UTRECHT UNIVERSITY

Efficacy of Restoration Measures in Grey Dunes

Master thesis

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1/6/2014

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Summary

Grey dune ecosystems in Europe show a decrease in area and quality. Lacks of natural dynamics and increased eutrophication have led to grass encroachment and increased shrub cover. Policy to improve the quality of these dry dune systems has been developed but the efficacy of measures for ecological restoration is not always clear. In this research the efficacy of sod cutting and increased aeolian sand dynamics as restoration measures to improve the quality and increase the area of grey dune is researched. To this purpose articles in international scientific literature and management reports from the Netherlands are reviewed.

The restoration measures are not often discussed in scientific literature and restoration measures are often not sufficiently monitored. Much of the literature on the effects of increased aeolian sand activity is mainly geomorphological. Scientific knowledge on the long term effects of restoration measures in grey dunes or comparable systems is scarce. However from the reviewed studies a few general trends became obvious.

Sod cutting and the increase of aeolian sand dynamics can be an effective way to increase both the quality and the area of grey dune ecosystems. Dependent on how the measures are performed both measures can have a beneficial effect on pioneer stages as well as species rich dune grasslands. Points of interest are the effect on SOM, the soil seed bank, sand deposition and pH, as well as the scale of the measures. These factors are crucial in the establishment of target communities.

Future research should focus on the effects of recovery measures on soil processes, soil biota and on the effects on the longer term. Effects of the restoration measures on species rich grey dune grasslands on the longer term are uncertain. Recovery in lime-rich sites seems to be slower while in acid dunes the grass encroachment is a bigger problem. Ecosystem managers should monitor recovery measures and report the results of these monitoring studies to improve the knowledge on ecosystem restoration and improve future management.

Introduction

Status

This report was written as a final thesis as part of the master program "Environmental Biology" at Utrecht University and deals on the efficacy of measurements for ecological restoration or recovery of grey dunes. It was supervised at Utrecht University, and Waternet, a drinking water company that manages the Amsterdam Water supply dunes (AWD). Extra supervision was given by Camiel Aggenbach senior eco-hydrologist at KWR Watercycle Research Institute. In a two month review study, an overview of recent scientific literature and relevant management reports was given. To discuss the effects of the measurements and the desired state of the system it was necessary to give a broad scientific background besides the general introduction.

Coastal dunes are situated in a naturally dynamic area. They are characterized by a large spatial and temporal variation in habitats and vegetation, in literature often described as "shifting mosaics". The variation in these systems is caused by the interplay of geomorphological and biological processes in which aeolian sand activity leads to disturbance while vegetation stabilizes the landscape. Species-rich grey dunes are a part of this dynamic landscape and are formed when sufficient organic matter has accumulated in the soil. In some grey dune habitats, vegetation is open and dependent on smaller scale sand deposition, while other habitats have stabilized and have a more dense vegetation. Worldwide dune ecosystems show a decline in area and ecological quality (Lithgow et al. 2013, Nordstrom et al. 2007); urging ecosystem managers and policy makers to take action to stop this process.

Policy context

Ecosystem managers in the Netherlands have a great responsibility in maintaining good status of the grey dune areas as 18 % of the total European grey dune habitat is found along the Dutch coast (Houston et al. 2008). Dry dune grasslands of the type "grey dunes" are a protected priority habitat under European Natura 2000 regulation, type H2130 (Houston et al. 2008). The Dutch PAS (Programmatische Aanpak Stikstof) program stimulates the protection of areas vulnerable to nitrogen deposition, and urges mitigation of habitat deterioration with management measures (Smits & Kooijman, 2012). The European Natura 2000 regulations and the habitat and bird directive are incorporated into Dutch law in the "Natuurbeschermingswet" (1998) and the "Flora- en faunawet". Dune managers together with different government levels are obliged to keep or bring the dunes in good ecological status and increase the area of grey dunes.

Problem setting

The combination of increased succession speed caused by a higher nutrient availability and a decrease in sand dynamics has led to a decrease in the surface area and quality of pioneer stages and mid-successional dune grasslands. The different stages of grey dune are currently threatened by tall grass encroachment (Veer & Kooijman 1997) especially in acid soils (Remke et al. 2008). The dune landscape has become more uniform because of stabilisation of sand dunes (Van Til & Kooijman, 2007). Mechanisms affecting the effectiveness of ecosystem recovery measures to improve quality and increase the area of coastal grey dunes are still not clearly understood. Experiences with different recovery measures are not always positive and can only partly stop the degradation of grey dune systems (Arens & v. Geelen 2007; Kooijman et al. 2005). Different recovery measures will have different short and long term effects for the vegetation but specific effects on vegetation succession and soil development are not yet clear.

Management in grey dunes

There have been a lot of efforts in the conservation of grey dunes. To develop knowledge on the management of these systems research has been done resulting in two large OBN reports (Ontwikkeling en Beheer Natuurkwaliteit). These reports came with a few concrete recommendations for the recovery of grey dune ecosystems. In multiple dune areas in the Netherlands and abroad projects have been carried out to improve the grey dunes. Two restoration measures that have been shown to be very effective in the short term are sod cutting and sand dynamics restoration (Kooijman et al. 2005). Both measures initially reduce the vegetation cover by stripping off the top soil layer. Restoring sand dynamics can take place at larger or smaller scale. In small scale restoration of sand dynamics stabilized sand blowouts are reactivated. Large scale restoration of sand dynamics includes the removal of vegetation and top soil of larger areas and restoring so called parabolic dunes. With sod cutting the nutrient rich top soil is removed but less deep as is done when reactivating sand dynamics (see appendix).

Research question

This research focusses on the effectiveness of ecosystem recovery measures in the dry dunes, which are applied in order to improve quality and increase the area of grey dunes in the Dutch Renodunal district. Central question in the research is "How do different recovery measures affect succession in grey dunes in the short and long term". To answer this question, effects of recovery measures on soil characteristics, the seed bank and soil processes will be reviewed. A second research question will be "Which factors influence the efficacy of recovery measures?". Because of time constraints I will focus mainly on two measures: "sod cutting" and "increasing sand dynamics".

Background of grey dune ecosystems

Syntaxa

In the Netherlands the Natura 200 classification for grey dune habitats (H2130) is divided into three subtypes, viz. lime-rich grey dune (H2130A), lime-poor grey dune (H2130B) and calcifuge grey dune grassland (H2130C). Typical grey dune vegetation consists of predominantly mosses and lichens, short grasses and herbs; typical communities are the Polygalo-Koelerion, Tortulo-Koelerion, Plantagini-Festucion, Corynephorion-canescentis and Nardo-Galion saxatilis (Smits & Kooijman 2012). Nardo-Galion saxatilis vegetation is mainly present in the Dutch Wadden district and of the south west delta of Renodunal district, but less in the dunes of the coast of Holland on which this research focusses. Besides harboring many plant species the habitat type is also rich in fauna as many thermophile and arthropods and mammals thrive in these areas.

Succession

Because of the high natural dynamism succession plays an important role in dune ecosystems. There are multiple hypotheses explaining mechanisms behind succession. Pioneers in a scientific theory on succession were Cowles and Clements (Miles, 1979). Clement's theory describes succession as a predictable deterministic process; pioneer plant species facilitate colonization and establishment of later successional species. Soil development (e.g. the accumulation of humus) by vegetation makes the conditions more suitable for later successional species. Vegetation changes gradually until a climax community is established that is self-maintaining (Clements, 1936). Cowles who studied succession at the sand dunes on the shores of Lake Michigan came up with a comparable theory. Another theory based on Gleason's interpretation of the plant community as "a fortuitous assemblage of species" (Gleason, 1926), sees succession as a more individualistic sequential dominance of species based on colonization potential, competitive ability and rate of growth. In this view there is more room for contingency in ecological succession.

A more modern succession theory is Tilman's resource ration hypothesis. Tilman models succession based on the assumption that in early successional communities succession is driven by competition for nutrients while in late succession plants compete mainly for light (Tilman et al. 1985). New insights can lead to new models of succession; Koske (1997) stated that in early dune succession invasion of new plant species may depend on the existence of a developed mycorrhizal hyphae network in the soil. Succession can be further specified as primary and secondary succession. Primary succession is the development of the first pioneer vegetation on fresh deposited substrate. In contrast, secondary succession is the development of vegetation on a formerly vegetated terrain where for some reason vegetation has disappeared (Emery et al. 2012). Secondary succession thus plays an important role after restoration measures or degradation of vegetation due to herbivore activity. Cyclic succession of grey dunes is a repeating form of secondary succession caused by sand deposition.

Vegetation succession in the dry dunes follows two main paths as described by Westhoff (1970), leading either to shrubland and forest or to open grassland. Stages with heathland vegetation are mainly abundant in the Wadden district, where soils are less lime-rich (Schaminee et al. 2010). In the Renodunal dunes lime is mainly present in the form of small seashell fragments which are subject to slow dissolution of $CaCO_3$. Pioneer stages in the "white dunes" consist mainly of Elymo-Ammophiletum vegetation with *Ammophila arenaria* as an important ecosystem engineer binding loose sand and decreasing aeolian activity.

When aeolian sand activity decreases white dune vegetation is typically succeeded by shrub vegetation of mainly *Hippophae rhamnoides* or grey dune vegetation of Phleo-Tortuletum ruraliformis and vegetation with *Carex arenaria* and *Festuca rubra sp*. This vegetation is characterized by an abundance of mosses, annual plants and lichens and is dependent on low level sand deposition. In spite of their small size the abundant mosses can stabilize the sand and start a slow soil development (Schaminee 1996). When sufficient organic matter has accumulated in the soil the Taraxaco-Galietum veri can become established. In partly decalcified dune grassland, vegetation of the Festuco-Galietum can become established.

