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SAND STABILIZATION AND DUNE BUILDING

BY

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AND

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1974

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The views in this article are the authors' own.

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Contents

Preface

This report deals with the results of research into sand stabilization, principally the biological aspects, and dune planting.
The research was performed by a working group with the following members:

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Summary

The growth of dune vegetation can be stimulated by the application of suitable fertilizers. Newly planted seedlings and sparse vegetation on the sea dunes can be very much improved by this means, provided the quantity of windblown sand is not excessive.
Otherwise sand fences have to be constructed for stabilization purposes.
Marram grass and sand twitch can be sown successfully. Marram grass, Baltic marram grass, sand twitch and lyme grass can be cultivated.
With proper fertilization, cuttings can be taken in the autumn from stock planted in the spring.
Withered dune grasses can be mown. With proper fertilization a new, vigorous vegetation of suitable height can be obtained.
Sand dams and embankments of dredged sand can be sown with a selected seed mixture. Fertilization is recommended. The sand can be stabilized rapidly and satisfactorily by this method.
Dykes of drifted sand can be constructed more successfully if a few practical conditions are complied with.

1. Introduction

For a long time now, wind-blown sand has been trapped at various points on the Dutch coast and used to strengthen the sea defences.
In the near future extensive areas of land will have to be protected from blown and drifting sand accumulating as a result of engineering works being carried out in coastal

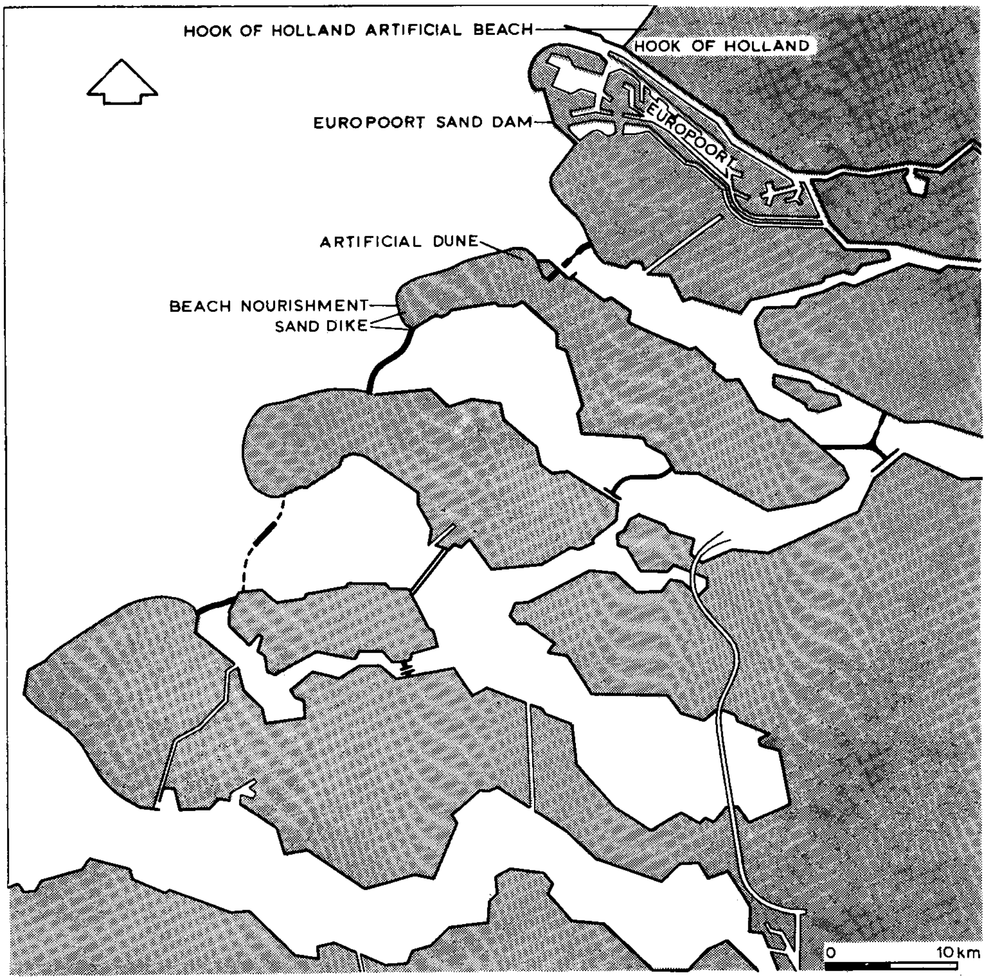


Figure 1. Sand stabilization measures in the coastal area in the Southern Netherlands

areas. The line of the barrier dams being built across the sea-arms of the south-western Netherlands under the Delta Project traverses at a number of points sand flats in process of draining and coastal plains (figure 1). Drifting sand blowing over the dams may interfere with traffic on roads built behind the dams and damage other amenities in the vicinity. Sand may also be loosened and blown about if established dune vegetation has to be disturbed in the course of the engineering works. This is unavoidable at the points where the Delta dams join the dunes on the islands and in places where the dunes have to be raised and strengthened.
Embankments made of dredged sand also need protecting as much as possible from drifting sand and against sand dispersal. Embankments of this kind have been built up along the southern harbour mole of Europoort and the northern part of the Delta dam across the Brouwershavense Gat (figure 1).
On the other hand it may be desirable, from the point of view of coastal defence or landscaping, to allow wind blown sand to accumulate at pre-determined points on the sand flats and so encourage the formation of dunes.
Finally, undesirable wind erosion sometimes occurs in the established dune areas if the vegetation is stunted or newly planted material has not yet grown sufficiently to act as a windbreak, or if the sand has been disturbed by members of the public walking over the dunes.
There are various methods of trapping wind-blown sand. This report deals with experience of several of them and with new research.
The measures selected depend on the quantity of drifting sand.
If the volume of wind-blown sand is relatively small, the sand can be induced to settle by introducing vegetation or by encouraging the growth of established or newly sown vegetation by applying fertilizers or binders. This constitutes interference with a natural biological process, and the biological aspects are discussed in Chapter 2. The results of tests using various kinds of artificial fertilizers and binders are reported in Chapter 3. Practical experience of sowing and planting dune vegetation is reported in Chapter 4.
If the volume of drifting sand is so great that all vegetation is choked, sand fences can be used. These are dealt with in Chapter 5.
Embankments built of dredged sand are a case apart. These are usually built so quickly that special measures are necessary to make sure the sand is stabilized immediately as the work progresses, regardless of the season. Recent experience of this work is described in Chapter 6.

2. Biological aspects

2.1 Ecological misgivings

A dune landscape consists of plant communities of diverse kinds, such as dune grassland (including sea-shore and shifting dune vegetation), the thickets of young and old dune valleys, brushwood, dune lakes and woodland. Since these stretches of country have great intrinsic value as nature reserves, we have reason to wonder whether it is biologically and ecologically justifiable to attempt to encourage beach and dune vegetation by applying artificial fertilizers and/or binders. After all, the environmental pollution all around us is partly attributable to the overenrichment of water and soil with plant nutrients (artificial fertilizers and organic waste, leading to eutrophication). Generally speaking, biological richness in our temperate regions (richness of species and the associated stability) is due to the establishment of cycles of matter of a *low* order in the course of vegetative succession. This is apparent if we compare the phosphate or nitrogen-containing ion content of the soil in natural plant communities with the content considered ideal for agricultural and horticultural purposes.
There are essential differences between pioneer vegetations (such as sea-shore vegetations) and the various types of dune vegetation growing to landward of them. In the course of time, the latter have developed in the direction of patently sophisticated structures, such as are to be found in woodland areas in the fixed dunes. The properties and structure of the living organisms are very different, and so is the environment (soil and bio-climate). Some of the more striking differences are shown in table 1 below.

Biotope: BEACH AND DUNES ADJOINING THE BEACH WITH VEGETATION	FIXED DUNE WOODLAND
Habitat: Low stability	*Habitat:* High stability
Soil: • very poor in organic material. • frequent, sudden changes in water content, especially in the surface layers.	*Soil:* • rich in mature humus. • balanced water content, gradual changes.

Biotope:

BEACH AND DUNES ADJOINING THE BEACH WITH VEGETATION	FIXED DUNE WOODLAND
• broad amplitude inorganic ion content with rapid changes.	• low inorganic ion content.
• very little adsorptively bound N and P.	• balanced and closed N and P cycle.
Climate:	*Climate:*
• great extremes and rapid changes in sunlight, air temperature, wind velocity and air humidity.	• moderate changes in light, air temperature, wind velocity, and air humidity, in particular in the lower air strata.
Plant life:	*Plant life:*
• specific pioneer characteristics, with few species.	• a large variety of species, each adapted to certain components of the complex habitat.
• plants specially adapted to this specific habitat and having special properties, such as: + ability to conserve water: deep-growing root system branching at different levels * high powers of suction * great capacity to transport nutrients * ability to close their pores if threatened with drying out. + salt balance: selective reaction to occasional sudden influx. + ability to withstand extremes of: * wind velocity * air temperature * wetting with sea spray	• adapted to the properties of that part of the habitat that they occupy, for example: + trees with sun and shade leaves, adapted to various levels of light for purposes of transpiration and carbon assimilation. + woodland shade plants: growth and flowering in the early spring before the leaves of the trees unfold + the various soil strata are occupied by specific root systems. + adapted to limited amplitudes specific to various localities of: * wind velocity * air temperature * composition of the atmosphere.
• in pioneer vegetations the emphasis is on the relation of the plant to his environment.	• in a mature woodland vegetation the biological inter-realtionships are to a high degree the determining factors.

Table 1. *Differences in the biotope of a beach supporting vegetation and a fixed dune woodland*

The essential feature of the sea-shore and shifting dune biotopes is an unstable habitat, as can be seen from the above table. To alter a factor in the habitat (such as the P and/or N content of the soil) is therefore – within physiologically determined bounds – a form of interference with is built in, as it were, in the natural ecological framework.
This is why the working group expressly confined its research to pioneer plants of beach and adjoining dunes. The results obtained can under no circumstances be taken to justify the application of these methods to non-pioneer communities, or forecasts concerning their application; therefore they can *not* apply to dune areas beyond the most seaward row of dunes.
The application of binders is no simple matter biologically, since the growth of the grass species used in the tests is actually stimulated by blown sand. Binders can however be useful in preventing seed and rhizomes being blown or washed away, in other words when a vegetation is first establishing itself.

2.2. Dune forming plants, a brief description

With the one exception of Tamarix, the plant species chosen for the tests were those which naturally act as sand binders along our coasts. They are at home in our coastal areas and are therefore adapted to the sometimes extreme environmental factors prevailing there. A brief description follows (figures 2a to 2g).

