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Contribution of laser altimetry images to the geomorphology of the Late Holocene inland drift sands of the European Sand Belt

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Abstract The paper explores the possibilities of applying the analysis of laser altimetry images to Dutch drift sands. All along the European Sand Belt, which stretches from Great Britain to the Ural Mountains, Late Glacial cover sands, river dunes and other ice–age deposits were reactivated as drift sand during the Holocene. New insights were obtained in three aspects of drift–sands geomorphology. First, the variety in forms of drift–sand landscapes is often described as chaotic. Laser altimetry images show that complex clusters are formed elongated in the direction of the prevailing SW wind and consisting of three zones which correspond to the successive aspects of the aeolian process: deflation, transport and deposition (dune formation). In densely populated areas, this structure has been ruined by human activities. Second, contrary to common belief, the drift–sand cells expanded against the prevailing SW wind whereas the characteristic comb dunes at the opposite NE edge remained fixed by vegetation. Third, the authors questioned the view that drift sands are due to anthropogenic activities. The origin of drift sands can best be explained by the climate with violent storms in the first part of the past millennium.

Keywords *Wind erosion (deflation), inland dunes, parabolic dunes, comb dunes, Netherlands.*

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INTRODUCTION

Holocene drift sands are an important component of the European Sand Belt, which stretches from Britain to the Ural mountain range and has been described by several authors (Högbom 1923; Koster 1988, 2005; Pyritz 1972; Bateman 1998; Göllnitz 1999; Kozarski 1991; Seppälä 1995; Manikowska 1995; Zeeberg 1995, 1998; Kristapavičius 1960; Satkūnas 2009; Baltrūnas *et al.* 1998; Bitinas 2004; Mangerud *et al.* 1999).

There are several sources of drift sands:

- The cover sands (Fig. 1) which dominate the western part of the European Sand Belt (Koster 2005, 2009). The main source are the youngest cover sands which have a more pronounced relief and contain less clay and silt (Hoek 1997), which makes them susceptible to wind erosion.
- The Late Glacial river dunes (Fig. 2) found along the length of the European Sand Belt (Pyritz 1972; Solger 1910; Koster 2005; Zeeberg 1998), reactivated due to topographic forcing and resulting flow acceleration observed in wind–speed profiles across obstacles (Mikkelsen 1989; Hesp *et al.* 2005).
- The deposits of post–glacial transgressions around the Baltic Sea. The Skersabaliai aeolian massif between the Neris and Vilnia rivers is representative for the aeolian relief of the last glaciation. The sand of the lower limnoglacial basin was reactivated during the Holocene (thermoluminesce age 6300 years (Satkūnas *et al.*

1991). There is a large post–glacial aeolian area in SE Lithuania, in the Merkys River catchment. Evidence of the reactivation of the inland dunes during the Younger Dryas and up to the Atlantic time has been found in Latvia (Vitalijs Zelčs, University of Latvia, pers. com.). There is a large area of inland dunes NE from Riga.

The aerial extent of drift–sand fields in NW Europe is estimated to be 3000 to 4000 km^2 (Koster 2009). The area of drift sand can also be estimated from the occurrence of Habitat type 2330: "Inland dunes with open *Corenephorus* and *Agrostis* grassland" (European Commission 1999), and from the extent of sandy soils with little or no profile development, such as Arenosols and Regosols (European Soil Bureau Network 2005).

The onset of major sand drifting is usually placed between the 10th and 12th century AD (Koster 2005, 2009; Castel 1991; Janotta *et al.* 1997). Some drift sand areas were converted to agriculture already in the 13th century, other areas remained partly active even to the present day, but all of them had reached their maximum outline by the end of the 18th century as is shown by the reliable topographic maps of De Man (1984). Large–scale afforestation, mainly with pine trees *(Pinus sylvestris)* heralded the final stage of the active drift–sand landscapes in most parts of Europe (Koster 2005). It began in the 19th century and continued well into the 20th century. The afforestation zeal in the Netherlands was triggered more by the need of pine wood to provide the rapidly growing coal mining industry with struts, than by the desire to stabilize the drift sands: the trees were mostly sown or planted on the surrounding more fertile heath land which was used for grazing sheep. The farmers objected but their protests were ineffective.

Presently the stabilization of the remaining active sands is accelerated by deposition of atmospheric nitrogen, which stimulates the growth of algae, often the first organisms to bind the drift sand (Graebner 1910; Van den Ancker *et al.*1985; Pluis 1994), and *Campylopus introflexus,* an invasive moss species (Van der Meulen *et al.* 1987). Small areas of active sand may be found scattered across the European Sand Belt (Fig. 3), but the largest active sand–drift areas are found in the Netherlands. Even there less than 2% remains of the previous 800 km^2 of active sand. Without human intervention, the last 14 km^2 active drift sand will soon turn into forest (Riksen *et al.* 2006).

Active drift sands are characterized by extremely harsh **ecological conditions** to which few organisms are adapted. In these so–called 'Atlantic deserts' (Fig. 1) daily temperatures in summer can run up to 50°C near the bare soil surface, with extremes of 60°C (Stoutjesdijk 1959). They harbour a number of rare bird and insect species that will disappear with the active sand (European Commission 1999). Funds have been made available by the Dutch government to preserve this landscape and its rich biodiversity by stimulating wind erosion in still active drift sands and reactivate wind erosion in stabilized drift sands. This requires insight in the geomorphological structure and functioning of drift sands. Within this framework we carried out a dozen geomorphological and ecological studies of large drift sands scattered across the country. This paper incorporates the results of these studies.