In decalcified sands with lower aeolian activity (<10 cm year), the association of Violo-Corynephoretum can follow-up the Elymo-ammophiletum, this association can persist for longer times on south slopes.. This association can also develop from Phleo-Tortuletum vegetation when soils have decalcified. Vegetation types of the Corynephorion canescentis alliance can also develop from secondary blowouts (Aggenbach & Jalink 1999; Westhoff & van Oosten, 1991) and thus rejuvenate via cyclic succession. Violo-Corynephoretum vegetation can form the end stage of succession on nutrient poor dry south slopes.

When vegetation is intensively grazed grassland can be the end stage of succession, otherwise Hippophae-Ligustretum vegetation will establish itself in lime-rich to medium lime-rich sites. *Hippohae rhamnoides* thrives in nutrient-poor soils as it is able to form a symbiosis with the nitrogen fixing bacteria *Frankia*. When soils decalcify Hippophae vegetation will disappear because the symbiotic *Frankia* bacteria cannot fix nitrogen in more acidic conditions, additionally nematodes will damage roots under acidic conditions (Zoon et al. 1995). In degraded Hippohae vegetation grassland stands with *Rosa pimpinellifolia* can establish and grey dune vegetation can develop, mainly belonging to T-G and F-G. Under more eutrophic conditions Hippophao-Sambucetum or tall grass vegetation with *Calamagrostis epigejos* can replace Hiphophae vegetation. In well-developed soils Hippophae vegetation can be followed by the Rhamno-Crataegetum and eventually by forested vegetation of Querco-Fagatea or Quercetea robori petraeae. But if large grazers as Fallow deer (*Dama dama)* are abundant, succession to forest is likely to be hampered.

History of the landscape

The dunes along the coast of Holland originated in three main time periods, the oldest were formed in the middle ages (1000-1200) the middle dunes were formed around 1500 and the dunes closer to the coast originated between 1700 and 1900 (Aggenbach & Jalink 1999; Van Til & Mourik 1999). The dunes of the south-west delta of the Netherlands differ from the dunes of Holland due to the existence and development of tidal outlets that have played a major role in their formation (Haperen, 2009).

Human influence

Human use of the dune landscape in the 20th century has led to a large decrease in semi natural dune area (CBS, 2008) and fragmentation of the habitat leading to isolated populations and a decrease in species richness. However, human exploitation of the dunes also formed the landscape as we know it today. Rabbits (*Oryctolagus cuniculus*) that were introduced in the Netherlands in the 13th century play an important role in keeping the vegetation open en preventing further succession to shrubland. Rabbit grazing was even controlled till the second half of the 18th century by herding rabbits in so called “warrandes”. Rabbit decline due to diseases such as myxomatosis (from 1954) and haemorrhagic disease (from 1990) led to a decrease in small scale dynamics and a decrease in grey dune vegetation as rabbit grazing normally prevents succession to shrubland (Haperen, 2009).

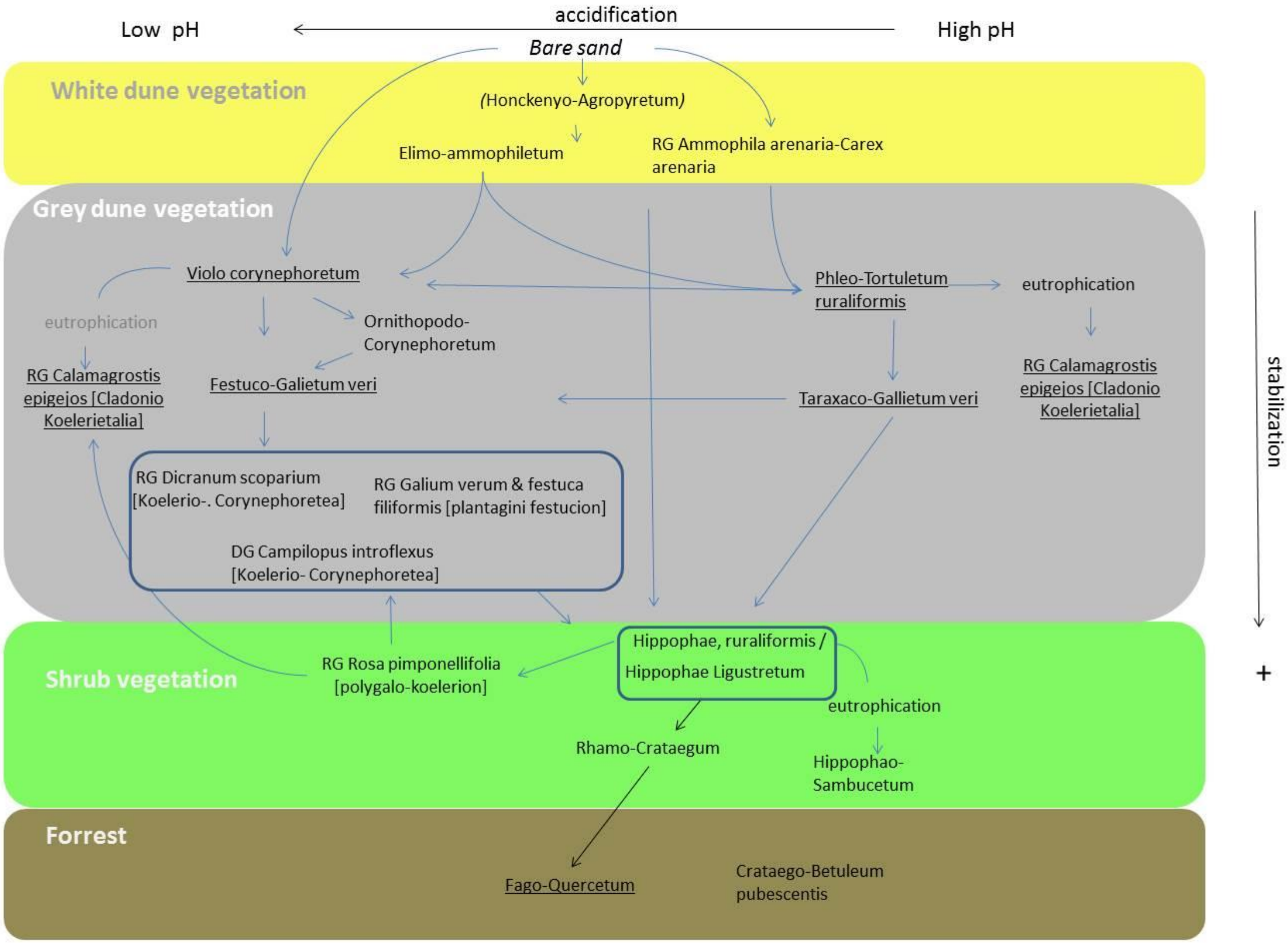


Fig 1. Possible vegetation succession in sand dunes in the xerosere based on Westhoff et al. (1970), Aggenbach & Jalink (1999) v. Til & Mourik, (1999) Schaminee et al. (1996) and Schaminee et al. (2010). Vegetation types that have been underscored can be stable for longer times or even be the end stage of succession. Not all possible transitions in vegetation are shown with arrows but a choice was made to display main routes of succession.

In the Amsterdam water supply dunes (AWD), in the 1970's, fallow deer were introduced (*Dama dama*); the population increased fast since 2000 and reached high densities since 2009. While grazing fallow deer increased, browsing roe deer (*Capreolus capreolus*) decreased. The population of *Dama dama* has had a strong impact on the vegetation of the dunes especially in older grey dunes (Haperen et al. 2013).

The dunes were used for a variety of human activities as the drying of fishing-nets, small scale agriculture, herding of livestock and harvesting scrub and coppice wood (Berendse et al. 2011; Haperen, 2009). These uses were especially common between the second half of the 18th century and the beginning of the 20th century (Haperen 2009). From 1851 on many dune areas in the Netherlands have played an important role in the water supply of larger cities as Amsterdam. This heavily influenced the dune landscape, because dune slacks desiccated while other parts were used for infiltration and water storage and thus were changed to aquatic environments (Til & Mourik, 1999). At the same time the coast was more and more valued for its esthetic and recreational value causing protection of the landscape but also increased tourism pressure.

From the beginning of the 20th century aeolian activity in the dunes was inhibited as much as possible by planting *Ammophila arenaria,* to protect the coast and prevent hinder from sand deposition in urbanized areas. Until the 1970's *A. arenaria* was planted on a large scale. (Til & Mourik, 1999). Large dune areas were also planted with *Pinus sylvestris* and other tree or shrub species to stabilize the sand during the 19th and early 20th centuries. *Prunus serotina* was often planted as accompanying vegetation (Haperen, 2009; Meijden, vd. 2005) to improve the soil quality and thereby the growth of mostly coniferous trees (Nyssen et al. 2010). *P. serotina* is easily spread by birds and has heavily influenced the dune landscape since 1995 as this species can be quite invasive, especially in the lime-poor areas. In the last few years *Prunus serotina* has decreased substantially due to extensive management measures. Since the 1980s stabilisation efforts have decreased and more recently there seems to be a slow change in paradigm in coastal dune management as natural dynamics are now incorporated into management policies (Walker et al. 2013).