Sand Twitch – *Elytrigia juncea* (Dutch: Biestarwegras)

Geographical distribution: the coasts of the whole of Europe, North Africa, Asia minor and America.

Ecology: forms primary dunes if sufficient sand is transported by the wind. Can tolerate inundation with sea water for a considerable time (withstands up to 6% NaCl).

Habitat: embryonic dunes on the sea-shore and shifting dunes.

Description: perennial. Creeping rhizomes with runners and upright stems (30 to 60 cm) forming bluish green loose clusters.
Leaves 10 to 35 cm long, up to 0.8 cm wide, upper surface with close parallel rubs and many rows of short hairs. Sheath without auricles, overlapping; the ligule, 0.5 to 1 mm long, is membranous and truncated. The leaves curl inwards in dry conditions.
Flower: spike, 5 to 15 cm long, 0.7 to 1.2 cm wide, green, in two rows, rigid; axis of the spike very brittle.

Marram Grass – *Ammophila arenaria* (Dutch: Helm)

Geographical distribution: Europe, Mediterranean, North America.

THE GRASS PLANT

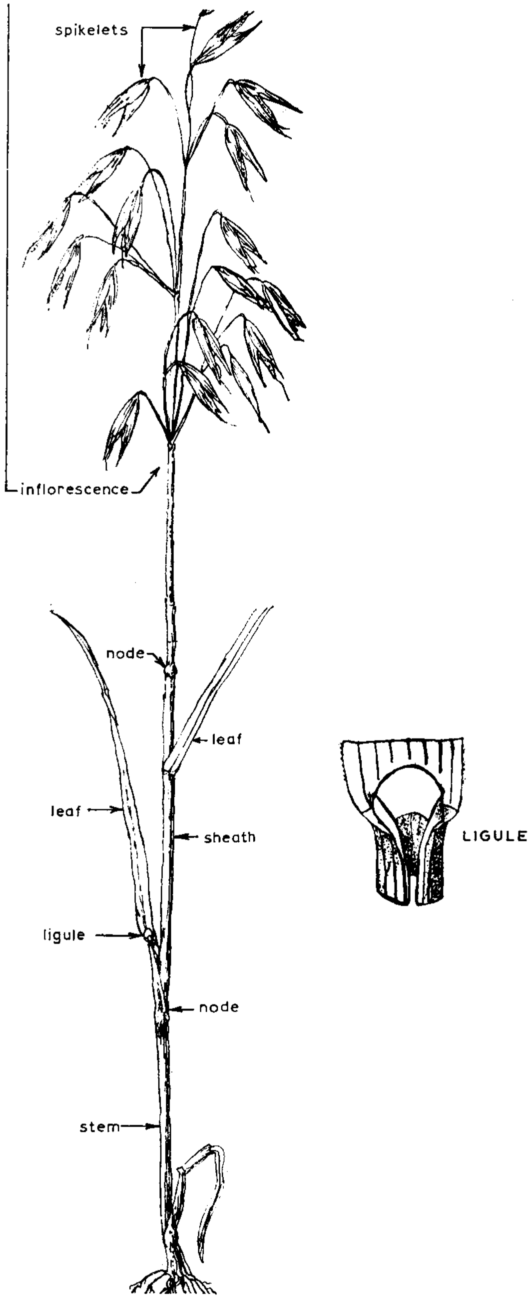
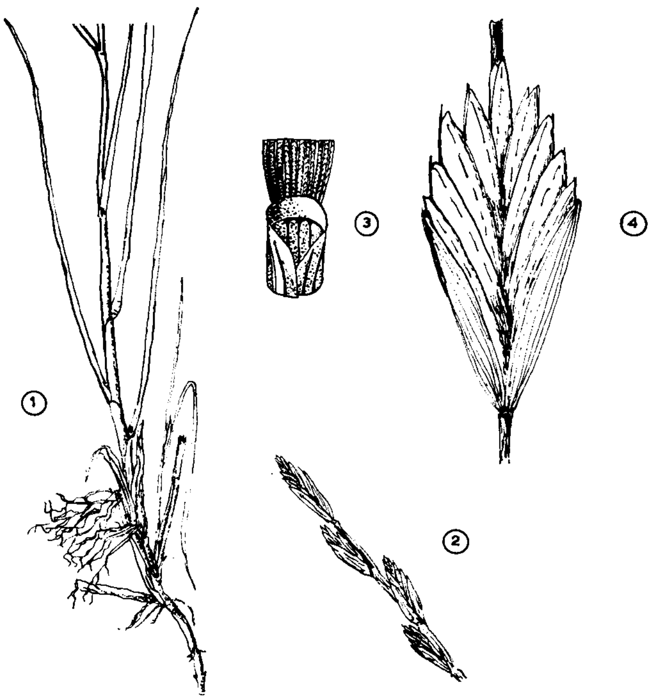


Figure 2a to g. Characteristics of dune forming plants

SAND TWITCH
(elytrigia juncea)



1 GENERAL VIEW
2 INFLORESCENCE (spike)
3 LIGULE WITH BEGINNING OF LEAF
4 SPIKELET

Figure 2b.

Ecology: An excellent dune builder in places which are not flooded by seawater during the vegetation period (salt tolerance up to at most 1% NaCl). Achieves optimal vitality in an abundance of wind-blown sand.

Habitat: Shifting dunes, but also futher inland in the fixed dunes in places where the sand is to some degree mobile.

Description: perennial. The strong rhizomes form vertical roots close together creating compact clusters, 60 to 100 cm high, light green in colour. Vegetative reproduction by means of long horizontally creeping rhizomes which form shoots at the nodules. Leaves up to 60 cm long, up to 0.6 cm wide, with short hairy veins protruding on the

MARRAM GRASS
(ammophila arenaria)

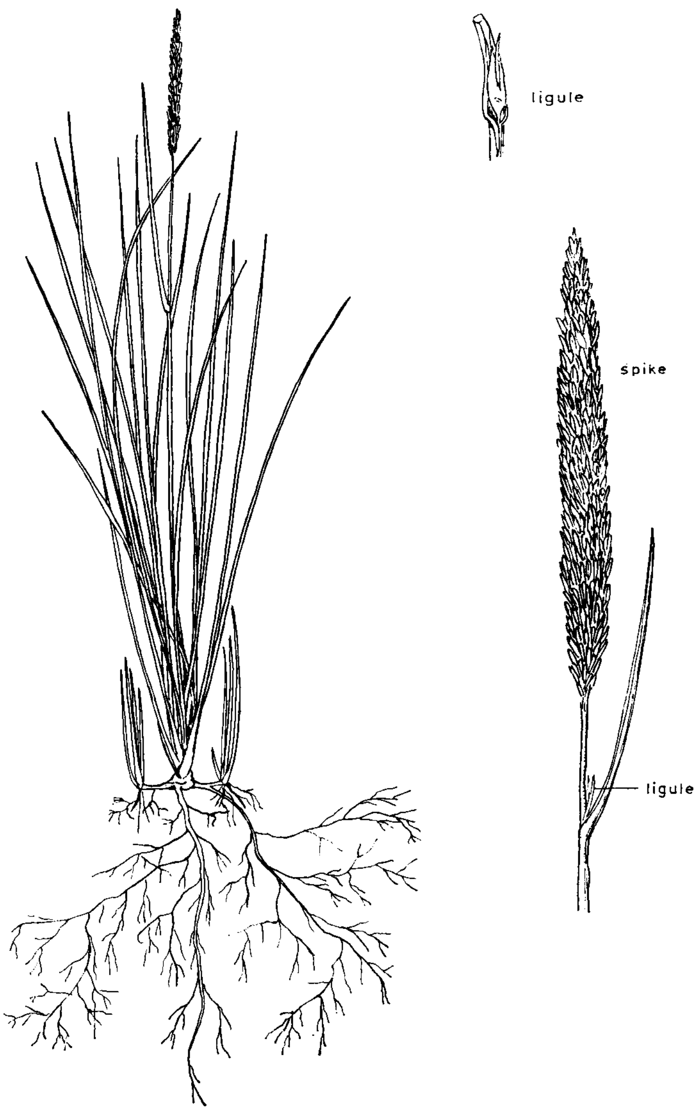


Figure 2c.

upper surface; the lower surface is smooth. Sheath smooth, overlapping, ligule up to 3 cm long and split at the top. Leaves mostly rolled; unrolled only in very wet weather.

BALTIC MARRAM GRASS
(ammocalamagrostis baltica)

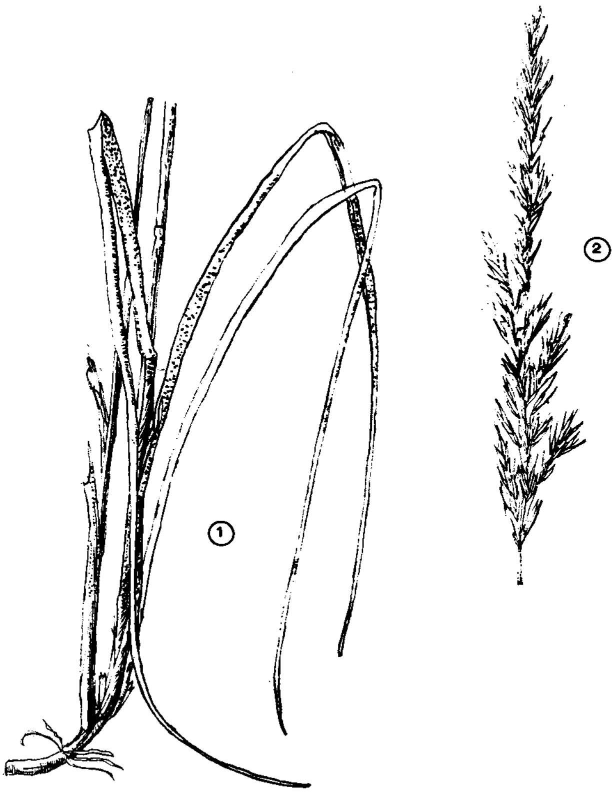


Figure 2d.

Inflorescence: spike-like panicle, 7 to 22 cm long, 1 to 2.5 cm wide, straw-coloured, compact, cylindrical.