Fig.1. The **Kootwijkerzand**,[1] an "atlantic desert". Photo by M. Riksen, 2007.

Airborne laser altimetry enables geomorphologists to bring argumentation based on landscape forms back in geomorphology. It is the aim of this paper to demonstrate the value of this tool for the geomorphology of the European Sand Belt. The images obtained with this technique throw new light on existing theories regarding the geomorphology of drift sand landscapes. We present arguments that drift sands:

- do not display a chaotic pattern of erosion and accumulation forms but have a regular structure,
- do not expand in the downwind, north-eastern direction thereby engulfing villages and farms, but towards the south-west,
- are not caused by human activities, but by climatic conditions favouring strong winds.

[1] Figures name in bold activate Google Earth.

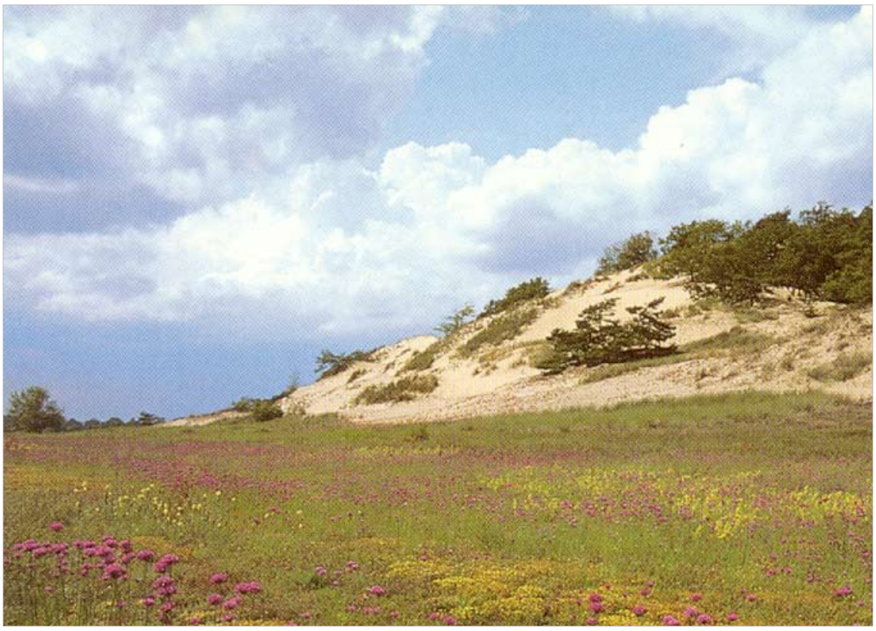

Fig.2. River dune near **Dömitz** along the Elbe, reactivated by up-hill wind flow acceleration. Photo by P. Jungerius, 2000.

Fig.3. Small drift sands such as the Gaidžių dune are renowned for their biodiversity. The Gaidžių dune is located in the village **Marcinkonys**, SE Lithuania, district Varėna. Photo by P. Jungerius, 2006.

MATERIAL AND METHODS

Geomorphologic analysis of aeolian forms requires images such as topographic maps and aerial photographs. To examine the drift–sand areas in the Netherlands also relief–shaded maps were used (Koomen *et al.* 2004). This technique came with the introduction of airborne laser altimetry (lidar). The images produced by laser altimetry give detailed information of the ground–level surface. For every 5 x 5 m grid cell an interpolated height is available. This gives insight in large landscape structures as a whole, as well as in the relationships between small landscape components, depending on scale. In contrast to aerial photographs, the vegetation cover has been filtered out so that the relief under forest can also be studied.

The laser altimetry images (data source: AGI-ITC Rijkswaterstaat, 2004) were combined with aerial photographs (Eurosense 2003) and compared with topographic maps. The first useful topographic maps of the Veluwe, where most of the active drift–sand areas are found, were made between 1802 and 1810 (De Man 1984). For the reconstruction of past phases of dune formation, archival data on storminess were studied.

Field work was indispensable to complete the information provided by the images, if only to distinguish Holocene drift sand from Late Glacial cover sand, which looks similar in many respects but has different geomorphological and ecological characteristics. The podzol profile that marks the surface of the cover sands is a useful aid for separating Late Holocene from Pleistocene deposits (see Van Vliet-Lanoë *et al.* 1993). We studied drift sands and cover sands, present-day soil formation and buried soils, with auger or in profile pits, using standard soil description procedures (FAO 1977, 2006).

The **bold place names** in the figure captions can be located with Google Earth.

RESULTS AND DISCUSSION

The geomorphological structure of drift–sand areas

Before laser altimetry images were available, the relief of drift sands was described as chaotic (see Koster 2005). It is now clear that the large sand-drift areas have a well organized internal structure with distinct morphogenetic units in downwind direction (Koomen *et al.*2004). The structure is preserved best in scarcely inhabited regions, because human activities spoil the structure in various ways.

The basic structural units are oval–shaped drift–sand cells, which are elongated in the direction of the prevailing wind and up to several kilometres in length. Complete cells have an internal configuration with three consecutive geomorphological (Fig. 4) compartments:

- The SW part, where wind erosion (deflation) dominates, has a hummocky topography of *deflation patches* alternating with *nabkhas*. Nabkhas are small phytogenic mounds of sand deposited within or around shrub canopies (Cooke *et al.* 1993). Vegetation–wind relationships of this kind in dune formation have been extensively studied by Hesp (1983).
- Leeward the deflation patches in between the nabkhas widen and merge to form elongated deflation planes. Flat–topped remnants of the original cover sand surface may survive as *plateau dunes* (Koster 1978).
- The drift sand is finally deposited in parabolic dunes at the leeward end. Characteristically the parabolic dunes are linked as comb dunes (or rake dunes). Individual parabolic dunes are rare.

