturbance, sites 1 and 8 were chosen as reference areas
3, 4, 5, 6, 7	Only minor disturbances	Mean values for H'_{dune} or N show lower values than for the undisturbed sites
9, 12	Medium disturbances	Either H'_{dune} or N show significant differences compared with one of the undisturbed sites
10, 11	Heavy disturbances	Both H'_{dune} and N show significant differences compared with both undisturbed sites
None in this study	Irreversible disturbances	Remobilization of the dune and/or large areas of intensive technical coastal defense measures

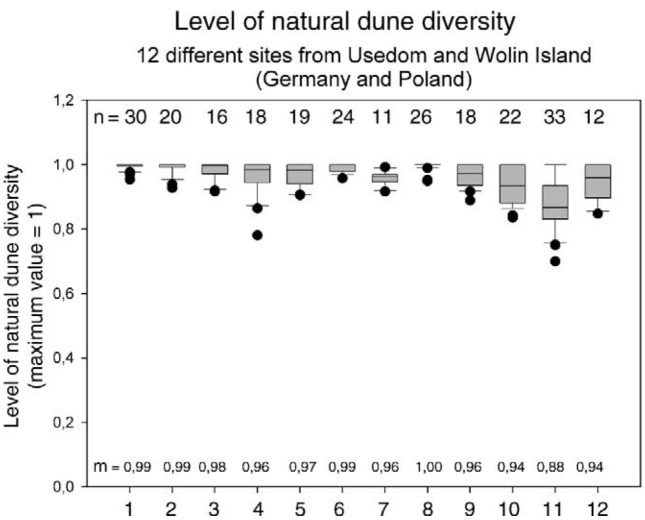


Figure 10. Comparison of tertiary dunes with different levels of recreational activities with the use of the degree of natural diversity (typical dune diversity). Boxes represent the second and third quartiles, the bar within the boxes indicates the median, and whiskers show the standard deviation. Small dots indicate extreme values (n = number of species, m = mean). 1 = Wolin, undisturbed; 2 = Wolin, near harbor; 3 = Wolin, harbor; 4 = Heringsdorf, resort; 5 = near Trassenheide; 6 = near Trassenheide; 7 = Trassenheide, resort; 8 = between Trassenheide and Karlshagen, undisturbed; 9 = Karlshagen, camping; 10 = Karlshagen, resort center; 11 = Karlshagen, northern resort; 12 = parking, north of Karlshagen.

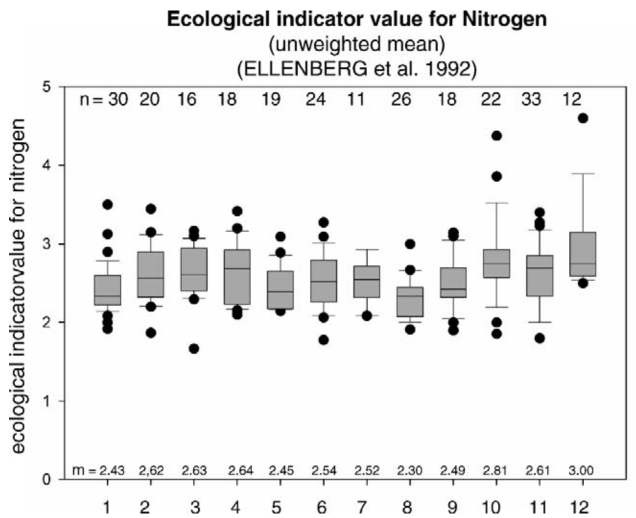


Figure 11. Comparison of tertiary dunes with different levels of recreational activities with the use of the ecological indicator value (unweighted mean, Ellenberg *et al.,* 1992) for nitrogen. Boxes represent the second and third quartiles, the bar within the boxes indicates the median, and whiskers show the standard deviation. Small dots indicate extreme values (n = number of plots, m = mean values). 1 = Wolin, undisturbed; 2 = Wolin, near harbor; 3 = Wolin, harbor; 4 = Heringsdorf, resort; 5 = near Trassenheide; 6 = near Trassenheide; 7 = Trassenheide, resort; 8 = between Trassenheide and Karlshagen, undisturbed; 9 = Karlshagen, camping; 10 = Karlshagen, resort center; 11 = Karlshagen, northern resort; 12 = parking, north of Karlshagen.

ly influenced by nutrient input. The calculated ecological indicator values (Ellenberg *et al.,* 1992) clearly indicate significant differences in nutrient availability between the sites as shown in Figure 11 and Table 3. However, these values do not completely support the hypothesis that eutrophication is the major factor leading to qualitative changes in species diversity. The qualitative changes in species diversity reflect the changing habitat conditions and the index N (degree of natural diversity) clearly showed differences between the sites, but these changes are most likely complemented by effects from the larger species pools at the urban sites (3, 10, and 11). Neighboring effects from nearby gardens, parks, or ruderal sites might play an important role for the species composition on the dunes (species pool hypothesis; Pärtel *et al.,* 1996).