Baltic Marram Grass – *Ammocalamagrostis baltica* (Dutch: Noorse Helm)

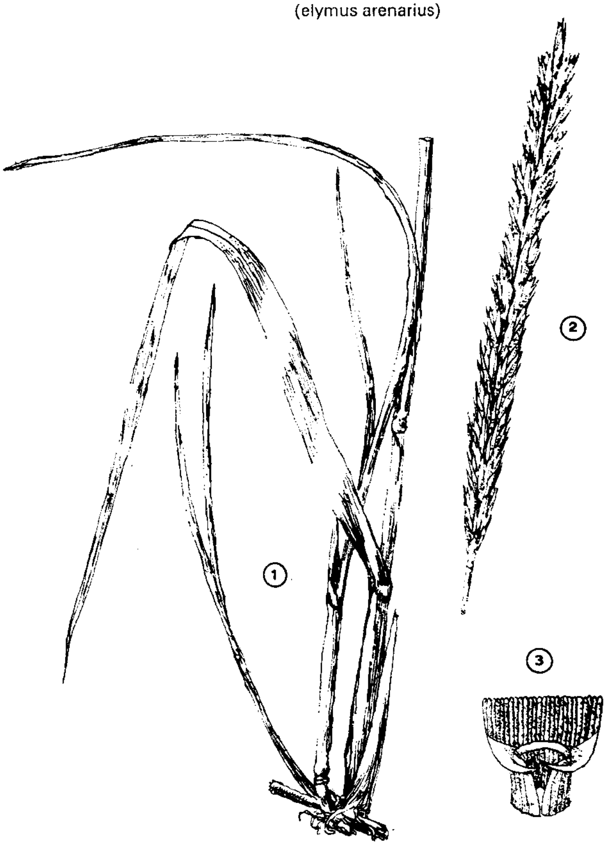
Geographical distribution: North Sea and Baltic coasts; Central Russia.

Ecology: the same as for Marram Grass, The plant excels because of its strong growth, but is sterile.

Habitat: This hybrid (a cross between Marram Grass and Wood Smell – reed) is

LYME GRASS

(elymus arenarius)



1 GENERAL VIEW
2 INFLORESCENCE (spike)
3 LIGULE WITH EARS; BEGINNING OF LEAF

Figure 2e.

found in the Netherlands mostly in the Wadden Sea area; on Voorne it is common in the shifting dunes, especially north of Rockanje.

Description: perennial. Growth as Marram Grass, but more robust. Dark green compact clusters up to 150 cm high are formed, which spread vegetatively by means of horizontal runners. Leaves up to 60 cm long, up to 0.7 cm wide. The upper surface with a clearly protruding rib, the under surface keeled. Sheath smooth and stiff; ligule up to 2.5 cm, split at the top. Leaves usually flat.
Inflorescence: panicle, 13 to 25 cm long, 1.7 to 3 cm broad, often tinged with purple, structure looser than in Marram Grass, lobate.

SEA BUCKTHORN
(hippophaes rhamnoides)

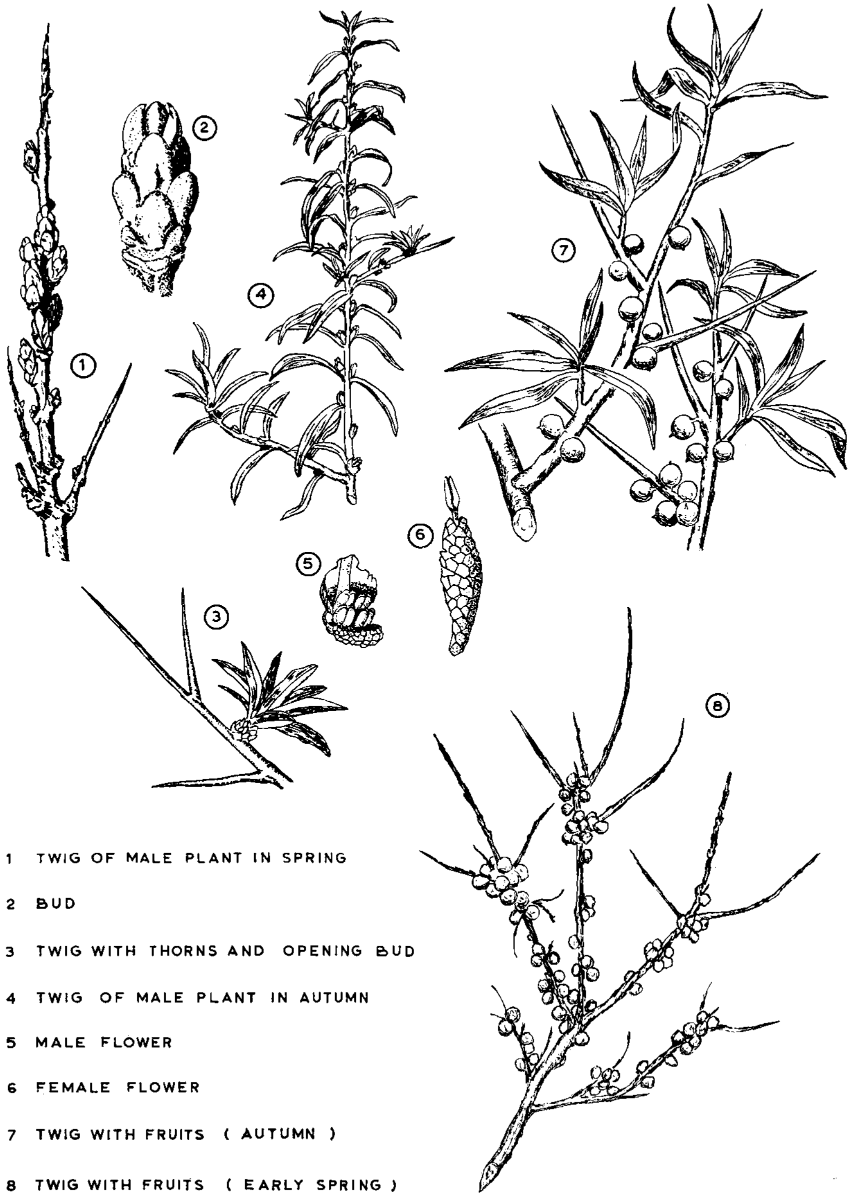
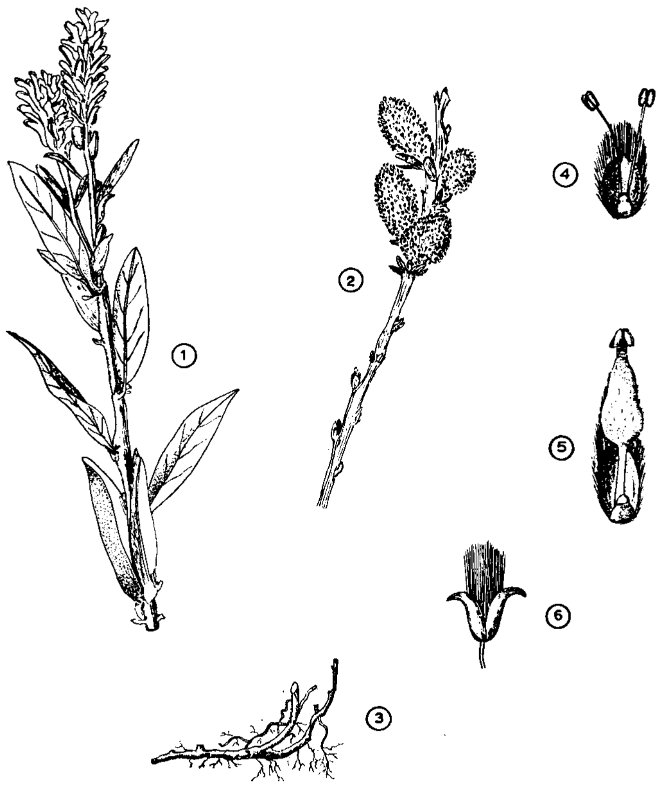


Figure 2f.

CREEPING WILLOW
(salix repens)



1 TWIG WITH FEMALE CATKINS
2 TWIG WITH MALE CATKINS
3 ROOTSTOCK
4 MALE FLOWER WITH BRACT
5 FEMALE FLOWER WITH BRACT
6 FRUIT CAPSULE

Figure 2g.

Lyme Grass – *Elymus arenarius* (Dutch: Zandhaver)

Geographical distribution: Central and Northern Europe, Siberia, North America.

Ecology: strong, robust grower and sand binder with a high salt toleration (up to 12% NaCl), but clearly sensitive to the wind. Useful for binding sand on the leeward side, provided there is plenty of drifting sand; moderately useful on the windward side.

Habitat: Shifting dunes all along the whole of the Dutch coast.

Description: perennial. The sturdy growth of the stout rhizomes, forming nodules,

produces large blue-grey-green clusters 60 to 150 cm high, which spread vegetatively by means of horizontal runners.
Stem stiff and upright, thick, smooth, and glabrous. Leaves: up to over 60 cm long, more than 1 cm wide, glaucous. Upper surface of the leaf rough due to slightly raised veins, the under surface smooth. Sheath smooth, ligule very short, sometimes measuring as little as 0.1 cm.
Inflorescence: light green spike, 15 to 35 cm long, 1.5 to 2.5 cm wide, with a stiff, upright stalk.

Sea buckthorn – *Hippophaë rhamnoides* (Dutch: Duindoorn)

Geographical distribution: Europe, Asia.

Ecology: A shrub inhabiting both dry and damp places in the dunes, occurring as soon as most of the sand in the shifting dunes has been stabilized by Marram Grass vegetations. Sea buckthorn vegetations promote the formation of humus due to their considerable biological mass.

Habitat: Common in the Dutch dunes, both in the shifting dunes and in the fixed dunes immediately adjoining them landward.

Description: a very thorny shrub. Leaves grey-green, lanceolate, up to 6 mm long, on short stalks. The underside clotted with white or grey scales, Fruit orange to light yellow. Spreads vegetatively by means of underground runners. The roots have nitrogen-binding nodules. Only the native coastal form (variety *maritima*) is suitable for dune plantation, and not the variety *fluviatilis*.

Creeping Willow – *Salix repens* (Dutch: Kruipwilg)

Geographical distribution: Europe, Asia.

Ecology: A dwarf shrub able to withstand some sand drifting, generally found in damp places; deep-growing roots in dry places.

Habitat: Common in the dunes, on marshy heathland and sandy soils.

Description: dwarf shrub 0.1 to 1 m high which spreads vegetatively by means of underground or surface runners. Leaves: oblong-lanceolate, up to 3 cm long; under surface white or grey, with silky hairs; the upper surface hairs are almost or entirely absent.
Catkins: stalks short, the male catkins egg-shaped to short cylindrical (1 : 1 to 2), the female very variable in shape (1 : 1 to 4).

Elder – *Sambucus nigra* (Dutch: Vlier)

Geographical distribution: Europe, North Africa, Western Asia.

Ecology: prefers places where fresh organic material (such as bird droppings) decomposes rapidly.

Habitat: The landward side of the shifting dunes, dunes lying further inland, and the edge of dune thickets and woods, etc.

Description: shrub, varying in height from 2 to 5 m.
Leaves: pinnate, leaflets 5 (sometimes 3 or 7); leaflets eliptical, dentate dull-green.
Twigs filled with white marrow.
Inflorescence: an umbel with white, stellate flowers.
Fruit: a black berry, 6 to 8 mm in diameter.