In the large drift–sand areas these cells are combined to complex clusters (see Fig. 4). The clusters are separated from the unaffected surroundings by walls of aeolian sand.

This paper concentrates on the drift sands of the Veluwe where the dominant wind blows perpendicular to the direction of the push moraine ridge (Fig. 5). The drift–sand clusters are arranged in two strings on both sides of a glacial valley between two push moraines ridges. Many of the clusters of this scarcely inhabited region have retained the original geomorphological structure, thanks to their status of protected nature parks.

Where wind and push moraine or cover sand ridge run parallel, the drift–sand clusters are linked like beads on a string in SW–NE direction.

The formation of parabolic dunes and comb dunes (linked parabolic dunes)

Parabolic dunes can be formed in various ways although they share the crescent shape with arms that point towards the prevailing wind. Catching sand in vegetation is the dominant process in their formation, resulting in upward growth. The effect of the increase of vegetation towards the crest on the windward side of a dune has been described by Tsoar and Blumberg (2002). These parabolic dunes belong to the "constructional forms due to aeolian deposition" (Klimaszewski 1963). Horizontal shifting of parabolic dunes is subordinate (Högbom 1923; Melton 1940), but a blow–out in the crest may act as a conduit to channel sand to the leeward side (Hellemaa 1998; Anderson, Walker 2006) and cause windward expansion.

How the development of a parabolic dune started was described already in 1910 by Solger and later by Melton (1940) and Hesp (2002). At places where the wind exceeds the resistance of the sand, a deflation hollow develops. The sand blown from the hollow will accumulate near the margin on the leeward side where it is caught in the vegetation. Nishimori and Tanaka (2001) modelled this situation. The process leading to the crescent shape was also explained by Solger (1910, p.104): *"Die seitlichen Sandrücken nähern sich infolgedessen einander mehr und mehr. Schließlich werden sie verschmelzen, und nun liegt die ganze Düne fest".* The process is described in a similar way by Cooke and Warren (1973) and McKee (1979). It is imperative for this development that the wind is unidirectional.

Parabolic dunes occur singly or as compound forms combining individual parabolic dunes in various ways (Forman *et al.* 2001; Bailey, Bristow 2004; Jeffrey *et al.* 2006; Hugenholtz *et al.* 2008). The formation of comb or rake dunes is a special case. It is characteristic for these dunes that their sand is not

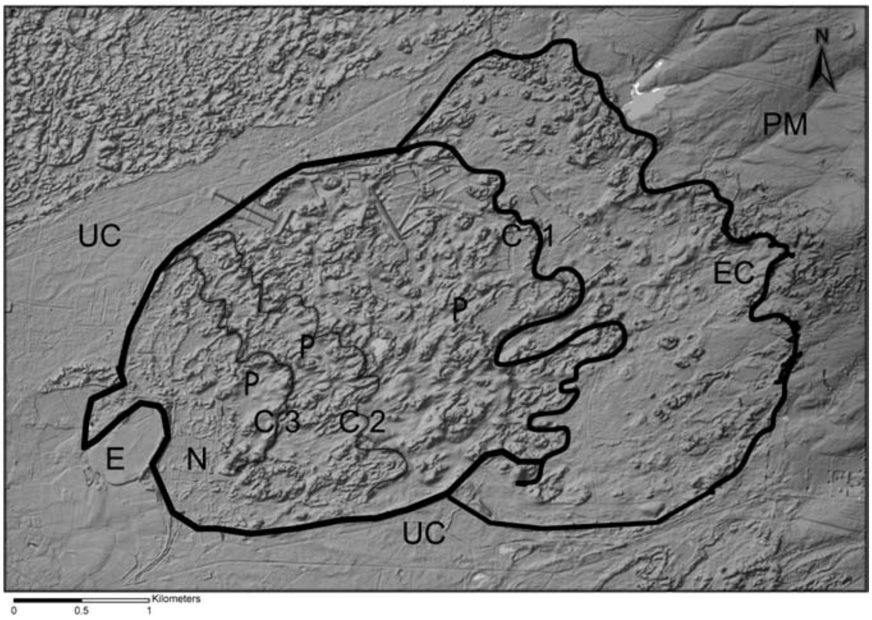

Fig 4. The drift sand cell east of **Harskamp**, terminating in comb dunes **C1**. **N** indicates the zone of nabkhas; **P** the deflation planes; **C2** and **C3** mark the comb dune ridges at various stages of windward expansion. Long before the 19th century the farmers protected their fields **E** with a wall, to check SW expansion of the drift sand. **UC**= unaffected old cover sand separating the Harskampsezand from the other clusters; **PM**=push moraine ridge; **EC**=terminating comb dunes of preceding cells. Compiled by M. Riksen, data source: AGI-ITC Rijkswaterstaat, 2004.