Nitrogen deposition and nutrient cycling

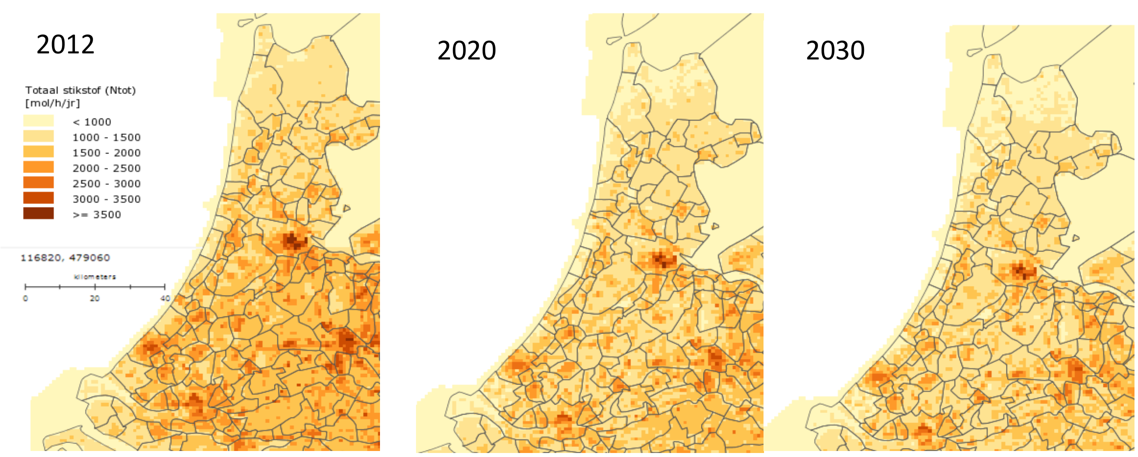


Fig 2 Deposition (2012) and predicted deposition (2020, 2030) of total nitrogen in Holland according to measurement s and model predictions of RIVM (2013).

Nitrogen deposition in the Netherlands has peaked in the 1980s and currently shows a decline as a result of government measures aimed at reducing deposition (Kooijman et al. 2009; Velders et al. 2013). Critical deposition on "stable coastal dune grasslands (grey dunes)" was determined based on empirical research in a conference in Noordwijk in 2010 and was estimated to be 8-15 kg N ha^{-1} yr^{-1} (Bobbink, 2010). When this critical load is exceeded, the report describes the following responses: "Increase of tall graminoids, decrease of prostrate plants, increased N leaching, soil acidification, loss of typical lichen species".

Actual deposition in the Netherlands is modeled by the RIVM based on measurements at different locations in the Netherlands. Measured values for ammonia deposition in dune areas are substantially a factor 2 to 4 higher than model predictions (RIVM, 2012). Deposition of nitrogen in dune area's recently (2005) showed values of around 15.1 kg N ha^{-1} yr^{-1} (Kooijman et al. 2009). In ca. 15 % of the dune areas in the Netherlands, critical loads were exceeded according to an older assessment scheme with underestimated N loads and higher values for critical loads (Kooijman et al. 2009).

Lime-poor grey dunes are more vulnerable to nitrogen deposition than lime-rich areas, mainly because availability of phosphorus in lime-rich or iron-rich conditions will be limited (Kooijman, 2005; Kooijman 2009). Lime and iron bind to phosphorus making it unavailable for vegetation uptake; vegetation in older lime-rich areas where nitrogen in the soil has accumulated therefore is often phosphorus-limited. Sulfur deposition in the 1980's played a large role in the decalcification of large parts of the dunes; sulfur forms acid SO_2 that dissolves $CaCO_3$ in the soil. At a lower pH more phosphorus will be available. Accumulation of soil carbon increases the mineralization of nitrogen and phosphorus and thus must be considered as an important factor in nutrient cycling (Sparrius, 2012). First vegetation of semi fixed dunes can appear within 10 years (Aggenbach et al 2013) or in dunes aged 20-60 yr (Jones et al. 2010). Species rich grasslands with a more fixed stage can appear in dunes that are 20 – 40 years old (Aggenbach et al. 2013) or 40-60 years old (Jones et al. 2010) and can persist for +/- 145 years old (Jones 2010) Increased nutrient availability led to an increased succession speed (Long et al. 2013) in dune ecosystems and a faster soil development (Jones et al. 2008).

Management measures

Ecosystem managers can take different measures to bring grey dunes back to a good ecological status. Recovery measures are mainly directed at removing nitrogen from the system and increasing pH. As a part of PAS regulations, sod cutting, topsoil removal, mowing, grazing, vegetation burning, removal of shrub vegetation and increased aeolian activity have been proposed as management measures suitable for recovery of grey dunes. Of these measures only vegetation burning has not been sufficiently tested to be proven effective (Jansen et al. 2012). Ödman et al. (2012), in a review of soil disturbance restoration measures in dry sandy grasslands, discusses harrowing, rotovation, ploughing, deep perturbation, topsoil removal and sod cutting as restoration measures. Harrowing and rotovation both are common agricultural practices that mix the upper soil layers but do not remove nutrients. Ploughing and deep perturbation inverse the soil layers so more nutrient-poor soil layers are brought to the surface. Topsoil inversal is sometimes used as a cheaper alternative to topsoil removal and shows good results (Jones et al 2010; Schnoor et al. 2010). To counteract encroachment of non-native species sometimes herbicides are used as a recovery measure (Hesp et al. 2012).

Methods

Sources in the international scientific literature and more local research and management evaluation reports formed the basis of this literature review. Only articles that dealt with dry sandy grasslands or dry coastal sand dunes were used to answer the first research question. In order to answer the second research question a broader range of scientific literature was used, including studies on inland sand dunes. Coastal dune ecosystems with issues differing from the Dutch situation where ecosystem recovery was directed at stabilizing sand dunes instead of increasing dynamics (e.g. Marchante 2011) were not selected in this survey.

In this study the efficacy of ecosystem recovery measures to increase the area and quality of grey dune is investigated. Successful recovery in this research was defined as " The rehabilitation of desired grey dune vegetation". Desired communities are defined by the Natura 2000 target communities as mentioned in the introduction section of this report.

Sod cutting in this research was defined as: "the removal of the organic matter (OM) and nutrient rich upper soil layer of 5 cm or more". A distinction was made with measures such as ploughing or harrowing which are not reviewed. In the latter the top layer was not removed but mixed with deeper soil or where soil layers were inverted. Increasing sand dynamics was defined as "the (re) activation of sand dynamics by aeolian activity on large or small scale". Several underlying processes that could play a role in the efficacy of measures (Jansen, 2012) were reviewed.

Table 1 *The proposed effects of recovery measures.*

Measure		Proposed abiotic effect	Proposed successional effect
Sod cutting		• Removal of nutrients • Increase in pH	• Restoration of pioneer stages • Restoration of vegetation from secondary succession •
Sand dynamics	Small scale	• Removal of nutrients • Increase pH	• Reverse succession due to sand deposition • Improving the diverse "mosaic" landscape
	Large scale	• Removal of nutrients • Increase in pH • Long term restoration of dynamics	• Long term restoration of pioneer conditions. • Idem as small scale dynamics

Google scholar and Web of science were used to search for international scientific literature. Keywords in searching literature were *ecosystem recovery, ecosystem rehabilitation, ecosystem restoration, sod cutting, topsoil removal, increased sand dynamics, increased aeolian activity, blowout, grey dunes, coastal dunes*. Literature was selected based on publication date, similarity to the dune sites studied and relevance for the research question. In addition to peer reviewed studies, 'grey' literature on management aspects of the Dutch grey dunes was included in the survey. For this purpose different dune managers were asked for monitoring reports (viz. Waternet, Staatsbosbeheer, Dunea, Evides and Natuurmonumenten)

Results

Sod cutting

Several articles were found dealing with sod cutting in sandy grasslands or sand-dunes. Experiments were performed mainly in Europe: Sweden (Olsson & Ödman, 2013), Germany (Kiehl & Pfadenhauer, 2007; Eichberg et al. 2010; Jentsch et al. 2009) and the Netherlands (v. Til & Kooijman, 2007; Kuiters)(fig 3). Only the study of Buisson et al. (2007) was conducted outside Europe, in the USA. The studies are summarized in table 2; site characteristics and treatment effects are displayes. Kiehl & Pfadenhauer (2007), Eichberg et al. (2010) and Olsson & Ödman (2013) dealt with restoration measures to create species-rich grasslands on former arable fields or pastures, while the other studies deal with nature areas that are in a degraded state and have to be recovered.

Literature on sod cutting in coastal dune ecosystems was very scarce; only the studies of Buisson et al. (2007) Kuiters et al. (2012) and van Til & Kooijman (2007) report on coastal systems. Therefore also the non-peer-reviewed studies of Van der Heiden et al. (2010) Annema & Jansen (1998) and Kuiters et al. (2012), all conducted in the Netherlands, were included in this review. The studies of Kooijman (2005) and v.d. Boom (2004) discuss the effects at multiple sites and therefore only used in the discussion section of the report. All studies encountered focus on the short-term effect of sod cutting on vegetation. In some cases a control or reference state is missing such as in Annema & Jansen (1998)

Fig 3 Sod cutting in the AWD (Appelen-Ezelenberg; Rozenwaterveld) before (2007)and after sod cutting (2010). The pictures give a clear view of the reduction of shrub vegetation. (foto: Joop Hilster).