Tamarisk – *(Tamarix ssp)*

Shrub from Southern Europe. Leaves filiform. Height 2 to 3 cm. Can tolerate a salt sea wind and can withstand occasional flooding by seawater. This shrub is not native and is often planted in this country for decorative purposes. Its ability to spread by means of underground runners might make the plant suitable for use as a sand binder. If it is to be used in a nature reserve, so let us not forget that it is not a native species.

2.3. Dynamics of dune vegetation

Fixing dunes is a never ending process of harmonisation of abiotic and biotic factors. The dynamics of the dune building plant are expressed in its behaviour, form, structure and growth which are fully adapted to the external conditions prevailing in the place where it grows. Germination and the growth of the seedling, the establishment of introduced root stock, the reaction of the growth process to drifting of sand, or erosion, flowering and setting of fruit, and the ability to maintain vital functions under rapidly changing and extreme conditions (such as absorbing water where the soil water content is very variable, ion absorption where the ion concentration in the soil water is very variable, carbon assimilation and transpiration) form one harmonious whole. A feature of this is a wide range of functions, according to a specific pattern in the case of each of the species concerned.
The part played by grasses in dune building begins on the sea-shore, with the establishment and growth of sand twitch (Elytrigia juncea). The limit of dune formation and dune vegetation lies where any substantial erosion, re-modelling and sedimentation cease. The position of the limit depends on storm tide levels which may cause erosion at the base of the dunes, and on the slope and width of the beach.
The following data on the limit of spontaneously growing sand twitch in very wide beaches were assembled by VAN DER STEGE (1965) and the working group.

Beach	Width of the dry beach (mean high water line - dune base)	Slope of beach (mean high water line - dune base)	Height of vegetation limit above mean high water line
Goeree (Kwade Hoek)	120 m	1 : 155	0.65 m+
Westplaat (Voorne)	195 m	1 : 245	0.70 m+
Voorne (Oostvoorne)	200 m	1 : 300	0.55 m+
Rottumerplaat (Centre)	200 m	1 : 600	0.50 m+
Rottumerplaat (East)	210 m	1 : 645	0.45 m+

The following data were assembled by the working group, for marram grass and lyme grass, in steeper, narrower beaches.

Beach	Width of beach (mean high water line - dune base	Slope of beach (mean high water line - dune base)	Height of vegetation limit above mean high waterline
Zeeuws Vlaanderen (Cadzand)	40 m	1 : 25	2.50 m+
Walcheren (Oost-Kapelle)	50-60 m	1 : 25	2.50 m+
Goeree	40-60 m	1 : 25	2.70 m-3 m+
Voorne (Rockanje)	50 m	1 : 40	2.70 m-3 m+

We find the sand twitch dunes lying nearest the sea on flat, wide beaches; these mark the limit of vegetation, but if these beaches are intensively used by the public the sand twitch will die off and the limit of vegetation will lie further landward. On narrow steep beaches marram grass and lyme grass are found in the same quantities as sand twitch at the most seaward limit of the vegetation.

Even when the vegetation has become permanently established it does not necessarily bring about the formation of dunes, as witness the extensive sand flats with low ridges covered with sand twitch on the sandbanks in the Wadden and Delta districts. These embryo dunes remain low because only a small part of the blown sand is trapped amongst the sand twitch with its fairly open, relatively low growth. The accumulation of sand is small. If the accumulation reaches a height above mean high water level such that other dune building plants can establish themselves, the growth becomes thicker and the quantity of fixed sand increases. A hinterland high enough not to be flooded is just as essential as vegetation if dunes are to be formed. If there is no such hinterland the flats may be flooded during storms, which raise the water level considerably, and the vegetation with its accumulated sand may be damaged by waves and currents.

If a row of dunes does emerge, the vegetation will help it to increase in height and width on the seaward side.

Sand twitch may establish itself by the germination of seed or by the growth of root stocks washed up on to the sand. Seed of sand twitch, marram grass and lyme grass may germinate in the autumn shortly after ripening. But the time before the onset of winter is too short for most of these seedlings to develop far enough to be able to withstand the winter and a large number of them succumb.

Seedlings that germinate in the spring have considerably better prospects. They do not grow to their full size during their first summer and consequently are still recognisable as young plants in the following year. Even as a seedling, sand twitch can withstand up to 6% of salt in the ground water. As a sand binder it plays an important part in creating the first embryonic dunes, on those parts of the beach lying within reach of the ground water.

A feature of the seedling is a root system with many branches; the plant tillers freely in the seedling stage. In the next phase of its life the plant forms horizontally creeping stems or roots as the case may be. If they grow above ground the growth of what is then the stem is virtually unlimited; leaves sprout from the nodes; the stem does not become woody. The flower spike forms at the tip of the stem. Below ground, a creeping root stock forms with a tendency to become woody. Shoots and roots appear at the nodes, and a few roots between the nodes. Root hairs are found at various depths, down to the layers a few centimetres above the ground water, an optimum being in the layer between -5 en -20 cm. The roots do not penetrate surface sand (roughly between 0 and -5 cm).

The growth form varies according to the distance from the tideline and the height in relation to it. Close to the tideline the plants are low growing, sterile and with a great many shoots close together. In this stunted growth 2 to 8 shoots per node are found; the roots lie partly on top of the sand. When the plants are higher up, the root stocks grow horizontally in the sand and do not usually have more than 4 shoots per node; These plants are clearly capable of producing flower spikes.

The sand twitch breaks the velocity of the wind so that sand will be deposited on the leeside of the plants. The sand-twitch dune begins to grow. A peculiarity of the plant is that it grows with the dune, as it were, since the presence of the newly deposited layer of sand stimulates the root to develop upwards (figure 3). In this way the covering of sand twitch can be said to keep pace with the dune formation, but only until such time as the conditions of the habitat no longer entirely suit the sand twitch and the conditions for marram grass are approached. The vitality of the sand twitch declines; marram grass begins to establish itself in its initial phase.

It sometimes happens, however, that if the direction of the wind changes, sand is blown away from between the sand twitch plants. The exposed roots can then temporarily continue to grow on the surface of the sand, and form rootlets and shoots, thereby protecting the emerging dune from further erosion.

Marram grass establishes itself through the germination of seeds. It is true of these plants too that the spring seedlings have a better chance than those which germinate in autumn. In places where marram grass is already established, the plant cover is strengthened and extended by the formation of shoots and roots on runners.

In the marram grass the shoots grow mainly vertically upwards into the heaped up sand, often branching intensively in the process. The result of this is that the clusters of marram grass occupy an ever larger area. It is not uncommon for the area originally occupied to be increased by a factor of 10 to 20.

The roots are formed in the buds of the shoots. The root system is found to be differently designed according to the nature of the soil and the age of the plant. The first development of the root system which takes place in the seedling or in the newly emerging bud as the case may be, exhibits secondary roots: a fairly large number of equal-sized roots grow downwards from one central point. This is followed at a later stage by a clear and far-reaching horizontal extension of the root system, in particular in the deeper layers. The roots that then develop and run horizontally are bundled together in layers, if the soil is in horizontal layers, so that the water and ion-absorbing layers accessible to the roots alternate with layers of sand and nothing else. If the soil is of a more or less homogeneous structure, the horizontal roots are found at arbitrary depths.

This pattern of roots is to be regarded as a sophisticated adaptation of the plant to its habitat: after a heavy shower the water gradually sinks downwards, while the soil in the upper layer can dry out very quickly. At various levels, according to the situation of the moment, the plant can therefore obtain capillary water from the ground by suction and absorb the ions dissolved in it. By these means the plant is to a great extent independent of the ground water.

Drifting sand is sometimes blown against the marram grass in large quantities. The plant reacts violently to this stimulus by putting out shoots that branch upwards. New layers of horizontal runners form in a layer of drifted sand so that the roots penetrate right through it.

Marram grass is therefore an excellent sand binder and dune former. Although the amplitude of marram grass as regards its behaviour in drifting sand is considerably greater than that of sand twitch, the salt tolerance of marram grass is considerably lower (in their natural state this is a maximum of 6% for sand twitch and 0.8% for marram grass). Sand twitch can therefore occupy lower sites at the base of the dune.

In his thesis entitled 'Organogene Dünenbildung', VAN DIEREN (1934) raised the point that the minimum amounts of nitrogen present in natural marram grass soils might be a limiting factor in the growth of the plant. Figures relating to these nitrogen contents were given later by DE VRIES (1961) (Vlieland). They do indeed prove to be very low. The nitrogen values for the dunes of Voorne are also minimal (figure 4). According