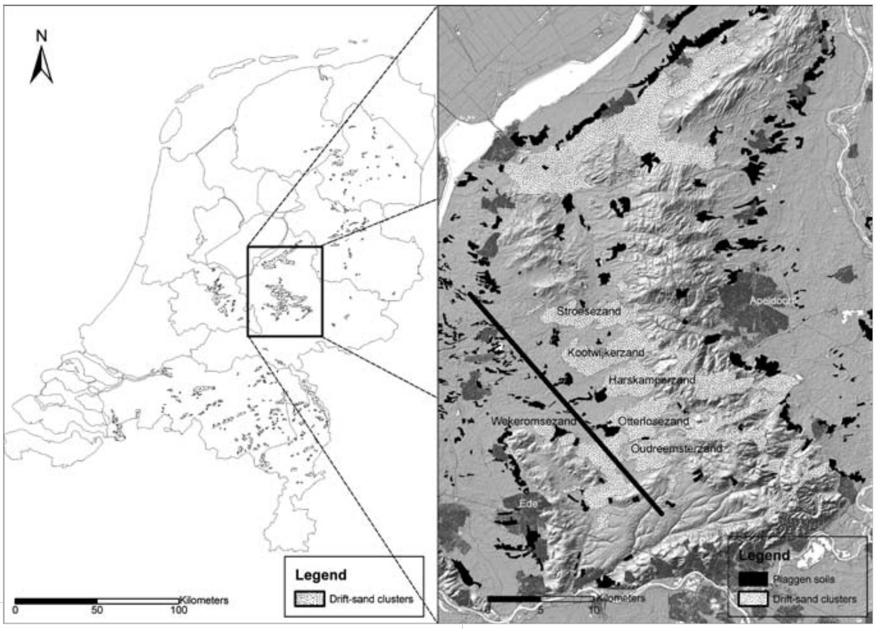

Fig. 5. Left: The drift sand clusters of the Netherlands (light grey). Right: the drift sand clusters (outlined patches) on the flanks of the **Veluwe** push moraine ridges on both sides of a former glacial valley (arrow). The agricultural fields ("essen") around the settlements with plaggen soils (black) are also indicated. Built-up areas are dark grey. Compiled by M. Riksen, data source: AGI-ITC Rijkswaterstaat, 2004.

derived from an individual point but from sources issuing sand over a wide front, for instance a beach, a river bed, a deflation plain or a sand sheet. Another characteristic is the way the individual sections are linked, often without overlap. This needs a source that is stationary or shifts gradually upwind in which case there are parallel strings of comb dunes (Fig. 6). If the source shifts back and forth as in the case of a meandering river, new comb dunes will cover previous comb dunes (Fig. 7).

Although comb dunes are intrinsically stable and have very short trailing arms, mobile specimen do occur where the vegetation cover offers insufficient protection, *e.g.* along the Baltic coast in Poland (Borówka 1990) and at Aberffraw in Wales (Bailey, Bristow 2004). Rates of dune migration in the latter case were derived from aerial photographs taken at intervals of several years.