***Table 2** Overview of the effects of sod cutting, as reported in the literature. Target systems varied from (coastal) grey dune till inland sandy grasslands. Effects were scored with --, - , +/-, + or ++.Where a "+" can men successful removal, positive effect or large abundance. Studies that were published in peer reviewed journals were assigned [PR]. Reports of Natuurmonumenten (v.d. Heide), State forestry service, SBB (v.d. Boom) and OBN (ontwikkeling beheer natuurkwaliteit) (Kooijman) were included in the survey. Fields were left blank if no information on the subject was found.*

Effects of sod cutting

First authour	pub year	Peer revieuw?	country	target system	time	depth	N removal	P removal	SOM removal	rise of pH	pioneer com	Grassland	mosaics	Lime content	Fertilisation history	seeds	target species
Buisson	2007	PR	USA	coastal prairy			+					+		-	?	planted (both from site and from other sites)	+
Kiehl	2007	PR	DE	inland sandy grassland	10	40						+		+	+	inoculated with hay	+
Eichhberg	2010	PR	DE	inland sandy grassland	4	30	+					+		+	+	inoculated	+
Jentsch	2009	PR	DE	inland acid sandy grassland	3	10	+				+	+/-	+	-	-	not introduced/ in proximity	+/-
Olsson	2013	PR	SE	inland calcarious sandy grasslands	6	30/ 50	+	-	+/-	+	+	+		+	?	not introduced/ in proximity	+
v. Til	2007	PR	NL (AWD)	grey dune	4	5			+	-	+	+	+	+	-	not introduced/ in proximity + seedbank	+
Kuiters	2012	-	NL (AWD)	Grey dune	8	5	+					+		+	-	not introduced/ in proximity + seedbank	+
v.d. Heide	2010	-	NL Voorne	grey dune	3				+	+	++	-	+	+	-	not introduced/ in proximity + seedbank	+
Annema	1998	-	NL Goeree	Several coastal dune systems	10						++	-	+	+	-	not introduced/ in proximity + seedbank	+/-

Physical and chemical effect

Sod cutting heavily reduced the amount of nutrients in the topsoil as can be seen in table 2 (Buisson et al. 2007; Eichberg et al. 2010; Olsson & Ödman 2013) and increased pH at most decalcified sites (Olsson & Ödman 2013), only with shallow sod-cutting no change in pH was found (v Til & Kooijman 2007). In situations where decalcification had taken place sod cutting leads to a higher pH (Kooijman et al. 2005). Total nitrogen decreased after sod cutting in all studies where it was measured, but Olsson & Ödman (2013) found no significant effect on NH_4 concentration[1]. Effects on phosphorus availability were less obvious, soil extractable phosphorus[2] showed no effects of sod cutting compared to control conditions in an inland sand ecosystem in Sweden (Olsson & Ödman, 2013). However, on a former arable field in Germany soil phosphorus content was successfully lowered[3] (Eichberg et al. 2010). Multiple studies have shown a strong decline in organic matter after sod removal (v Til & Kooijman, 2007, vd. Heiden et al., 2010), other studies have reported a decline in organic matter but without a quantitative estimation. Literature on the effect of measures on soil processes was scarce.

Effect on the vegetation

Essential in the restoration of ecosystems is the establishment of vegetation in the restored sites. Depending on the depth of the sod-cutting, the vegetation can regrow from the seed bank or rhizomes or become reestablished via seed dispersion. When original vegetation is still present in the adjacent area, species can migrate to the sites from the edges or colonize the area by seed rain (Jentsch et al. 2009). Seed dispersal by zoochory can also play a large role in the reestablishment of vegetation (van Til & Kooijman, 2007). In areas that have been fragmented to a large degree, dispersal is hampered (Eichberg et al. 2010). When colonization of the original vegetation cannot be realized in the natural way, sod cutting is often combined with species introduction by planting (Buisson et al. 2007) or inoculation of the soil with seeds, or the introduction of seed-containing hay from neighboring nature reserves (Keihl & pfadenhauer 2007). Sod cutting after eight years can lead to a shift in the vegetation from shrub vegetation to grey dune grasslands (Kuiters et al. 2012). In general sod cutting especially improves the pioneer stages of succession (Annema & Jansen 1998) while effects on mid-successional grasslands are not always clear. Especially with deeper sod cutting the area of dune grassland can decrease (Annema & Jansen 1998) while shallow sod cutting can successfully restore mid-successional species-rich dune grasslands (v. Til & Kooijman 2007; Kuiters et al. 2012; appendix). Sod cutting can be beneficial to mid-successional grasslands when applied on a small scale and for a shallow soil layer. By variation in topsoil removal depth, and the creation of removed patches, diversity in the landscape can be restored (Van Til 2007). Follow-up management with grazing shows good results in preventing the cover of shrub vegetation after restoration measures (v.d. Heide et al. 2010)

Most studies reported the first signs of recovery of pioneer stages within a few years (Keihl & Pfadenhauer 2007, Buisson et al. 2007, Eichberg et al. 2010); recovery of grey dune grasslands is also possible within years (van Til & Kooijman 2007). In lime rich sites recovery is generally slower than in lime poor sites (van Til & Kooijman 2007). Few studies reported longer-term results of sod-cutting; one unique opportunity to study the effects was created in Germany where a meadow was stripped to create an airplane landing site in 1945 (Kiehl & Pfadenhauer 2007). But in this site species richness was still lower than in and ancient (pristine) grassland due to the lacking of certain typical grassland species that had not colonized the site because of habitat fragmentation.

[1] BaCl extraction
[2] Bray 1 extraction
[3] Unknown extraction method

Effects of increased sand dynamics

The increase of aeolian sand activity to maintain dynamic ecosystems is applied in multiple areas around the world. In this study examples were found in Canada (Darke et al, 2013), USA (Psuty & Silveira, 2013; Pickart et al. 2013), New Zealand (Hesp et al. 2013), Israel (Kutiel 2013), UK (Pye & Blot 2012) France (Rozé & Lemauviel 2004), Germany (Nordstrom et al. 2007) and the Netherlands (Arens, 2006; Boxtel et al. 1997; Kooijman et al. 2005; Boom et al. 2004; v.d. Heide et al. 2010) both in scientific literature and in monitoring reports. Outside the Netherlands, efforts in creating larger scale sand dynamics are mainly focused on the foredune, the first dune ridge that runs parallel to the coast as this zone in the dunes is naturally the most dynamic (Psuty et al. 2013; Darke et al. 2013). Less research was found on the increase of small scale dynamics in blowouts. Studies on increased sand dynamics as a recovery measure are still scarce and mainly focused on geomorphological processes (Darke et al., 2013; Hesp et al. 2013). An increase in sand dynamics is also often used to create new dune slacks, which happens after sand is blown away till ground water level (Boom et al. 2004).

In many areas outside Europe, the stabilization of dunes is not directly related to the encroachment of grasses as a result of increased levels of nitrogen deposition but rather to the invasion of European marram grasses (Darke et al. 2013). In such areas restoration of dynamic dune systems involved the eradication of marram grasses. This is done by spraying herbicide on the grasses (Hesp et al. 2013) or simply by digging and pulling (Pickart et al. 2013). Subsequently, native dune forming grasses are often reintroduced in the area (Hesp et al. 2013). In other cases, the main cause of dune stabilization was the cessation of the traditional use of the dunes (Kutiel 2013; Kooijman et al. 2005). In Israel, grazing by life stock such as goat, sheep and camels was reintroduced as a measure to restore semi-stabilized dunes (Kutiel 2013). Partial removal of vegetation was applied as a management measure (Kutiel et al. 2013).

Fig 4 restoration measures in the AWD (rozenwaterveld) shortly after topsoil removal, 2009, and in 2010. Sod cutting is combined here with low level sand acivity (foto: J. Hilster)

Table 3 *Overview of the effects of increased sand dynamics. country of origin, CAN: Canada, USA: United States of America, NL: The Netherlands, ISR: Israel, FR: France. Effects were scored with - -, - , +/-, + or ++. Where a "+" can men successful removal, positive effect or large abundance. If no information was found the field was left blank. Studies that were published in peer reviewed journals were assigned [PR]. Reports of Natuurmonumneten (v.d. Boom) State forestry service, SBB (v.d. Heide) and OBN (Ontwikkeliing en Beheer voor Natuurkwaliteit) (Kooijman) were included in the survey. Research of Kutiel was pubished as a book chapter (Kutiel).*

Effect of increased aeolian dynamics

	Author	Year of publication	Country	Peer reviewed	Years of study	Target system	Measure	Succesfull Restoration	Nutrients	pH	Pioneer com	Grasslands	Lime rich MM	Previous	Mosaics
Large scale dynamucs	Darke	2012	CAN	PR	3	open coastal dune	repeated removal of foredune vegetation	+						Protective dune	
	Nordstrom	2007	USA	PR	7	Open coastal dune	repeated removal of foredune vegetation	+/-				+		Protective dune	
	Arens Geelen	2006	NL	PR	8	open coastal dune	Fill up of a infiltration canal; topsoil removal of surroundings	+/-			++		+	Infiltration area	
	Kutiel	2013	ISR	-		Open coastal dune	vegetation removal combined with grazing	+/-						Nature area	
	Rozé	2004	FR	PR	10	partly open coastal dune	Not specifically mentioned	+/-			+			Camping/ touristic	+
	Kooijman	2005	NL De Blink	-	20	open coastal dune	creating larger scale dynamics	+/-	+	+	++	-	+	Nature area	+
Small scale dynamics	Kooijman	2005	NL	-	20	open coastal dune	Reactivation of blowouts	+/-	+	+	++	+/-	+	Nature area	+
	v.d. Heide	2010	NL voorne	-	7	open dune / dune grassland	removal of vegetation and humus.	+/-			++	+/-	+	Nature area	+
	Boxtel, van	1997	NL	PR	5	Open coastal dune	Reactivation of blowouts	+		+			+	Nature area	+

Physical and chemical effects
The impact of topsoil removal for increasing sand dynamics is the largest at the very sites where soil has been removed but a large-scale impact is also created by the in-blow of sand towards surrounding areas (v.d. Heide et al. 2010). At the very site were the measure is applied, nutrient rich topsoil is removed en nutrient poor and lime rich deeper soil is exposed. Sand spray can spread over wide areas, approximately 6 times the size of the blowout area (v. Boxtel et al. 1997) depending on the landscape structure. For instance, on dune tops the deposition area will be larger; but when blowouts are out of wind, deposition will be minimal. Aeolian sand dynamics are the strongest near the beach where the wind speed is the highest (v.d. Heide et al. 2010; Darke et al. 2013). Kooijman (2005) showed that sand deposition can lead to an increase in pH in dunes with a degraded, decalcified state. In-blow of nutrient-poor and lime-rich sand also creates more nutrient-poor conditions in the surrounding vegetation (Kooijman et al. 2005). In-blow of sand in the surrounding area thus plays a large role in the effect of increased dynamics on the vegetation.