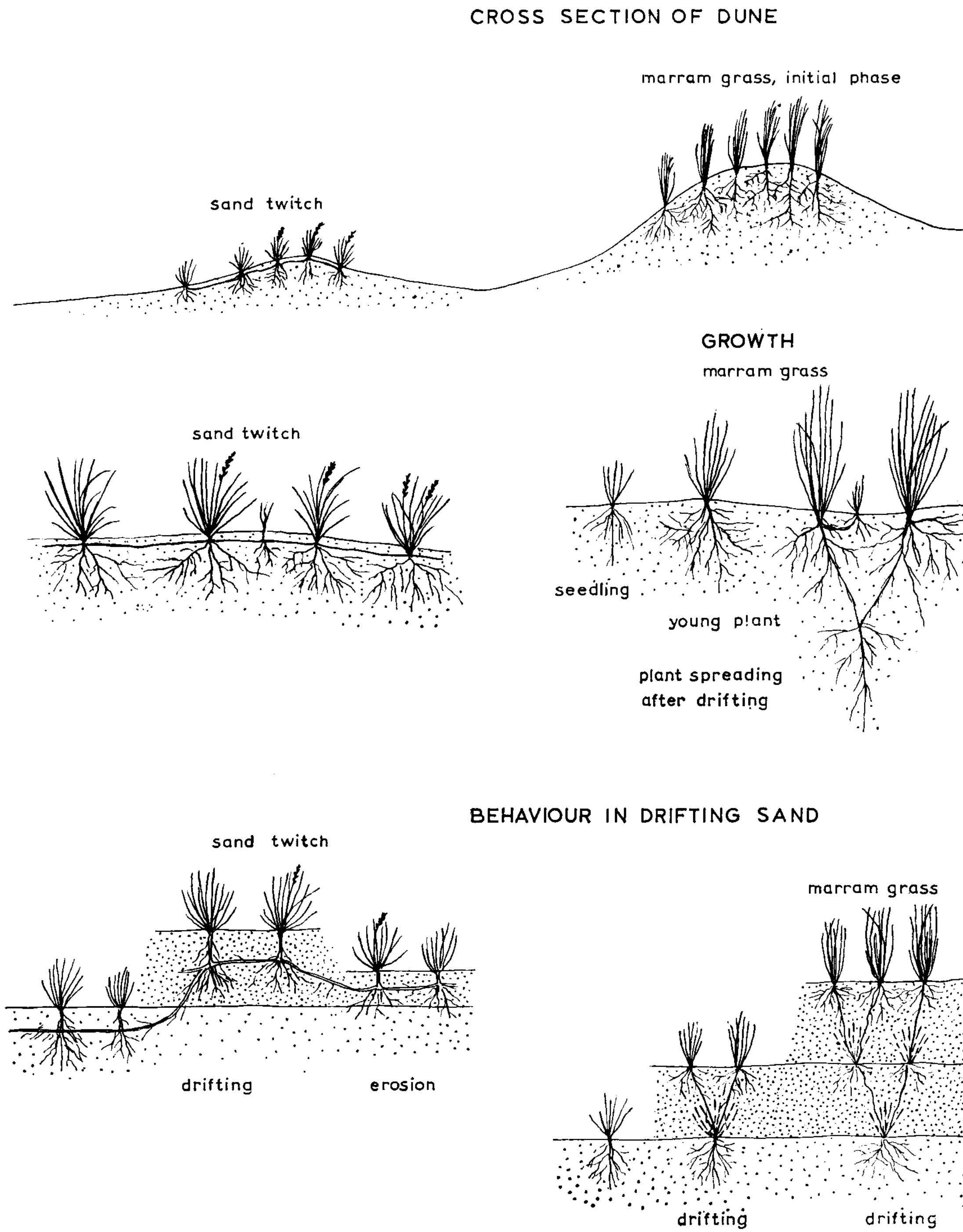
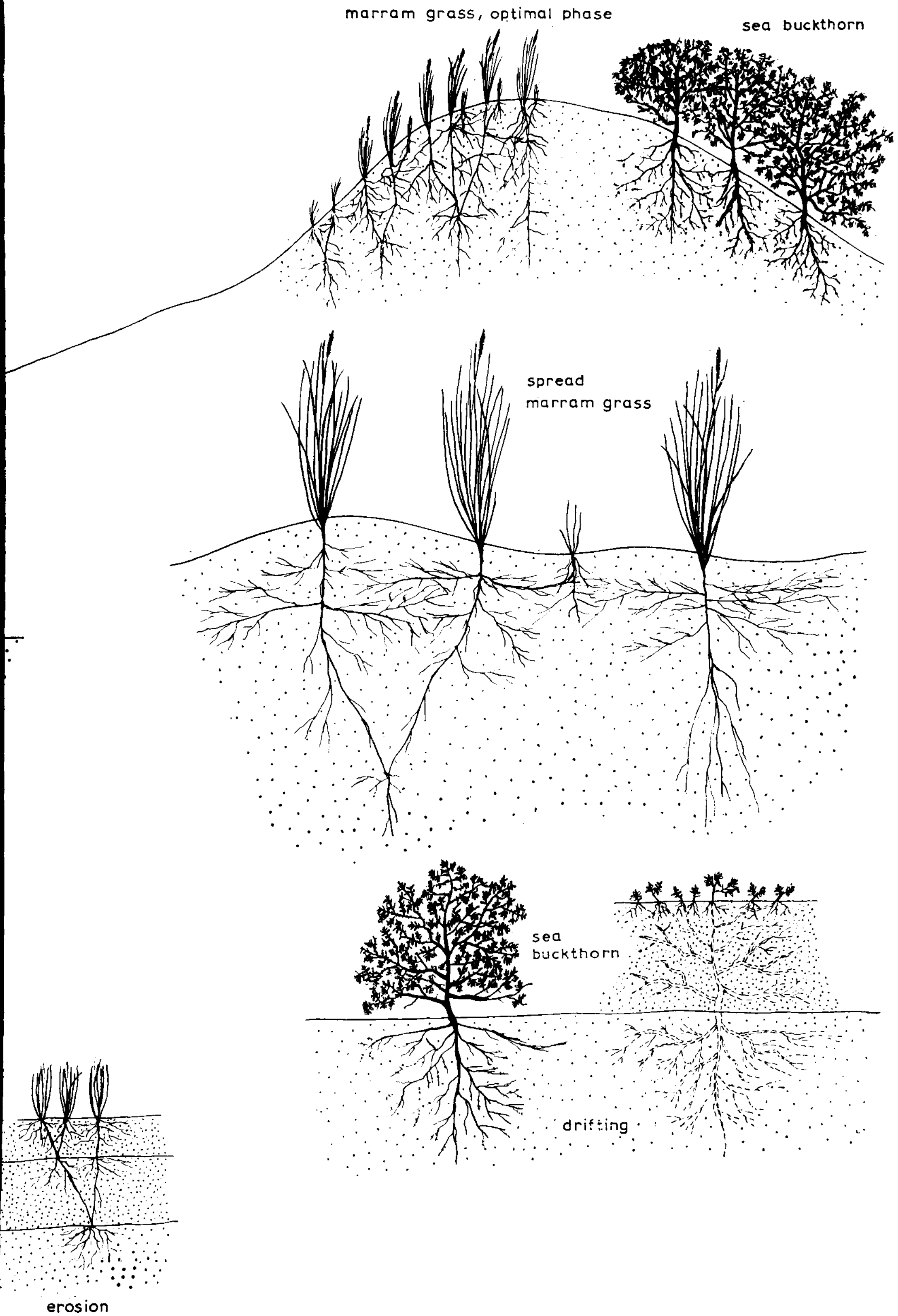


Figure 3. Cross section of dunes adjoining beach



marram grass, optimal phase
sea buckthorn
spread
marram grass
sea
buckthorn
drifting
erosion

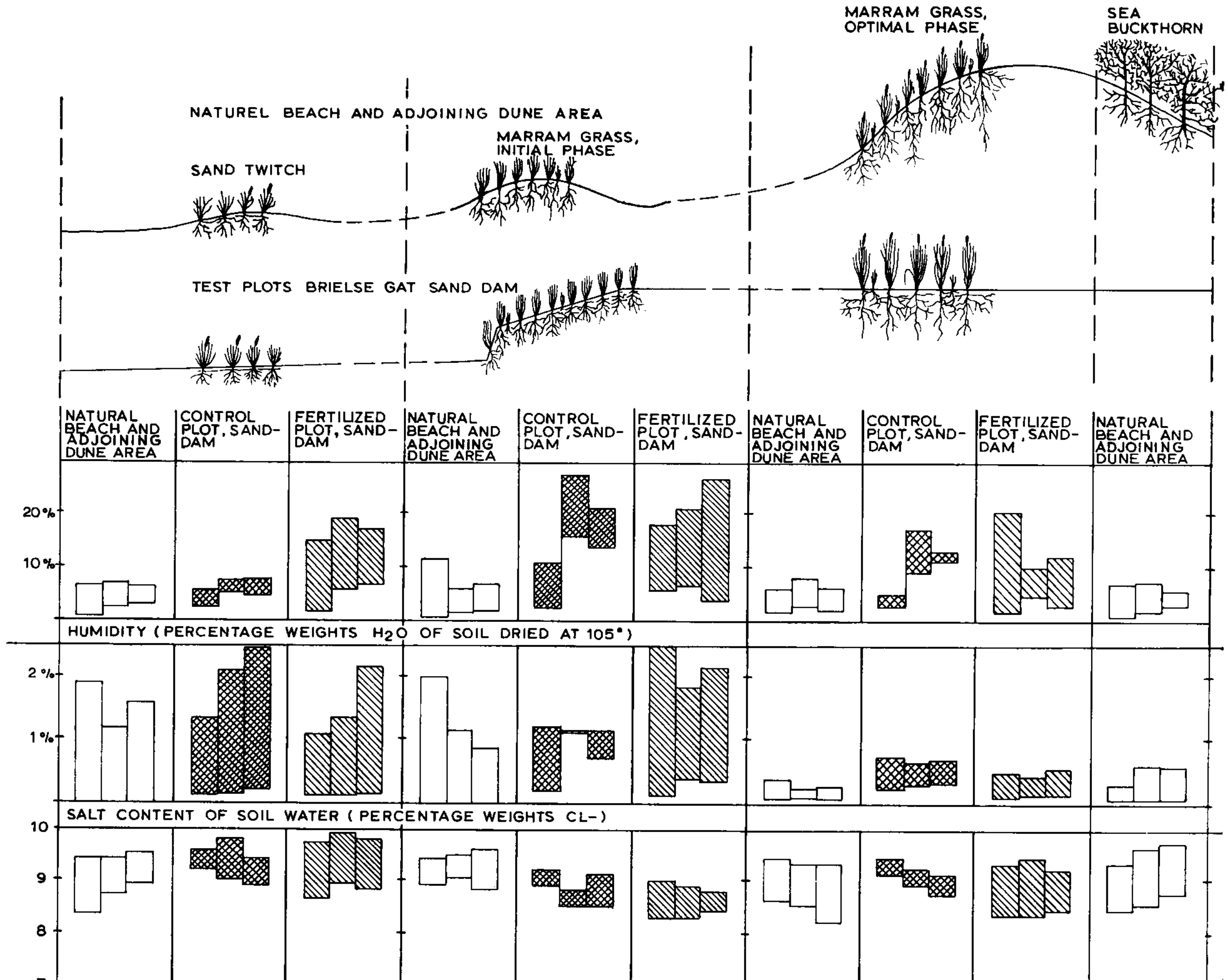
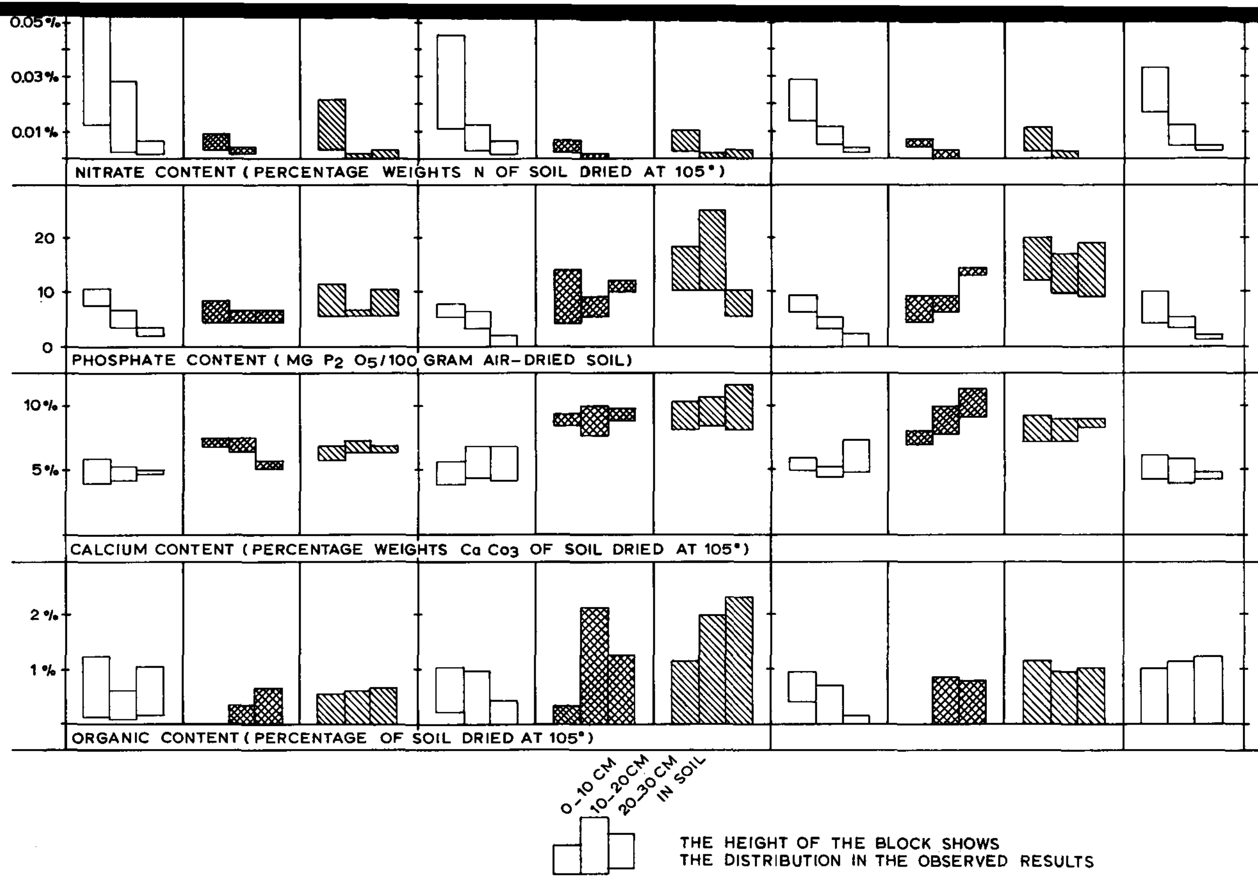