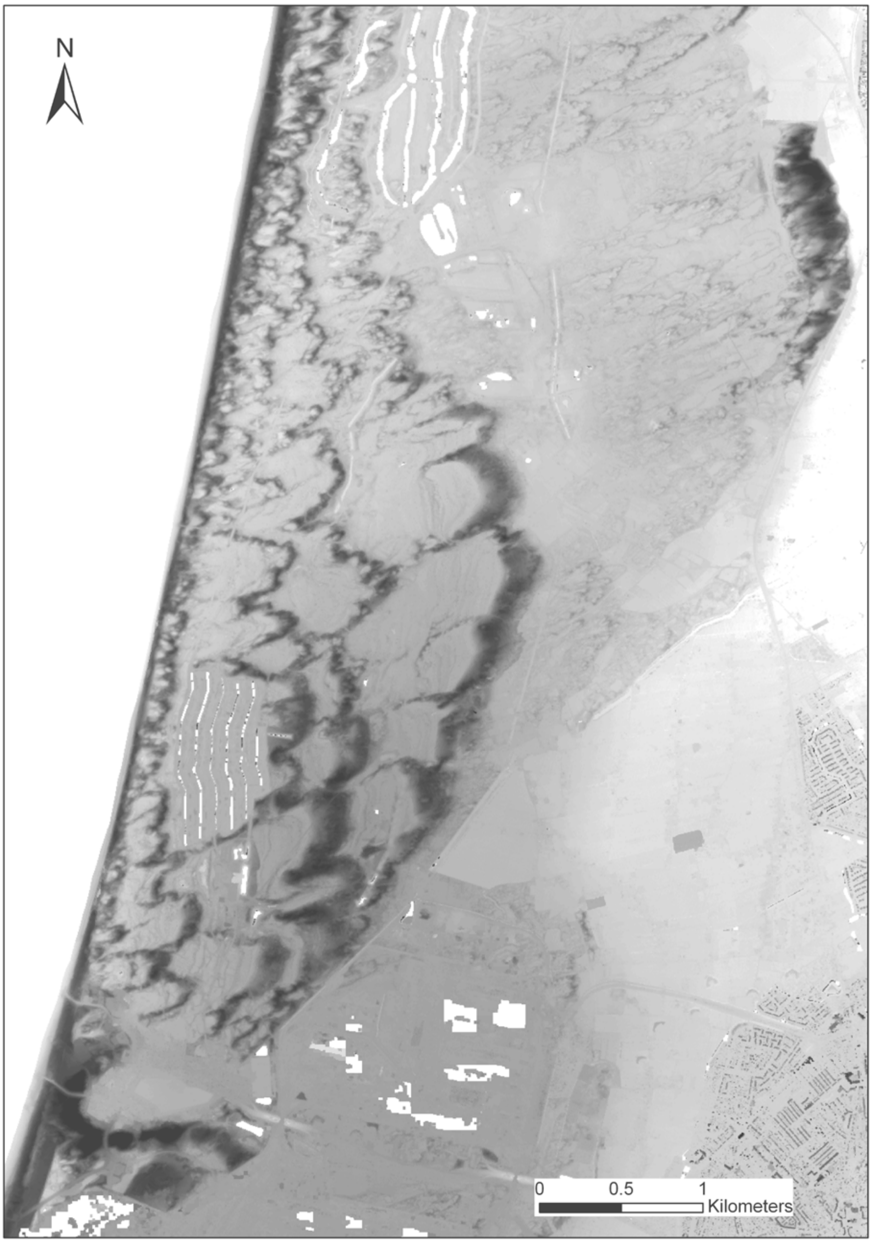

Fig. 6. The comb dunes along the North Sea coast near **Castricum**. The well-developed ridges on the right side are dated pre-16th century, allegedly contemporaneous with their counterparts in the inland dunes. Compiled by M. Riksen, data source: AGI-ITC Rijkswaterstaat, 2004.

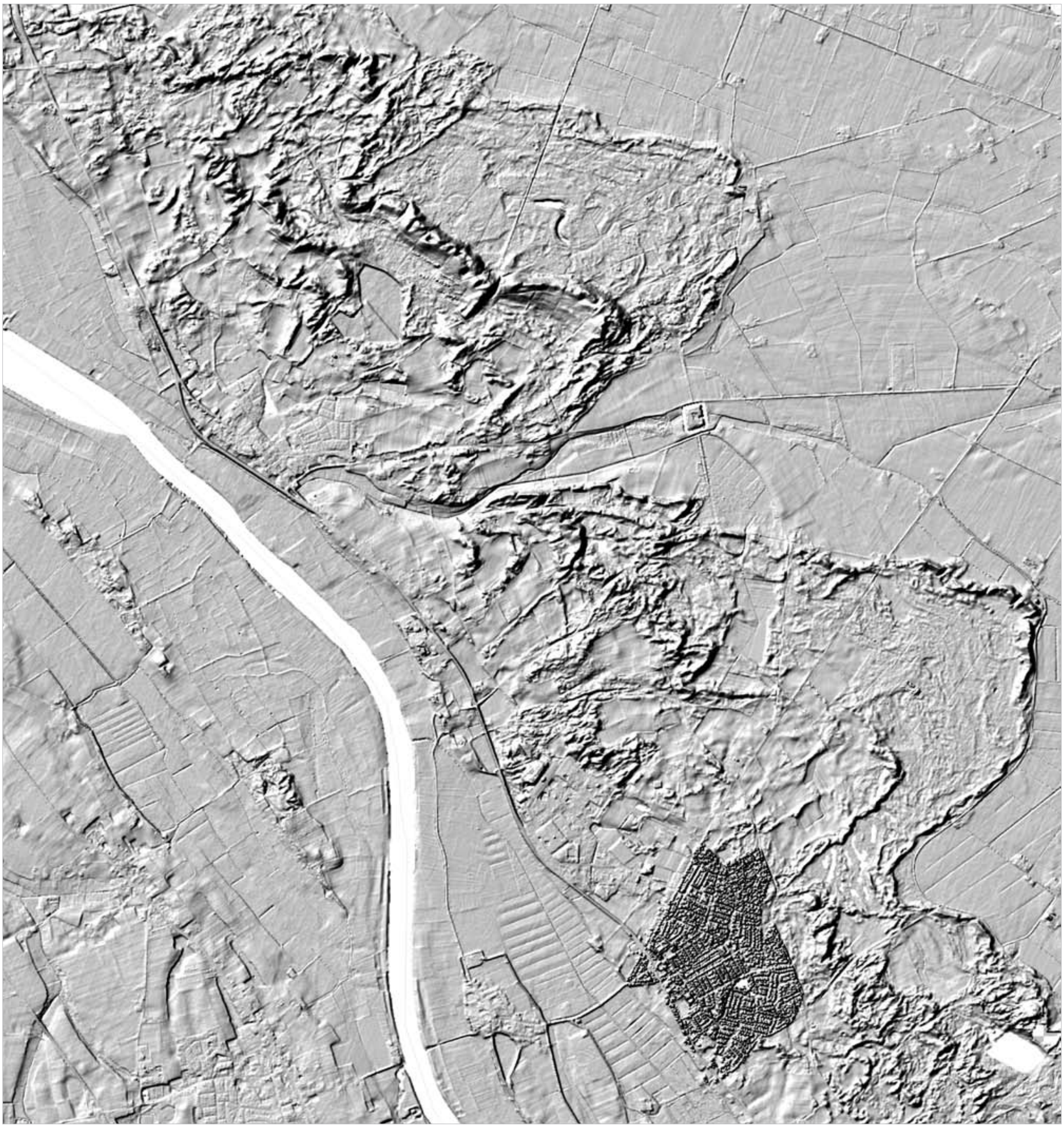

Fig. 7. The superimposed river dunes along the Meuse near **Nieuw Bergen**. Compiled by M. Riksen, data source: AGI-ITC Rijkswaterstaat, 2004.