Response of the vegetation
In many studies the pioneer stages (e.g. Violo corynephoretum and Phleo-Tortuletum ruraliformis) increased in area and quality (v.d Heide et al. 2010; Kooijman et al. 2005; Boom et al. 2004). The stabilization of blowouts is strongly enhanced by the Phleo-Tortuletum ruraliformis in lime-rich systems and the Corynephoretum canescentis in lime-poor systems. Species-rich grasslands of the Festuco-Galietum veri and the Taraxaco-Galietum veri often decreased in size in situations where areas with open sand increased (Kooijman et al. 2005; v.d Heide et al. 2010). However, when lime-rich sand is deposited in encroached grasslands, an amelioration of the system may take place (Boom et al. 2004). The invasive moss *Hypnum cupressiforme* does not tolerate deposition of sand, *Campylopus introflexus* does not tolerate deposition of lime rich sand (v.d. Meulen et al. 1987). Mosses of pioneer-communities of secondary succession thrive well in the deposition area (v. Boxtel et al. 1997).

Sand deposition is often not sufficient to decrease the area of shrubland (Arens, 2006). Boom (2004) even reported that deposition of small amounts of sand in grasslands may lead to increased growth of shrub vegetation due to an increased mineralization. When large scale deposition takes place *Ammophila arenaria* colonises these sites; therefore total cover of *A. arenaria* might in some places increase due to increased sand dynamics (v.d. Boom 2004). Multiple studies have reported the successful restoration of the dune mosaic landscape where multiple successional stages are present (Kooijman 2005). A mosaic landscape can be created by the existence of sites with a different deposition history next to each other.

Fig 4 Groot boeveld in the AWD before and after the reactivation of a blowout. (foto: Mark van Til)

Long term effects

No studies have been found on the effects longer than 20 years, however from the literature some trends that can affect the long term success of measures becomes clear. Lasting effects of dynamic dune restoration seem to depend on the location where the measures are applied. Closer to the coast, restoration of blowouts and shifting dunes seems to be more successful in the longer term than more inland (v. Boxtel et al. 1997). For a long-term effect of restored sand dynamics repeated management is probably necessary (Kutiel 2013, Boom et al. 2004), although little research has been done on the lasting effects of increased sand dynamics.

Stabilization of the sand begins with the formation of an algal crust at the top of the soil (Arens & Geelen 2007) whereafter pioneer vegetation becomes established. Trampling by larger herbivores can prevent the formation of this algal mat (v.d. Heide 2010). In most cases resprouting of root fragments of *Ammophila arenaria* and *Hippophae rhamnoides* occurred after the removal of the humus-rich layer of the soil. In some studies these sprouts were manually removed (Boxtel et al. 1997) or grazed by lifestock (Kutiel, 2013) to prevent restabilisation (Arens & Geelen, 2007). Kooijman et al. (2005) report that within 20 years species rich dune grasslands have not reestablished. However, deposition of lime rich sand might have positive effects on the vegetation on the longer term.

Discussion

Sod-cutting and the increase of aeolian dynamics are effective measures to increase the area and quality of grey dune ecosystems. Both measures can set back succession from a degraded state. Successful restoration depends on scale and execution of the measures and on follow up management. Crucial in the establishment of grey dune grasslands is the amount of SOM that is left in the soil. Depending on the amount of SOM left, species-rich grasslands or pioneer communities will be favored. Reestablishment of target vegetation is dependent on the soil seed bank and immigration by zoochory, anemochory or via intact refugia of target vegetation. When the soil seed bank is largely removed or not present and the ecosystem is fragmented to a larger degree, human introduction of vegetation can be an appropriate measure.

Pioneer species of secondary succession are often rare in Europe due to a lack of natural dynamics. These communities characterized by a.o. *Corynephoris canescens* in acid dunes and the moss *Tortula ruralis* in lime rich sites, are favored by both measures as they increase the disturbance regime. Some of the encountered studies specifically aimed at restoring disturbance conditions for the establishment of these pioneer communities (Olsson & Ödman 2013; Jentsch et al. 2009). The grassland communities are less dependent on disturbance regime but can benefit from the measures due to their effect on soil nutrients counteracting eutrophication.

Sod cutting

The effects of sod cutting on soil edaphics heavily depends on the depth with which the measure is applied. Sod cutting can be an effective measure to reduce nitrogen and phosphorus and organic matter in the soil and can effectively increase the pH. The removal of phosphorus has not always been proven successful, but a high lime content that is found after deeper sod cutting will cause a decreased availability of phosphorus for vegetation. Removal of SOM by sod cutting will have implications for nutrient availability as will be discussed further in this report.

Kooijman (2005) reported successful restoration after sod cutting; however, seven years after sod cutting had taken place species diversity was not as high as in the reference sites and species number is lower than with yearly mowing of the vegetation. In acid sand dunes a negative impact of topsoil removal on the establishment of cryptogam species was found over a three year period (Jentsch et al. 2009). However positive effects of sod cutting on mosses and lichens in partly decalcified dunes were found. Sod cutting in lime-rich systems may lead to an increased cover of *Hippophae rhaminoides* (Kooijman et al. 2005) especially when soil microfauna in the organic layer that parasitizes on the plant is also removed. Recovery of early successional stages of grassland can be successful within a few years after sod-cutting. Reestablishment of later successional or mid successional vegetation types such as the Taraxaco-Gallietum veri might take longer, but when shallow sod cutting is applied can also be successful on the shorter term (v. Till & Kooijman 2007; Kuiters et al. 2012; appendix). Especially in lime-rich conditions, recovery is known to be more slow (van Til & Kooijman 2007). Besides soil edaphics the proximity of target vegetation is very important in the reestablishment of vegetation (v.d. Heide et al. 2010). Especially when deeper sod cutting is applied, the soil seed bank will mostly be removed and dispersal of seeds by aerochory is often not sufficient to restore species rich grasslands when the landscape is fragmented to a larger degree. A strategy that has been successful to help the establishment of a target community is the safeguarding of small “refugia” of target vegetation amidst the area where topsoil is removed (Jentsch et al. 2009).

The direction of succession on the longer term will depend on the levels of recent, current and future nitrogen deposition. Grass encroachment is still a possible danger when current levels of nitrogen deposition would not show a further decrease and phosphorus availability due to soil decalcification is not limited. In that case sod cutting needs to be regarded as a recurring measure that has to be repeated. When topsoil removal is repeatedly applied, systems can approach groundwater levels affecting soil moisture and thereby vegetation. If restoration measures are directed at the reestablishment of communities that are dependent on an intermediate disturbance regime repeated sod cutting can mimic the natural dynamics (Olsson & Ödman, 2013; Jentsch et al. 2009). Recovery of vegetation of disturbed lime grasslands from bare sand can take up to five decades (Hirst et al. 2005) if succession is not disturbed by nutrient deposition.

Sand dynamics

Increasing the aeolian dynamics in coastal ecosystems will lead to the rejuvenation of the landscape. The deposition of sand in the surrounding area partly determines the success of the measure. Blow in of lime-rich and nutrient poor sand can set back succession and decrease nutrient availability (v.d Boom et al. 2004). In the reactivated blowouts nutrient conditions are restored to pre N-deposition conditions. Sand inblow can cause vegetation to shift back to previous successional types (Schaminee, 1997). In areas where the complete organic layer is removed it is likely that the soil seed bank is also removed, dependent on the depth of the o-horizon and the persistent seed bank. Where sand is deposited by wind dispersal the seed bank will still be intact, but when sand is deposited at a large scale the seed bank might be too deep to act as a source for vegetation renewal (Maun et al. 2009). In that case pioneer vegetation of *Amophila arenaria* might start succession from the start, or in cases of lower sand deposition, wind dispersal and zoochory might introduce species of secondary succession.

Whether stabilization occurs in restored sites depends largely on climatic conditions, nitrogen deposition and the presence of (larger) herbivores. In many of the reviewed cases reactivated sand blows became stabilized in time. Successful restoration of dune dynamics can lead to favorable conditions for rare pioneer communities on the mid to longer term. Vegetation types like the Violo-Corynephoretum can exist in cyclic succession over longer time periods. Stabilisation of the reactivated dunes might also lead to natural succession to species rich grey dune grasslands. Aeolian sand dynamics increase the area of open sand, mostly at the expense of the area of grassland. Van der Heide (2010) suggests that especially the pioneer communities benefit from the measures, while grasslands become less dominant. Kooijman (2005) and Boom (2004), however, show that small scale deposition of sand in degraded grasslands can improve their quality. Success of the measure seems to be partly dependent on deposition of sand from the opened sites. In some of the reviewed cases deposition of sand to the surrounding environment did not take place; this seems largely related to local topography (Arens & Geelen 2007).

Long term success of large increased large scale dynamics depends on the sustained activity in the treated areas. Sand activity is dependent on strong winds that occur mostly in winter; on the other hand winds have more impact when the sand is dry in summer conditions (Arens & Geelen 2007). Especially if conditions are wet, pioneer vegetation will colonize blowouts and dynamic dunes more easily (Kutiel 2012). Sprouts of marram grass or sea buckthorn are often removed once every few years to prevent stabilization of the dunes. However stabilization might also lead to the establishment of dune grasslands it is not clear how long this vegetation can exist with current deposition levels. To ensure long-term success of dynamic dune restoration, good follow up management is necessary (v.d. Heide et al. 2010).

A disadvantage of increased dynamism in the dunes is that shifting sands are a-selective and thus may also cover vast areas of intact target vegetation. However, the measure provides a natural way to restore a diverse landscape where multiple successional stages are present. Most of the reactivated blowouts spontaneously stabilize via natural succession, and only a small percentage reaches maturity (v Boxtel et al. 1997). In this natural process pioneer communities of the grey dunes take the place of bare sand and can be succeeded by dune grasslands. Therefore stabilization of artificially reactivated blowouts is not a problem and might be part of a successful management strategy.