Figure 4. Parameters of soil chemistry on the beach and dune; a natural beach and a control and test plot on the Brielse Gat dam


0.05 %
0.03 %
0.01 %
NITRATE CONTENT (PERCENTAGE WEIGHTS N OF SOIL DRIED AT 105°)
20
10
0
PHOSPHATE CONTENT (MG P2 O5/100 GRAM AIR-DRIED SOIL)
10 %
5 %
CALCIUM CONTENT (PERCENTAGE WEIGHTS Ca Co3 OF SOIL DRIED AT 105°)
2 %
1 %
ORGANIC CONTENT (PERCENTAGE OF SOIL DRIED AT 105°)
0-10 CM
10-20CM
20-30 CM
IN SOIL
THE HEIGHT OF THE BLOCK SHOWS
THE DISTRIBUTION IN THE OBSERVED RESULTS

to this argument, raising the nitrogen content of the soil through artificial fertilization, as was done in the tests with which this report is concerned, should have a clearly positive effect. This effect was indeed one of the most obvious results of the test. This is an experience that is very valuable in the practice of binding sand on sand embankments, and one which also contributes to our knowledge of the specific life pattern of marram grass.

It must be pointed out, however, that the tests showed that the vegetative growth was stimulated to an exceptional degree by fertilization with large quantities of N and that under these circumstances no flower spikes were formed in the long run. Great flexibility seems to be a feature of marram grass with regard to the nitrogen factor (bound N).

The above outline clearly shows that marram grass can act as an effective shifting dune plant and sand binder in many phases of dune formation, and therefore in geomorphologically very different situations. If the habitat conditions continue to vary within the tolerances valid for marram grass, it is safe to say that the growth will become all the more vigorous the greater the amounts of drifting sand. Marram grass vegetations of varying vitality will be found in the shifting dunes successively from the seaward to the landward side.

Where marram grass establishes itself on slightly raised dunes already covered with sand twitch, the growth of dune and plant will be more restricted due to the modest quantities of sand than in higher, exposed sand hills to seaward, especially if the latter are bounded by a wide dry beach. In such cases very large quantities of sand can be blown, resulting in intensive growth of marram grass and dune. The suboptimal vitality of the marram grass plants in the initial phase of their development is also evident from the small number of flower spikes. These can become very plentiful in groups of marram grass in their optimal phase, in places with a great deal of drifting sand.

Further inland, in natural dune areas, the quantity of sand brought in by the wind becomes smaller, and the vitality of the marram grass decreases. Shortage of nutrients limits the development of dune grasses. If the soil already contains some humus, other plants can establish themselves among the stunted dune grasses and in the long run will replace them.

Sea buckthorn is the most important plant in this respect. If the nutrient content of the soil is very low, the vegetation will only develop with difficulty and a thick covering of plants will not be able to establish itself. The vegetation in these zones is vulnerable. The results of the sparse vegetation is dispersal of sand and the formation of wind hollows behind the shifting dunes, and this has a considerable effect on the dune relief. If sand is blown about behind the shifting dunes it is difficult to stabilize, because the fixed dune plants grow relatively slowly. This may mean that it is a long time before a good plant cover is achieved which will stabilize the sand.

Sea buckthorn establishes itself in natural dune areas by germination of seeds, which are deposited on the surface of the sand after passing through the digestive tracts of birds. The seedlings can withstand extremes of habitat factors, but they cannot tolerate brackish or salt water. Even the sea buckthorn growing in the outer dunes forms runners at a depth of between 5 and 15 cm, from which shoots and roots appear. In this way the bushes become thicker and in the long run the surface they occupy increases.

While sand- twitch ridges and marram- grass dunes are strikingly similar in their vegetation dynamics (to live in a world full of moving sand), the sea buckthorn presents a different picture. In its pioneer phase it forms bushes with many twisting branches more or less adjoining each other, and the roots are mostly to be found in the soil layer between −10 and −30 cm. In the places that sea buckthorn readily establishes itself, the ground level is about 140 cm underground. Sea buckthorn cannot stand being covered with blown sand nor being flooded with salt water; bushes buried under fresh sand become choked (see diagram). If sand is blown away from an established thicket, the exposed parts die off. If there are no subsequent disturbances, the surviving part can put out new shoots and the continued existence of the vegetation at that spot is assured. The function of the belt of sea buckthorn in the history of dune formation is not to bind blown sand, but to establish a new vegetation equilibrium. One of its features is that it takes the first step in the formation of humus in the soil (absorption of water and binding of mineral components essential to plant nutrition; nitrogencontaining ions and phosphates; moreover the nodules on the roots of sea buckthorn contain nitrogen-binding micro-organisms), and another is that it regulates the microclimate. Through the combination of these two factors, the way is opened for the establishment of numerous other plant and animal species and the succession, such as we find it in dry dunes, is thus introduced.

3. Stimulation of dune vegetation

3.1. Introduction

The development of a shifting dune vegetation can be stimulated by the application of artificial fertilizers after sowing and planting. The object of the research was to establish what combination of artificial fertilizers was the most suitable and how long the fertilizer should continue to be applied. Experiments were also made to see whether binders have a favourable effect on sown and planted dune grasses. Binders cause temporary adhesion of the sand grains on the soil surface, which is said to prevent the seed blowing away and the roots of the plants being laid bare, thereby preventing the plants from dying off prematurely. But the doubful point is to what extent substances are released from the binders which have an unfavourable effect on plant growth.
The research was performed on a test plot situated on the dam across the Brielse Gat (figures 1 and 5) which had been made of dredged sand. This area was chosen because the ground was sterile and without vegetation of any kind.
As fertilizers it was decided to use nitrogen, phosphorus and potassium, because it is known from the literature that dune grasses usually react favourably to these substances. The quantities applied and the combinations investigated are given in table 2.

Fertilizers	Dosage	Reference in this report
Nitrogen (Calcium ammonium saltpetre)	20 kg N/ha	N-20
	80 kg N/ha	N-80
Phosphorus (Superphosphate)	20 kg P_2O_5/ha	P-20
Nitrogen + phosphorus	20 kg N/ha + 20 kg P_2O_5/ha,	N-20, P-20
	80 kg N/ha + 20 kg P_2O_5/ha	N-80, P-20
Nitrogen + phosphorus + potassium salt	80 kg N/ha + 20 kg P_2O_5/ha + 20 kg K_2O/ha	N-80, P-20, K-20

Table 2. *Fertilizers applied*

Between the fertilized plots, control plots were planted where no fertilizer was applied. The test plots were 10 m wide. When the tests began there were three binders on the market. Two of them are bitumen emulsions, viz. COLAS made by Key & Kramer N.V. and Shell Sandfix.
The third product, UNISOL, made by the International Synthetic Rubber Company Ltd., Southampton is an emulsion on a synthetic rubber base.
The binders were applied on both sown and planted test plots, both fertilized and not fertilized.

3.2. Arrangement of test plots and research methods

The part of the dam used for the tests was finished in June 1966. Before laying out the test plots we waited until the water had drained sufficiently out of the dam and until the top layers of the soil had become considerably desalinated.
The test plots were laid out at the end of September 1966 in accordance with the plan shown in figure 5.
The whole test area was treated with a basic fertilization of N-20, P.20 at the end of September 1966 in order to improve the nutrition content of the sand in the last stage of the growing season of the plants. The test plots were fertilized on 22 March, 21 June and 18 September 1967 in accordance with the plan shown in figure 5. Test beds of 4 m^2 were staked off in the middle of the test plots for the botanical research, with the exception of the test plots for sown material, where beds 1 m^2 in size were made.
The effect of fertilization and the application of binders on the growth of the plants was established by reference to the following data:
- number of leaves;
- degree of coverage, i.e. the surface covered by the projection of the leaves on the ground;
- the height of a few clusters (height of vegetation);
- root depth of a typical cluster;
- width of a number of fully grown leaves;
- number of flower spikes in all eligible test beds (fertility); (the Baltic Marram grass forms spikes but they are sterile);
- the colour of the vegetation, which was established by comparing it with Caran d'Ache crayons.

The average and the standard deviation of the numerical values of the various properties in each bed were determined, and if possible the significance of the differences between the beds was determined by means of Student's t-test. A confidence limit of 95% was used to indicate the significance.