The upwind expansion of drift sand areas

Upwind growth of the source of the sand traditionally receives little attention in aeolian geomorphology, downwind migration of the resulting dunes being considered more important. It is therefore commonly believed that drift–sand areas expanded downwind. Whereas it is true that particles taken up by the wind travelled in the same direction as the wind, the deflation zone expanded south–westward, against the dominant wind. They share this property with other deflation features such as blowouts in the coastal dunes (Jungerius *et al.* 1981; Carter *et al.*1990; Jungerius 2008). According to Melton (1940) the blow–out excavation which marks the start of the formation of a parabolic dune has migrated against the wind in at least two localities in the USA.

The reason is that wind exerts its full erosive power when reaching the upwind edge of a deflation area (Jungerius 2008), but looses energy as soon as it has to transport the sand grains it has taken up. This was realized already in 1910: *“. . . denn solange kommt der Wind mit viel Sand beladen an und hat nicht die Kraft, den schon vorhandenen Sand noch stark um-*

zulagern" (Solger 1910, p.175). At a certain distance from the beginning of the deflation zone, erosion stops altogether because all energy of the wind is spent in sand transport. When there is not even enough energy to keep the sand grains in the air, the wind drops its load and a dune is formed.

In the case of a single parabolic dune, a new parabolic crest is formed in front of the earlier dune when the distance from the source of the sand exceeds a critical distance, leaving nested parabolic dunes as described by Melton (1940) and Cooke *et al.* (1993). In drift–sand areas windward expansion results in parallel rows of comb dunes (see Fig. 4). The resulting pattern resembles the parallel series of fore–dunes following the retreating sea on a prograding coast as described by Borówka (1990) for the Świna Barrier in Poland and by Hellemaa (1998) for prograding beaches along the coast of Finland. Postglacial uplift of the land (isostatic rebound) is an important cause of prograding coasts in northern Europe (Eberhardt 1998).-

Windward expansion of most drift–sand areas has been brought to a halt for three reasons:

- Planting of trees on and around the deflation zone that began in the 19th century. The interference with the natural aerodynamics of the terrain damaged the structure of the nabkha zone beyond repair.
- Exhaust of the supply of young cover sand susceptible to wind erosion. Windward expansion of the Wekeromsezand, where remnants of the undulating relief of the young cover sand can still be observed, continues up to the present day, but a church at the extreme SW edge of the Loonse en Drunenese Duinen, the largest drift–sand cluster of the province of Noord–Brabant, was rebuilt at a safer place in 1394 when threatened by the encroaching SW deflation zone. By that time almost the whole of the more than 7 km long drift sand cluster was completed.
- A third, little known reason for the termination of the windward increase of the deflation zone are the conservation measures of early farmers. Tales circulate of villages that had to be abandoned in the past because houses and fields were engulfed by drift sands, but in reality it is more likely it was because of increasing wind erosion associated with the approach of the expanding drift–sand area from the NE. Farmers at the SW side of the Harskamperzand and the Otterlosezand built walls to protect their fields against the windward expansion of the drift sand (see Fig. 4). Farmers built walls to check wind erosion already in the 16th century. Strategically the sand produced by deflation elsewhere was caught in plant cover to strengthen the wall. The map of De Man (1984) and the present laser altimetry images confirm the existence of these walls.