Multiple factors affecting the efficacy of measures

In the last years evidence is building for the Intermediate Disturbance Hypothesis (IDH) that states that diversity will be highest at sites with a moderate disturbance (Grime et al. 1973). Dynamic dunes are an ideal ecosystem to test this hypothesis. An elaborated version of this theory is the Dynamic Equilibrium model (DE) by Huston (1994): in this model species richness is determined by both disturbance and community productivity. Stressed ecosystems such as nutrient poor dry dunes can only sustain a few specialist species. When productivity increases generalists will survive until in later succession a few strong competitors will be able to dominate the system. Many red-list species are specialists and have their preference for a specific disturbance regime (Olsson et al. 2013), this underlines the importance of variation in disturbance regime and successional stages in dune ecosystems. Highest biodiversity is often created when a mosaic landscape is formed; most times reflecting historical (agricultural) land use with long periods of fallow (Ödman et al, 2012).

Soil carbon, mostly present in the form of soil organic matter, a.o. ensures the retention of water in the soil and affects the main soil processes as nutrient cycling, decomposition and mineralization. Mineralization of nitrogen is proven to be higher at higher concentrations of soil carbon (Sparrius, 2013; Melis 2013). Removal of organic matter or decrease in carbon concentration will thus lead to lower values of mineralization. Lime content of the soil can also influence the availability of nitrogen as immobilization of nitrogen under base rich conditions is higher than in acid soils due to a higher abundance of bacteria that have a lower CN ratio then bacteria. (Kooijman & Besse 2002). Nitrogen is an important explaining factor in vegetation composition in grey dune systems (Kuiters et al. 2012). In P limited systems the amount of phosphorus left in the soil will also determine the rate of nitrogen mineralization on the longer term as SOM buildup at these sites is largely controlled by available P (Kooijman & Besse, 2002).

In the establishment of a new vegetation on restored sites the composition of the microbial- and microfaunal community will play an important role. A functionally diverse soil community may enhance the storage of nutrients in the soil, i.e. net N immobilization will take place (Kemmers et al. 2013). The presence of mycorrhizae might facilitate the establishment of certain plant species while the presence of parasitic microbes and nematodes might prevent the establishment of others (Brussaart et al. 2001). A diverse soil fauna generally suppresses dominant species thereby giving room to subordinate species and increasing biodiversity. It is known that mycorrhizae can extend their mycelia upwards when they are overblown by dune sand (Maun et al. 2009). When sod cutting was applied to forest soils of *Pinus sylvestris,* mycorhizzal diversity increased while plant feeding nematodes decreased (Brussaard et al. 2001). Effects of sod cutting on microbial and microfaunal composition in dune ecosystems are still largely unknown.

Rabbit populations are hard to control and form an important factor in controlling vegetation in grey dune ecosystems. Sod cutting can have a positive impact on the rabbit population (Til & Kooijman, 2007); reactivation of aeolian dynamics also seems to improve rabbit populations (v.d. Heide et al. 2004). While rabbits can keep the vegetation open, larger herbivores can maintain of open sand. Horses open up vegetation to feed on plant roots and trampling of deer can prevent the formation of an algal crust on open sand. However, in large numbers rabbits can also create spots of open sand. Grazing of larger herbivores facilitates the establishment of a viable rabbit polulation (Kooijman et al. 2005). Also ants play an important role in dune ecosystems; they can change soil chemistry at a micro-scale and are of importance in the distribution of seeds (Maun et al. 2009).

Reestablishment of vegetation is the key process in ecosystem restoration. When seed banks are depleted due to removal of the top soil or agricultural use colonization of target vegetation is necessary. Seed dispersal is however considered a limiting factor in calcareous grasslands (Ödman et al. 2012). This may be caused by a lower investment in sexual reproduction in P-limited systems (Fujita et al. 2013). In decalcified systems colonization therefore might be faster than in calcareous sites (v. Til & Kooijman 2007). Pioneer plant and moss species are often adapted to wind dispersal.

Synthesis

Both sod cutting and the increase of sand dynamics have their advantages and disadvantages and depending on target communities and site topography. Effects of the different measures and knowledge-gaps are displayed in table 4. Measures have a positive effect on pioneer vegetation but a positive effect on dune grasslands is still uncertain in some cases. Follow-up measures are necessary after both measures to prevent systems falling back in a degraded state.

Table 4 *Assessment of the two measures on the basis of the reviewed literature. Measures were assigned - ; +/- ; + or ++ based on their effect on different assessment criteria.*

	long term	nutrients	pH	pioneer vegetation	Dune-grasslands	landscape mosaics
sod cutting	+/-	++	+	+	++	+
	Uncertain, possibly repeated.	Drastically reduces soil N possibly also P	Increases pH dependent of depth	Can recreate pioneer vegetation	Successful When shallow, uncertain.	Variation in depth leads to variation in the landscape
Large scale dynamics	+	+	+/-	++	-	+
	Possibly more durable when stabilization is prevented Uncertain.	Reduced nutrient uptake by sand inblow	Can increase pH via inblow or outblow of sand.	Pioneer conditions on the longer terms	Can reduce the area of dune grassland	Leads to landscape rejuvenation and tereby mosaic landscape
Small scale dynamics	+/-	+	+	+	+	++
	Majority of the blowouts will stabilize in time	Reduced nutrient uptake by sand inblow	Can increase pH via inblow or outblow of sand.	Creates pioneer conditions due to inblow and outblow	Increase of quality due to sand depostion	Due to variation in deposition regime

Long term effect of the measures

As is mentioned in Jentsch (2008) "*given atmospheric nitrogen input … the restoration goal cannot be the re-establishment of past conditions but consists in restoring ecosystem dynamics… so that a mosaic of different resource levels and plant communities can interact in form of self-sustaining dynamics for a while*". In the dunes of rhenodunal origin, the effect of restoration measures on the availability of phosphorus is crucial. Phosphorus is often limited in these systems, especially at high deposition of nitrogen as is currently still the case (Kooijman et al. 2005; Kooijman & Besse, 2002). Only Active sand-blow or repeated sod cutting are can maintain lime-rich sites where phosphorus availability is naturally low. When nitrogen is limiting e.g. in partly decalcified sites management should be directed at lowering soil nitrogen.

Future research

A review study of Bonte (2005) stressed the need for a more process based approach to restoration in dune systems, and more research into the processes affecting biodiversity in these systems. It seems that since the study of Bonte these processes are more studied and applied in ecosystem management. However, still much is unclear about how underlying processes as decomposition and mineralization are affected and how effects differ with different soil edaphics. Effects of restoration on soil fungi and the soil faunal community are still largely unknown and deserve further attention because of the important role they perform in dunal succession.

Long term monitoring of restoration measures is often not performed, and especially absent in scientific literature. Effects of increased dynamics longer than 20 years have not been found while succession in grey dune systems may take much longer. Monitoring is also often focused on the geomorphological effects of the measures neglecting the ecological effects. While stabilization of dynamic dune might be considered as a failed restoration effort it might be a successful restoration from an ecological perspective.

Management recommendations

- Both sod cutting and the reactivation of aeolian sand dynamics are useful measures in the restoration or recovery of dry coastal dune ecosystems. Both measures have a proven positive effect on biodiversity and landscape diversity. Increasing sand dynamics seems to be a favorable measure to increase the area of pioneer communities of secondary succession as in a dynamic landscape, rejuvenation can take place on a regular basis.

- Caution should be taken that both measures might reduce the cover of species rich grasslands. Of the reviewed measures only shallow sod cutting seems to be effective in restoring these grasslands. On the longer term however grey dune grasslands might establish via succession in stabilized blowouts.

- It seems that for the reestablishment of species in dunes where large scale remobilization measures or top soil removal has taken place it is crucial that target vegetation is in the vicinity of the restored sites. It is advisable to create small "refugia" of intact target vegetation amidst the removed soil (Jentsch et al. 2009)

- Follow-up measures are essential in the long term success of measures; mainly in sustaining long term dynamic's in blowouts and shifting dunes. Grazing seems to be the best management for these areas. Rabbit populations should be promoted, but in absence on rabbit populations larger herbivores can also play an important role. Horses for example can open up small patches of vegetation to feed on plant roots.

- In areas where sod cutting was applied follow-up management with grazing shows good results as in this way the growth of shrub vegetation can be prevented (v.d. Heide et al. 2010)

- Monitoring the results of restoration efforts is important to produce knowledge to improve restoration practices. In monitoring soil nutrients, also phosphorus should be measured.

- Long term studies are necessary to create knowledge on the lasting effects of restoration efforts in grey dune ecosystems.

Aknowledgements
I'd like to thank Mark van Til of Waternet and Camiel Aggenbach for their cooperation in this masterthesis. Their comments, suggestions and valuable advice have made this thesis what it is. It was very stimulating to work with such experts in the field. I'd like to thank Jos Verhoeven for his supervision and advice on the process. Thanks for the flexibility to ajust the plans on the way to reach a sattisfactionary result. I'd like to thank my parents for their moral support and advice.

Literature

Aggenbach, C. Jalink, 1999, Indicator soorten voor verdroging verzuring en eutrofiering, droge duinen. Staatsbosbeheer, 1st edn. Driebergen

Aggenbach, C., Kooijman A.M., Bartholomeus, R.P., Fujita, Y., 2013 Herstelbaarheid van droge duingraslanden in relatie tot accumulatie van organische stof en stikstof in de bodem. KWR, Niewegein.

Annema, M., Jansen, A.J.M., 1998, Het herstel van het vroongebied Midden- en Oostduinen op Goeree. Stratiotes (17)

Arens, B., Geelen, L., Hagen, H. & Slings, R. 2007, *Duurzame verstuiving in de Hollandsche duinen kans droom of nachtmerrie*, DPW, Amsterdam.