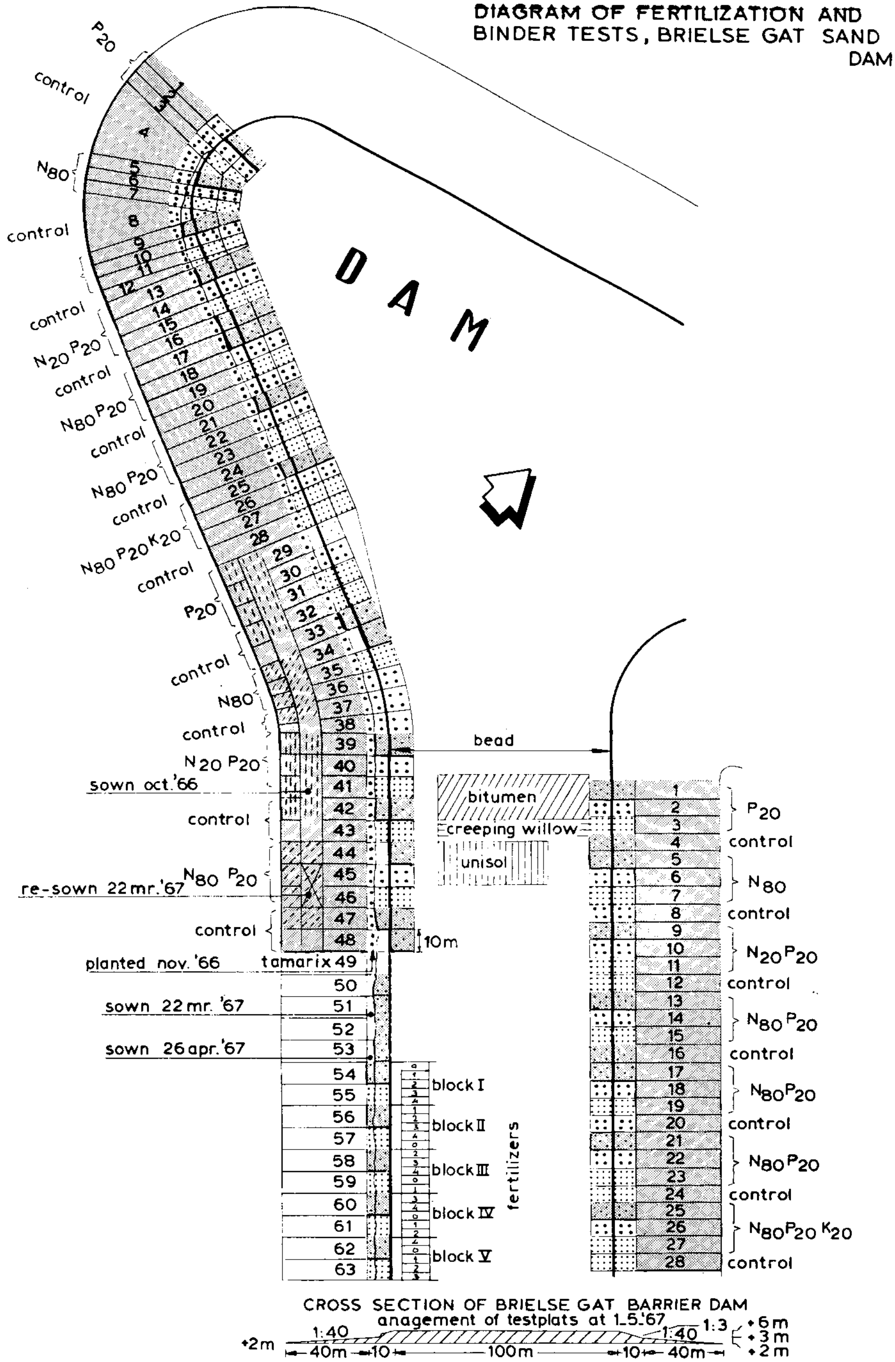
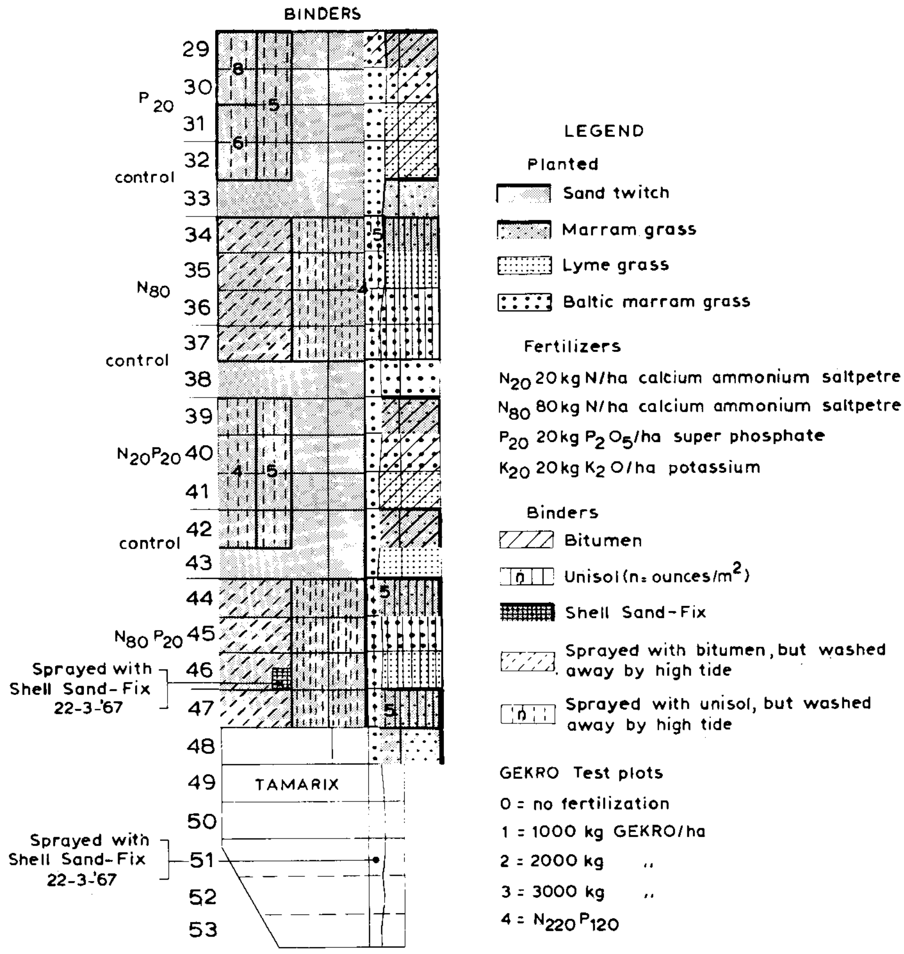


Figure 5a and b. Diagrams showing the fertilizers and binders used in the Brielse Gat sand dam tests



In the case of sand twitch, only the number of leaves and the degree of coverage were determined.

The determination of root depth was hampered by the inhomogeneity of the soil. Although it consisted mainly of sand, clay-layers and lumps of clay of varying sizes, shapes and thickness were present in some places. Normal root growth such as occurs in dune sand was therefore seriously disturbed.

A few beds on the north side were blowing bare at an early stage, so that sometimes results were obtained which would probably have been different without this factor. Lyme grass suffered especially from this, because of its initially very low degree of coverage. This was caused by the fact that too little material was planted and what there was was eaten by rabbits.

Table 3 shows the dates on which certain observations were made.

Date	15/4/67	1/6/67	15/6/67	1/7/67	1/8/67	1/9/67	15/10/67
Number of seedlings	S M	S M		S M			
Number of leaves	S L	M B	S L	M B	S M B L	M B	
Degree of coverage	S		S		S L	M B	
Height of vegetation				M B	L	M B	
Root depth							B M L
Fertility					M L		
Green colouring				B	S M B L		
Width of leaves				M B	L		

S = Sand twitch M = marram grass
B = Baltic marram grass L = lyme grass

Table 3. *Dates of observations in* 1967

3.3. Results

Sand twitch – *Elytrigia juncea*

Sand twitch seed germinated well and the plants grew satisfactorily. The effect of artificial fertilizers and binders on sown sand twitch could not be properly established because at the beginning of the test period a great deal of seed, many seedlings and large quantities of binder were washed away during a storm and also because of an exceptionally luxuriant vegetation of sea-rocket (Cakile maritima) in 1967, which greatly influenced the findings of the observations.

Planted sand twitch reacted best to fertilization with N-80, P-20 (figures 6 and 7). However, the net effect of fertilization on sand twitch is not great. What the plant needs above all is wind-blown sand. Indeed, the most thriving sand twitch plants were found on the most seaward side of the beach, where wind-blown sand was rife. Moreover, it was found that the fertilization of the sand twitch also encouraged the growth of thistles, so that the sand twitch was partly overgrown by thistles.