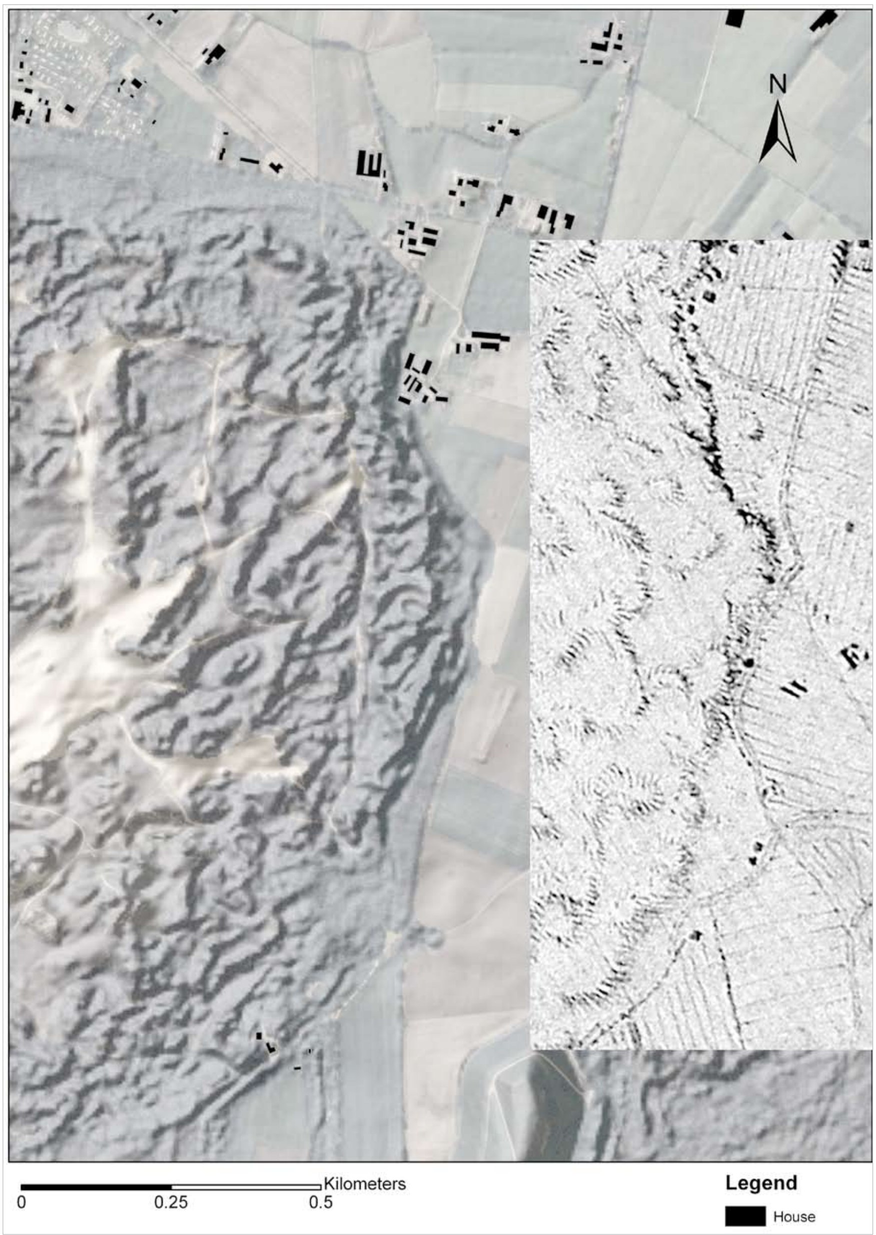

Fig. 8. The NE edge of the Wekeromsezand SW of Wekerom has not shifted between 1802/1810 (insert, De Man 1984) and 2003. Black dots on the insert indicate farms built in the shelter of the terminating dune. Compiled by M. Riksen, aerial photographs: © Eurosense 2003; data source: AGI-ITC Rijkswaterstaat, 2004.

Farms and villages hardly existed at the opposite, NE side of the drift–sand clusters, and where they did they were protected by the high, wooded comb dunes. The farmers of Wekerom even built their houses there, clearly expecting no sand coming from the still active drift–sand area behind the dunes (Fig. 8). Soil profiles confirm the absence of drift sand deposition beyond this edge.

THE CAUSE OF DRIFT SAND FORMATION

The cause of the drift sands in Europe is not yet fully understood, but analysis of laser altimetry images throws new light on this problem. Current theories hold human and natural causes responsible.

Anthropogenic origin

No doubt the drift sands of Europe are in so far linked with human activities that it needed the open landscape remaining after the deforestation that came with agriculture to give the wind free play. But it takes more than absence of vegetation to explain the drift sand clusters. Concentrated trampling can damage the protective soil and expose the underlying sand to wind erosion. These drift sands are usually of limited extent. Examples are linear drift sands linked to roads and cattle or sheep drifts (Pyritz 1972), manoeuvres on military drill–grounds (Göllnitz 1999) and modern recreation activities.

More doubtful as cause of sand drifting are human activities that have been blamed although they do not reach the subsoil, such as forest clearance, fire, overgrazing, or ploughing ((Pape 1970; Koster 1978; Castel *et al.* 1989; Seppälä 1995). No research in the Netherlands has ever confirmed this link. The oldest written sources in the 16th century report the existence of the drift sands without referring to the origin (Hesselink 1926). The local authorities worried about expansion of the existing drift sands and forbid heath burning and later herding sheep through the drift sands. Both measures were not effective.

Since about four decades, more than a century after its effects could be witnessed, cutting the sod of heath soil for fertilizing the poor sandy soils of the agricultural fields, the so-called *'essen'*, was blamed for the development of drift sands. It is now known that this practice started in the 16th century or even later, a long time after the main phase of drift sand formation and it was even much later that the erodible sand below the heath soil was exposed to the wind (Koster 2009; Spek 1004; Dijkmans *et al.* 1992; Vera 2002). Moreover the laser-altimetry images show that wind erosion of the 'essen' which were by far more extensive than the small plots in the heath soil left by cutting the sods, left no more than insignificant dunes without recognizable structure along the leeward margin.

Deforestation served not only the agricultural sector. Dulias *et al.* (2008) associated the activation of drift sands in the 12th and 13th century with large-scale deforestation to provide the mining industry with charcoal. This is different on the Veluwe where the iron industry reached its peak in the ninth century, long before the formation of the drift sands (Koster 2009).

Recent SE Baltic geomorphological investigations support the approach of playing down the role of human impact and emphasizing the role of climatic changes on the re-activation of the European Sand Belt in the 11th to 18th century (Povilanskas, 2004; Povilanskas et al., 2009).

Climatic control

The European wide extent of the drift sands, the regular spacing of the clusters on the flanks of the push moraine ridges and their ordered internal structure with comb dunes are indications for a natural control. Climate is known to be an important factor influencing the mobility of sand (Tsoar 2002).

Many authors in the USA associate aeolian activity with periods of aridity (Melton 1940; Forman *et al.* 2001; Muhs, Holliday 1995; Hesp *et al.* 2005; Hanson *et al.* 2008; Hugenholtz *et al.* 2008). These studies mostly apply to the arid and semi-arid zones of America where wind speeds exceed the critical value for sand movement during 30-60% of the time (Muhs, Maat 1993). Provided sufficient sand is available, the actual dune formation is then controlled by the vegetation cover, which is largely a function of the balance between precipitation and evaporation. This means that dunes are preferably formed in periods of drought.