Arens, S.M. 2006, "Dune landscape rejuvenation by intended destabilisation in the Amsterdam water supply dunes", *Journal of Coastal Research,* vol. 22, no. 5, pp. 1094-1107.

Berendse, F. 2011, Natuur in Nederland, KNNV, 1st edn. Zeist

Bobbink, R. & Hettelingh, J. 2010, *Review and revision of empirical critical loads and dose-response relationships. proceedings of an expert workshop, noordwijkerhout*, B-ware, Noordwijkerhout.

Boom, B. v.d, Holtland, J., Lamerts, E., 2004, De duinen van staatsbosbeheer, evaluatie van herstelbeheer in de kuststrook. Staatsbosbeheer, Driebergen.

Bonte, D., Hoffman, M. 2005, "Are coastal dune management actions for biodiversity restoration and conservation underpinned by internationally published scientific research?" Proceedings ‘ dunes and estuaries 2005’ international conference on nature restoration, Practices in European coastal habitats, pp 165-178

Boxel, J.H.van, Jungerius, P.D., Kieffer, N. & Hampele, N. 1997, "Ecological effects of reactivation of artificially stabilized blowouts in coastal dunes", *Journal of Coastal Conservation,* vol. 3, pp. 57-62.

Buisson, E., Holl, K.D., Anderson, S., Corcket, E., Hayes, G.F., Torre, F., Peteers, A. & Dutoit, T. 2006, "Effect of seed source, topsoil removal, and plant neighbor removal on restoring california coastal prairies.", *Restoration ecology,* vol. 14, no. 4, pp. 569-577.

Brussaard, L., Kuyper, T.W., Goede, R.G.M. de, 2001, On the relationschips between nematodes, mycorrhizal fungi and plants: functional composition of species and plant performance. *Plant and soil,* vol 232, pp 155-165

Clements, F.E., 1936, Nature and structure of the climax, *Journal of ecology,* vol 24, pp 252-284.

Darke, J.B., Eamer, J.B.R., Beaugrand, E.R. & Walker, J.J. 2013, "Monitoring considerations for dynamic dune restoration project: pacific rim national park reserve, Brithish Columbia, Canada.", *Earth surface processes and landforms,* vol. 38, pp. 983-993.

Deyn, G. de, Raaijmakers, C.E., Zoomer, H.R, Berg, M.P., Ruiter, P.C. de, Verhoef, H.A., Bezemer, T.M., Putten, W. v.d., 2003, Soil invertabrate fauna enhances grassland succession and diversity. *Nature,* vol. 42, pp 711-713

Eichberg, C., Storm, C., Strah, M. & Schwabe, A. 2010, "Is the combination of topsoil replacement and inoculation with plant material an effective tool for the restoration of thereatend sandy grassland?", *Applied Vegetation Science,* vol. 13, pp. 425-438.

Emery, S.M., 2012, Succession: a closer look, *Nature Education Knowledge*, http://www.nature.com/scitable/knowledge/library/succession-a-closer-look-13256638

Fujita, Y., Olde Venterink, H., Bodegom, P. van, Douma, J.C., Heil, G., Hötzel, N., Jablonska, E., Kotowski, W., Okruzko, T., Pawlikowski, P., Ruiter, P.D. de, Wassen, M., 2013, Low investment in sexual reproduction threatens plants adapted to phosphorus limitation. *Nature letters, online.*

Grime, J.P., 1973, Control of species density in herbaceous vegetation. *Journal of environmental management*, vol 1, pp 151-167.

Gleason, H.A., 1926, The individualistic concept of the plant association, *Bulletin of the Torrey botanical club.* vol 53, pp 7-26

Haperen, A.M.M. 2009, *Een wereld van verschil*, Wageningen Universiteit.

Haperen, A.M.M., Kooijman, A.M., Kuiters, A.T., Nijssen, M., Roon, J.A., Schotsman, N., Slings, Q.L., 2013, Damherten in de Amsterdamse Waterleidingduinen, hun invloed op het landschap en de kwaliteit van enkele habitats. OBN-deskundigenteam Duin- en kustlandschap. Bosschap, Ministerie van EZ. Den Haag

Hermy, M., Blust, G. de, 2012, Natuurbeheer, Argus, Antwerpen

Hesp, P.A., 2013, Conceptual models of the evolution of transgressive dune field systems. *Geomorphology*, no 199, pp. 138-149

Hirst, R.A., Pywell, R.F, Marrs, R.H., Putwain, P.D., 2005, The resilience of calcareous and mesotrophic grasslands following disturbance. *Journal of applied Ecology,* no 42, pp 498-506

Houston, J. 2008, *Management of Natura 2000 habitats. 2130 Fixed dunes with herbatious vegetation ("grey dunes")*, Technical report edn, European commission, Brussels.

Huston, M.A., 1994, Biological diversity, The coexisting of species on changing landscapes, Cambridge university press, Cambridge

Jackson, N.L. & Nordstrom, K.F. 2011, "Aeolian sediment transport and landforms in managed coastal systems: A review", *Aeolian research,* vol. 3, pp. 181-196.

Jansen, A.J.M., Schaminee, J.H.J., Bobbink, R., Smits, N.A.C., Weersink, H., 2012, Herstelstrategien stikstofgevoelige habitats, ecologische onderbouwing van de programmatische aanpak stikstof (PAS) Deel I hoofdstuk 3 herstelmaatregelen. Ministerie van economische zaken.

Jentsch, A., Friedrich, S., Steinlein, T., Beyschlag, W. & Nezadal, W. 2009, "Assessing Conservation Action for Substitution of Missing Dynamics on Former Military Training Areas in Central Europe", *Restoration Ecology,* vol. 17, no. 1, pp. 107-116.

Jones, M.L., Sowerby, A., Rhind, P.M., 2010, Factors affecting vegetation establishment and development in a sand dune chronosequence at Newborough Warren, North Wales. Journal of Coastal conservation.

Jones, M.L.M., Sowerby, A., Williams, D.L. & Jones, R.E. 2008, "Factors controlling soil development in sand dunes: evidence from a coastal dune soil chronosequence.", *Plant and Soil,* vol. 307, pp. 219-234.

Keihl, K. & Pfadenhauer, J. 2007, "Establishment and persistence of target species in newly created calcareous grasslands on former arable fields", *Plant Ecology,* vol. 189, pp. 31-48.

Kemmers, R.H., Bloem, J. & Faber, J.H. 2012, "Nitrogen retention by soil biota; a key role in the rehabilitation of natural grasslands?", *Restoration ecology,* vol. 21, pp. 431-438.

Kooijman, A.M., Besse, M., Haak, R., 2005, Effectgerichte maatregelen tegen verzuring en eutrofiering in open droge duinen. OBN eindrapport fase II. Directie kennis Ministerie van Landbouw, Natuur en voedselkwaliteit, Ede.

Kooijman, A.M., Noordijk, H., Hinsberg, A.v. & Cusell, C. 2009, *een analyse van N-depositie, kritische niveaus, erfenissen uit het verleden en stikstofefficiëntie in verschillende duinzones.*, Planbureau voor de leefomgeving, Amsterdam.

Kooijman, A.M., Besse, M., 2002, The higher availability of N and P in lime-poor than in lme-rich coastal dunes in the Netherlands. *Journal of Ecology,* vol 90, pp 394-403.

Koske, R.E. & Gemma, J.N. 1997, "Mycorrhizae and Succession in Plantings of Beachgrass in Sand Dunes", *American Journal of Botany,* vol. 84, no. 1, pp. 118-130.

Kuiters L., 2011, Analyse permanente kwadraten ondiep plaggen AWD. Alterra, Wageningen

Kutiel, P.B., 2013 restoration of Coastal sand dunes for conservation of biodiversity the Israeli experience. In Martinez, M.L., Gallego-Fernandez, J.B., Hesp, P.A., Restoration of Coastal dunes. Springer verlag, Berlin Heidelberg.

Lithgow, D., Martinez, M.L., Gallego-Fernandez, J.B., Hesp, P.A., Flores, P., Gachuz, s., Rodriguez-Revelo, N., Jimenez-Orocio, O., Mendoza-Gonzalez, G., Alvarez-Molina, L.L., 2013, Linking restoration ecology with coastal dune restoration. *Geomorphology.*vol 199, pp 214-224.

Long, Z.T., Fegley, S.R. & Peterson, C.H. 2013, "Fertilization and plant diversity accelerate primary succession and restoration of dune communities", *Plant Ecology.*

Marchante, H., Freitas, H. & Hoffman, J.H. 2011, "The potential role of seed banks in the recovery of dune ecosystems after removal of invasive plant species", *Applied Vegetation Science,* vol. 14, pp. 107-119.

Maun, M.A., 2009, The biology of coastal sand dunes, Oxford university press, Oxford.

Meulen, F. v.d., Hagen, H. & Kruijsen B. 1987 "Campylopus introflecxus. Invasion of a moss in Dutch coastal dunes. Proceedings of the Koningklijke Nederlandse Academie voor wetenschappen.

Meijden, R., vd., 2005, Heukels flora, Wolters Noordhof.

Miles, J. 1979, *Vegetation dynamics, outline studies in ecology,* 1st edn, University press, Cambridge, Cambridge.

Nordstrom, K.F., Hartman, J.M., Freestone, A.L., Wong, M. & Jackson, N.L. 2007, "Changes in topography and vegetation near gaps in a protective foredune",*Ocean and coastal management,* vol. 50, pp. 945-959.

Nyssen, B., 2010, Inburgering van de Amerikaanse vogelkers, De moeilijke omgang met biologishe globalisering. Bosgroep Zuid Nederland, Geldrop.

Odman, A.M., Marterson, L.M., Sjöholm, C. & Olsson, P.A. 2011, "Immediate responses in soil chemistry, vegetation and ground beetles to soil perturbation when implemented as a restoration measure in decalcified sandy grasslands", *Biodiversity and Conservation,* vol. 20, pp. 2039-3058.