The special features of the naturally nutrient-limited dune ecosystem lead to an ambivalent reaction to anthropogenic activity consisting of a combination of physical and chemical disturbances that often overlap. This system is complicated by the level and frequency of human disturbance. The intermediate disturbance hypothesis (Connell, 1978) shows that low levels of disturbances that occur frequently, creating habitats for some species, will lead to a habitat patchiness pattern with higher diversity than the undisturbed original habitat. Applying this hypothesis on the special conditions of dune habitats, the following can be concluded. Grey dune ecosystems are characterized by a high level of natural (mechanical) disturbances and normally already show a patchwork of different stages of dunal succession. Because dunes are made up of well-sorted aeolian sand deposits, dunes are considered very fragile ecosystems and very sensitive to trampling. Any further frequent mechanical damage is likely to exceed the level of intermediate disturbances, leading to decreasing species numbers, but this remains a hypothesis at this stage.

With the use of the traditional index H', fewer and also different significant differences were detected (Table 3) compared with H'_{dune}. Because even the most obvious differences between the mostly undisturbed reference site 1 on Wolin and the heavily disturbed site 11 (holiday resort of Karlshagen) with low coverage values (Figure 4) were not detected, these results support the use of H'_{dune} as a better index of disturbance. With respect to coverage, the common procedure of calculating H' regularly neglects the trampling effect on plant cover because of normalization to 100%. As shown in Figure 6 and in Grunewald and Schubert (2005), H' is consequently not able to detect such a combination of disturbances. In fact, with respect to eutrophication and neighboring effects, the use of H' for calculating the degree of natural diversity as described above sometimes will result in N values well above 1. If, *e.g.,* the three dominant species in C2 (Figure 6) happen to be alien species and would be omitted from calculation, H' would actually rise (from C2 to C3, Figure 6). This makes an interpretation of the degree of natural diversity with H' much more complicated. If normalization of total coverage is left out, the newly proposed H'_{dune} becomes a fair measure of disturbance status.

However, in many cases, plots from disturbed and undisturbed sites still overlap. Plots with a lower degree of natural diversity at undisturbed sites can be explained by the occasional presence of alien species on all dunes (in fact, in almost all central European habitats). This results from both the general botanical pollution as well as eutrophication effects by atmospheric deposition of nitrogen that was estimated at an average of 50 kg ha^{-1} yr^{-1} in central Europe (ELLENBERG, 1996). In this study, *C. canadensis* was found on some plots on Wolin Island and *C. introflexus* was occasionally found on Usedom, as well as on Wolin. *Campylopos introflexus* is considered an invasive species in more western parts of central Europe (*e.g.,* on North Sea dunes in Germany or The Netherlands; PETERS and POTT, 1999), but further east it has not spread as much. This could be because of climatic reasons or because of less time to establish itself so far in the Baltic Sea region.

Overall diversity according to H'_{dune} seems to be an appropriate measure for quantitative changes on coastal dunes, and the level of natural diversity (N) could serve as an additional independent measure for qualitative changes for determining the strength of the anthropogenic disturbance. It is capable of detecting eutrophication and any neighboring effects, whereas physical effects are already reflected by H'_{dune}. The pooling of data from the so-called extreme transects with those from a representative transect diminishes the remaining element of subjectivity.

CONCLUSIONS AND MANAGEMENT PROPOSALS

The method presented can be seen as a new approach toward analyzing human disturbance on dunes. The unified plot size and the use of the relative coverage percentage (with respect to the plot size) was chosen so that the adapted index H'_{dune} incorporates not only information on the relative abundance of species and species richness but, in contrast with H', also includes information on plant cover or species density (as an additional component of diversity and dune stability that is being reduced by mechanical damages). Trampling will cause heavy damage along clearly defined pathways, but adjacent areas might not be affected at all, so the complete range of different levels of disturbance needs to be documented. In the vicinity of holiday resorts, dune species composition clearly shifts toward more common ruderal generalists, which could be jointly linked to increasing nutrient levels on those dunes or the neighboring effects from a nearby holiday resort. In addition, dunes have often also been planted with a variety of different species. Some are useful in reducing erosion on degraded dunes (*R. rugosa, Elaeagnus* sp.), but others were introduced purely for aesthetic reasons (*e.g., S. albus*); furthermore, most of these are alien species that can oust typical native dune species, reducing natural biodiversity (ISERMANN, 1997). Thus, as was shown in this study, the degree of natural diversity of the dunes can decrease while biodiversity indices detect a rise in quantitative diversity, which makes it necessary to look at the qualitative changes on a species level.

Because study sites were *inter alia* selected according to their accessibility, the results suggest that access to the beach, as well as the development of recreational facilities, plays a major role for the condition of the dunes along the Pomeranian Bight. Remote sites 1 and 8 showed no signs of permanent disturbance and were therefore chosen as examples for the undisturbed ecological state. Tourist numbers were also lower at these sites, and KAMMLER (2003) found the highest numbers of visitors on beaches of the southern Baltic Sea coast in the immediate vicinity of holiday resorts and parking lots. Hence, low or little access seems to be the best conservation method because most people are reluctant to walk any distance from parking areas or hotels to the beach. This effect seems to be overlaid by the level of control of the beach (and the dunes). Sites that were adjacent to lifeguard posts or that were easily observed from the beachside promenade, official dune crossings, or the beach showed less change than others (sites 4–7). If the promenade is on the higher dunes overlooking the younger ones, trampling might be low, but the promenade itself will destroy a large portion of the dune habitat. If, however, the promenade lies some distance inland and the dunes cannot be observed, then the overall level of trampling on the dunes is higher (*e.g.,* northern dunes in Karlshagen at site 11). A possible solution could be the installation of a few well-maintained, elevated lookouts that protrude from the promenade (further inland) onto the dunes and that would probably become popular for visitors.

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