This is different in Europe. From the zonal soils, we know that the two soil-forming factors climate and vegetation played a fundamentally different role on the two continents during the Holocene. In most of the European Sand Belt, the Holocene was a climatically relatively stable epoch, with fluctuations in temperature and precipitation that were generally not sufficient to destroy the vegetation cover except perhaps locally. Even the removal of the vegetation and the humic surface soil over many hectares in agriculture and in present nature restoration projects has not been sufficient to remodel the landscape by aeolian processes. Of course, Europe has known periods of drought, but their effect on aeolian processes is ambiguous. According to Van Vliet–Lanoë *et al.* (1993) a lowering of the groundwater level associated with forest fires caused reactivation of a Finnish dune field during the Middle Age Optimum and is still active today. Moerman (1934) and Heidinga (1984) have observed regional lowering of the groundwater level and droughts on the Veluwe, but no evidence for the drought is found in peat sections (Koster 2009). It could be objected that pollen data can be translated in terms of temperature and humidity (Davis *et al.* 2003) but not of storm frequency, which is apparently the principal climatic parameter for aeolian processes in Europe.

There have been two periods during the previous millennium that are considered favourable for aeolian activity, but for different reasons. Some authors hold the instable atmospheric conditions of the Little Ice Age responsible for reactivation of drift sands (Dijkmans *et al.* 1992; Fagan 1999; Bateman, Godby 2004; Van der Valk, Van der Spek 2008), others point to the dry conditions of the preceding Medieval Warm Period (Van Vliet–Lanoë *et al.* 1993; Helama *et al.* 2009) although this was not a period of strong winds in the Baltic region (Dippner, Voss 2006). Janotta *et al.* (1997) warn that correlation of past aeolian activity with these climatic fluctuations tends to give confusing results.

It is considered best to use the information on storm events provided by historic sources. Those of the North Sea, British Isles and northwest Europe are given i.a. by Lamb (1984) and Lamb and Frydendhal (1991). In the Netherlands, detailed records of the devastating megastorms that damaged the coastal areas were kept by monasteries, local administrations and water boards since the 9th century AD. There was a clear peak in the frequency of violent storms in the 13th century (Table 1). They broke up the dune coast in islands and created the Zuyder Zee which gave Amsterdam access to the North Sea and set off its world trade. It coincides with the first phase of the Younger Dunes which started in the 12th century according to radiocarbon dating and archaeological finds (Jelgersma *et al.* 1970). The comb dunes of the second phase which are similar to their counterparts inland (see Fig. 7) were formed between 1400 and 1600 AD. It is interesting to note that archaeologists found intensive accumulations of marine sand on the SE Baltic Sea coast from the 1500 to 1800 AD (Povilanskas 2004; Žulkus 1989–1990). The onset of this process in the 11th and 12th century AD could be witnessed indirectly by the decline of the late pre–historic SE Baltic sea-ports in that very period (Žulkus 2004).

Table 1. Storm floods in The Netherlands since 1000 AD; after *Wikipedia*.

Year AD	Number of storm floods
1000-1100	2
1100-1200	5
1200-1300	12
1300-1400	5
1400-1500	5
1500-1600	6
1600-1700	4
1700-1800	2
1800-1900	4
1900-2000	4

Heidinga (1984) believed in the simultaneous formation of the Dutch coastal dunes and inland dunes. This is supported by the principle of analogy: from the similarity of two geomorphologic systems as complex as comb dunes we may conclude that they were formed by the same combination of factors and processes.

Once the drift sands were formed the conditions to keep them active were much less severe, and many of the large drift sand areas are partly active even today. It is commonly assumed that the movement of sand is controlled by three variables: sand supply, wind strength, and lack of a stabilizing vegetation cover. In practice, the relationship between critical wind speed and sand transport is controlled by more than a dozen factors. In inland Europe, other factors such as frequency of precipitation, turbulence caused by vegetation and relief, algae and coarse fragments control wind efficiency also. Local archives reveal that the drifting sand of the Veluwe needed attention in six periods with a length of 8 to 28 years between 1530 and 1855 (Hesselink 1926). Research is needed to determine which combination of factors is responsible for these periods.

Active drift sand landscapes today

The present day wind and water erosion processes in drift sands landscapes are discussed by Riksen *et al.* (2004). Rain–wash and rill formation are often more effective than wind, due to water repellence of the sand (Dekker, Jungerius 1990; Jungerius 2008). It appears that NE winds are also important, and take over part of the role of the SW winds as major transporting agent as soon as the SW winds are checked by the trees planted on the leeward side.

Insight in the geomorphologic principles sketched in this paper is essential for successful conservation of active sand drift areas. The consequences of ill–considered interference with the natural aerodynamics of the terrain are devastating for the structure of the drift sand. Removing the vegetation from the crest of the comb dunes to reactivate the drift sand is a notorious example: first a precipitation ridge is formed on the windward flank of the parabolic section by slip–face deposition in the form of high–angle beds dipping in the downwind direction (Goldsmith 1989), then the ridge gradually flattens and finally disappears altogether, because no new sand reaches the dune from the windward side.

CONCLUSIONS

The analysis of the laser altimetry images offers no ground for the theory that drift sand areas display a chaotic pattern of erosion and accumulation forms. Their regular internal structure with comb dunes is the product of a guiding geomorphologic principle. Chaotic patterns are found only where man has interfered with the natural processes.

There is no evidence that the sand–drift areas expanded in windward direction. The laser altimetry images indicate that, from the moment that the first comb dune was formed, further extension of the drift sand cluster proceeded towards the SW, against the dominant wind.

There is abundant evidence that the formation of sand–drift areas is not primarily caused by human activities. The similar geomorphology of coastal and inland comb dunes, shown by the laser altimetry images, points to country–wide climatic change. Storminess is the most likely climatic parameter.

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