Odman, A.M., Schnoor, T.K., Ripa, J. & Olsson, P.A. 2012, "Soil disturbance as a restoration measure in dry sandy grasslands", *Biodiversity and Conservation,*vol. 21, pp. 1921-1935.

Olsson, P.A. & Odman, A.M. 2013, "Natural establishment of specialist plant species after topsoil removal and soil perturbation in degraded calcareous sandy grassland", *Restoration ecology,* , pp. 1.

Pickart, A.J., Dune restoration over two decades at the Lanphere and Ma-le'l dunes in northern California. Chapter 10 in, Martinez, M.L., Gallego-Fernandez, H.B., Hesp, P.A., 2013. Springer verlag Heidelberg.

Psuty, N.P., Silveira, T.M., Restoration of coastal foredunes, a geomorphological perspective: Examples from New York and from New Jersey, USA. In Martinez, M.L., Gallego-Fernandez, H.B., Hesp, P.A., 2013. Springer verlag Heidelberg.

Pye, K. & Blott, S.J. 2011, *Kenfig sand dunes - Potential for dune reactivation*, countryside council for Wales.

Remke, E., Brouwer, E., Kooijman, A.M., Blindow, I., Roelofs, G.M., 2009, Low Atmosperic nitrogen loads lead to grass encroachment in coastal dunes, but only on dry acid soils. *Ecosystems,* vol 12, pp 1173-1188

Rozé, F. & Lemauviel, S. 2004, "Sand dune restoration in north brittany, France: a 10 year monitoring study", *Restoration ecology,* vol. 12, no. 1, pp. 29-35.

Schaminee, J., Sykora, K., Smits, N. & Horsthuis, M. 2010, *Veldgids plantengemeenschappen van Nederland,* 1st edn, KNNV Uitgeverij, Zeist.

Schaminee, J.H.J., Weeda, E.J., Westhoff, V., 1996, De vegetatie van Nederland. Opulus press

Schnoor, T.K., Olsson, P.A., 2010, Effects of soil disturbance on plant diversity of calcareous grasslands. *Agriculture, ecosystems and Environment,* vol 139, pp 714-719

Smits, N.A.C., Kooijman, A.M., 2012, Herstelstrategien stikstofgevoelige habitats, ecologische onderbouwing van de programmatische aanpak stikstof (PAS), Deel II Herstelstrategie H2130B Grijze duinen (Kalkarm), ministerie van EZ.

Sparrius, L.B., 2011, Inland dunes in the Netherlands, soil, vegetation nitrogen deposition and invasive species. PhD thesis, University of Amsterdam.

Suding, K.N., Gross, K.L. & Houseman, G.R. 2004, "Alternative states and positive feedbacks in restoration ecology", *Trends in Ecology & Evolution,* vol. 19, pp. 46.

Til, M.van, Kooijman, A.M. 2007, "Rapid improvement of grey dunes after shallow sod cutting", *Coastline reports,* vol. 7, pp. 53-60.

Til. M. van, Mourik, J., 1999, Hieroglyfen van het zand, vegetatie en landschap van de Amsterdamse Waterleiding Duinen, Gemeentewaterleidingen amsterdam, Amsterdam.

Tilman, D., 1985, The resource ratio hypothesis of plant succession. *The American Naturalist,* vol 125, no 6, pp 827-852.

Veer, M.A.C., Kooijman, A.M., 1997, Effects of grass-enchroachment on vegetation and soil in Dutch dry dune grasslands. *Plant and soil,* vol 192, pp 119-128

Velders, G.J.M., Aben, J.M.M., Geilenkirchen, G.P., den Hollander, H.A., Jimmink, B.A., Swaluw, E. vd., Vries, W.J., Wesseling, J., Zanten, M.C. van., 2013, Grootschalige concentratie en depositiekaarten Nederland, rapportage 2013, RIVM.

Walker, I.J., Eamer, J.B.R., Darke, I.B., 2013, Assessing significant geomorphic changes and effectiveness of dynamic restoration in a coastal dune ecosystem. *Geomorphology*, vol 199, pp 192-204.

Westhof, V. & Oosten, M.F. 1991, *De plantengroei van de waddeneilanden,* KNNV, Oosterbeek.

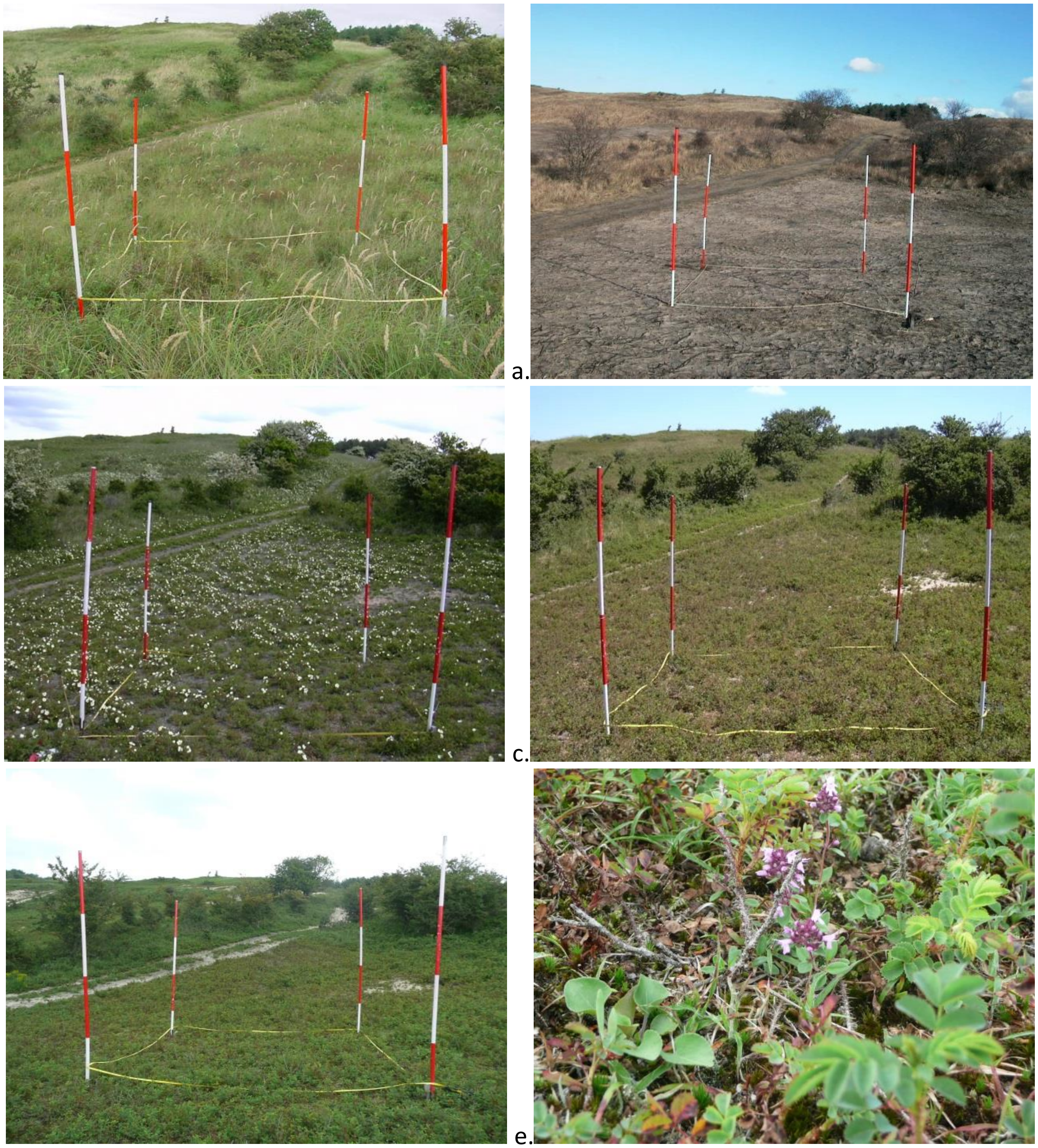
Westhof, V., Bakker, P.A., Leeuwen, C.G. van, Voo, E.E. v.d., 1970, Wilde planten flora en vegetatie in onze natuurgebieden, deel 1. Vereniging voor behoud van natuurmonumenten in Nederland

Zoon, F., 1995, Biotic and abiotic soil factors in the succession of sea buckthorn, Hippophae rhamnoides L. in coastal sand dunes. Dissertation. Wageningen University

Online sources

RIVM, http://geodata.rivm.nl/gcn/, accessed 09-10-2013
PAS herstelstrategien http://pas.natura2000.nl/pages/herstelstrategieen-deel_ii.aspx
CBS PBL, Wageningen UR (2008) http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl1122-Areaalverandering-van-duinbiotopen.html?i=4-26

Appendix, Permanent quadrants in the AWD



a. b. c. d. e. f.

Fig 5. Permanant quadrants at the Rozenwaterveld in the Amsterdamse waterleiding duinen (AWD) where shallow sod cutting was applied, after vegetation of Taraxaco-Galietum very was overgrown by *Calamagrostis epigejos* and *Rosa pimpinellifolia.* a) before sod-cutting 2002 b) shortly after sod-cutting 2003 c) one year after sod cutting 2004 d) 2008 e) 2011 f) detail picture with target species *Viola rupestris* and *Thymus pulegioiges*. (Foto: Mark van Til)

Fig 6. Permanant quadrants in the infiltration area in the Amsterdamse waterleiding duinen (AWD) where shallow sod cutting was applied, after vegetation of Phleo-Tortuletum ruraliformis was overgrown by tall grasses *Calamagrostis epigejos* and *Elytrigia maritima*. a) before sod-cutting 2002 b) shortly after sod-cutting 2003 c) one year after sod cutting 2004 d) 2008 e) 2011 (Foto: Mark van Til)