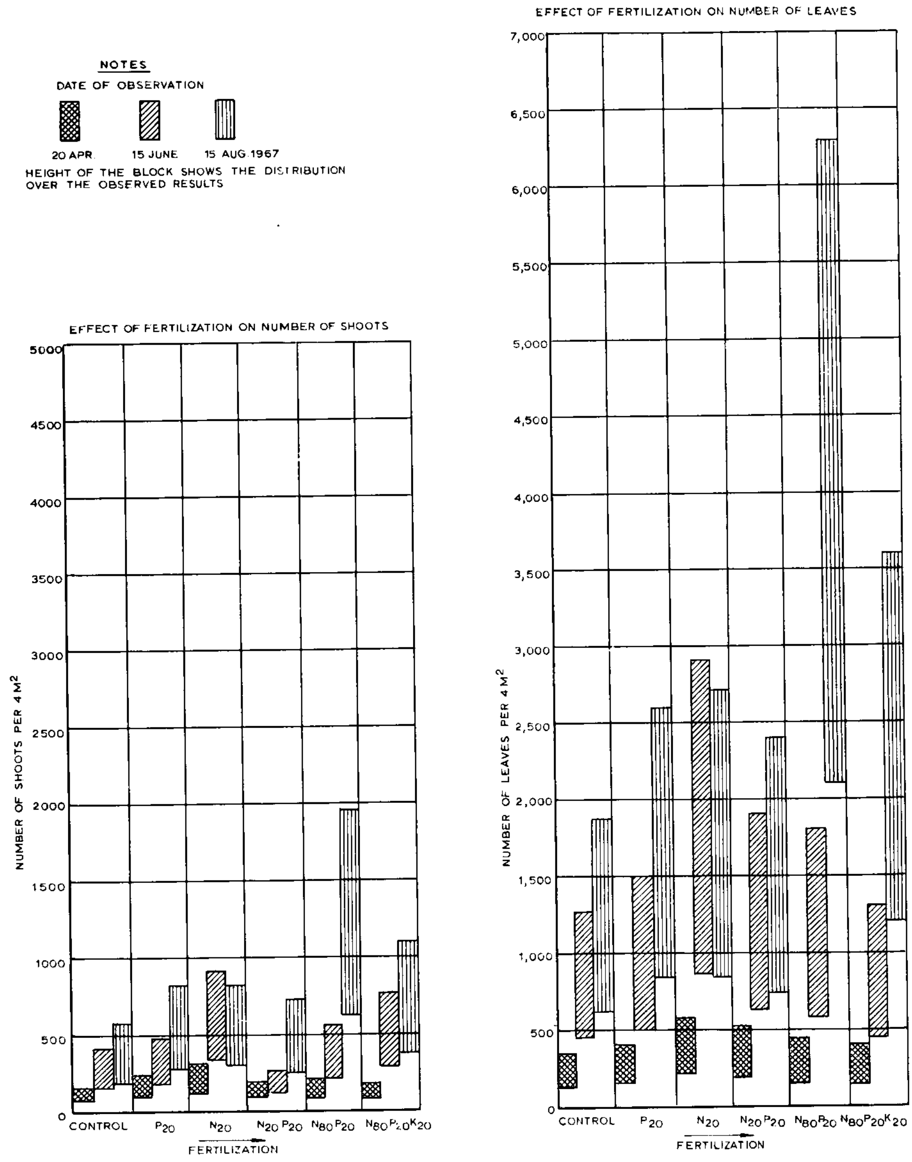


Figure 6. Effect of various fertilizers on the growth of sand twitch

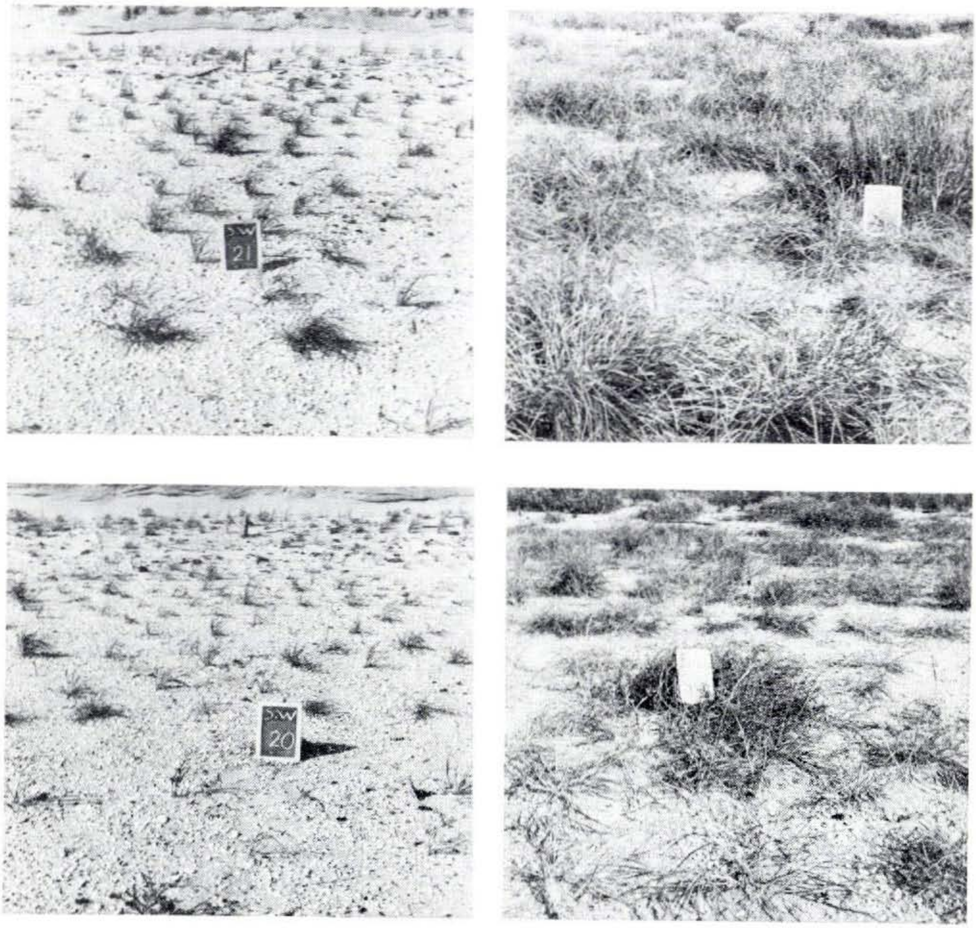
Marram grass – *Ammophila arenaria*

The marram grass seed, too, germinated well and the plant growth was satisfactory. On plots fertilized with N-80 and N-80, P-20 and treated with Unisol binder, the vegetation height was found to be twice as great and the degree of coverage about three

SAND TWITCH

FERTILIZED

NON FERTILIZED



8 JUNE 1967 — 22 NOVEMBER 1967

Figure 7. Comparison of fertilized and non-fertilized test plots of sand twitch

times as great as in the control plots. This is most probably attributable to fertilization with nitrogen.

In the planted marram grass, the N-80-fertilization proved to have a clearly positive effect on the number of leaves, the degree of coverage and the vegetation height (figures 8 and 9). The significance of the effect of the various fertilizers on the number of leaves of marram grass is shown in table 4a. The P-20 fertilization had little positive effect on growth.

Fertilizers	P_{20}		N_{80}		$N_{20}P_{20}$		$N_{80}P_{20}$		$N_{80}P_{20}K_{20}$		$N_{20}(P_{20})$		$N_{80}(P_{20})$		$P_{20}(N_{80})$		$K_{20}(N_{80}P_{20})$		$N_{60}(N_{20}P_{20})$	
Date	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9
Slope SS	*	*	*	*	+	+	+	+	+	+	*	*	*	*	*	*	o	o	o	o
Top SS	−	o	+	+	o	o	o	+	o	+	o	+	+	+	o	o	o	o	o	+
Top BS	−	−	o	+	o	+	o	+	o	+	+	+	+	+	o	o	o	+	o	+
Slope BS	o	−	o	+	+	o	−	+	−	o	+	+	−	+	−	o	o	o	−	o

Table 4a. *Effect of the various fertilizers on the number of leaves in marram grass*

Fertilizers	P_{20}		N_{80}		$N_{20}P_{20}$		$N_{80}P_{20}$		$N_{80}P_{20}K_{20}$		$N_{20}(P_{20})$		$N_{80}(P_{20})$		$P_{20}(N_{80})$		$K_{20}(N_{60}P_{20})$		$N_{60}(N_{20}P_{20})$	
Date	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9	1/6	1/9
Slope SS	*	*	*	*	+	+	+	+	+	+	*	*	*	*	*	*	o	−	o	+
Top SS	o	o	+	+	+	+	+	+	o	+	+	+	+	+	o	o	−	−	o	+
Top BS	+	−	+	+	o	o	+	+	o	o	o	+	+	+	+	+	−	−	+	+
Slope BS	o	−	+	+	+	+	o	+	−	o	+	+	o	+	−	−	−	−	−	o

Note: $N_{80}(P_{20})$ means: the influence of N_{80} on plots fertilized with P_{20}.

+ means: significant positive effect		SS = seaward side
− means: significant negative effect		BS = Brielse Gat side
o means: no significant effect		1/6 = June 1st, 1967
* means: no observations		1/9 = September 1st, 1967

Table 4b. *Effect of the various fertilizers on the number of leaves of Baltic Marram grass*

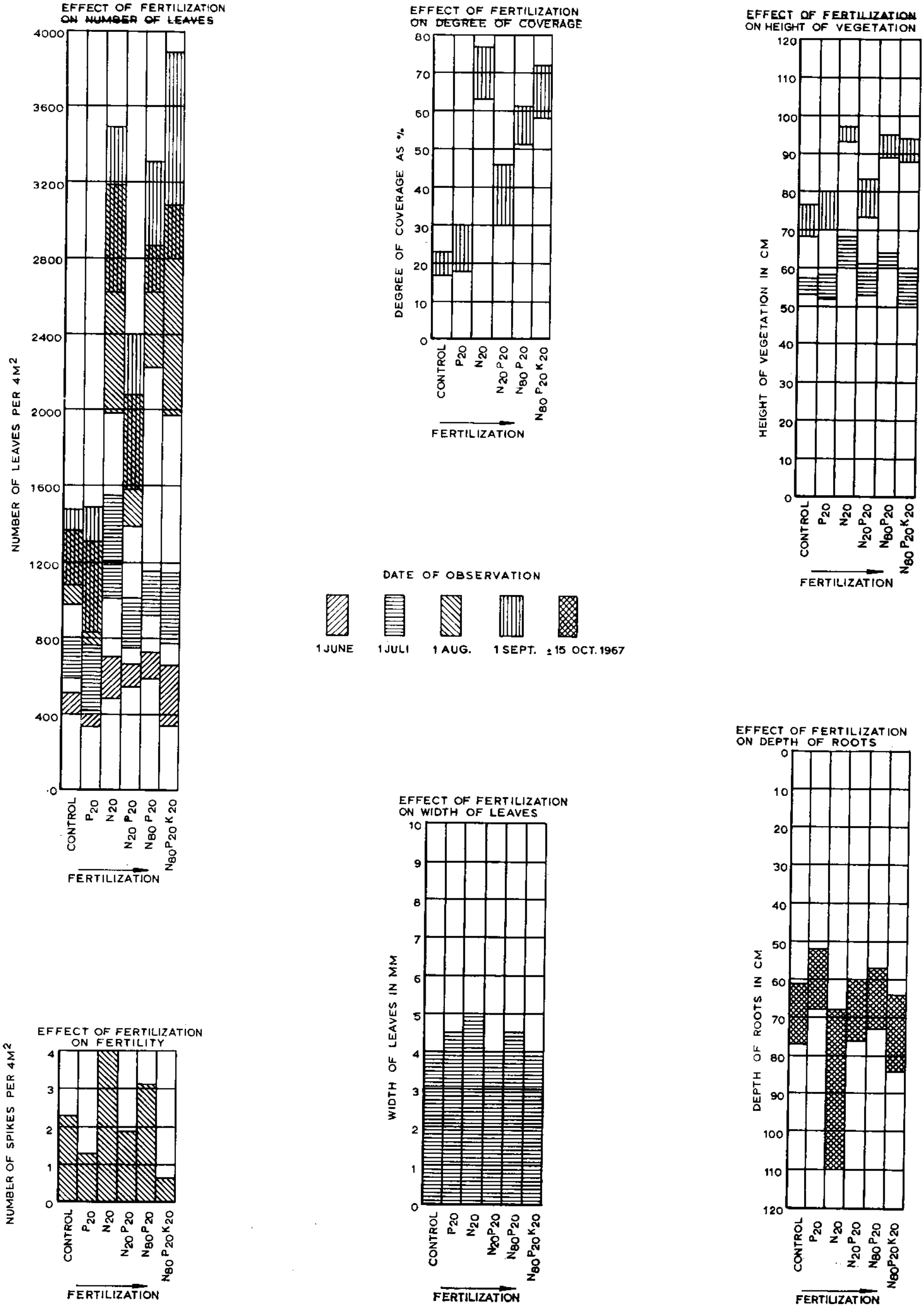
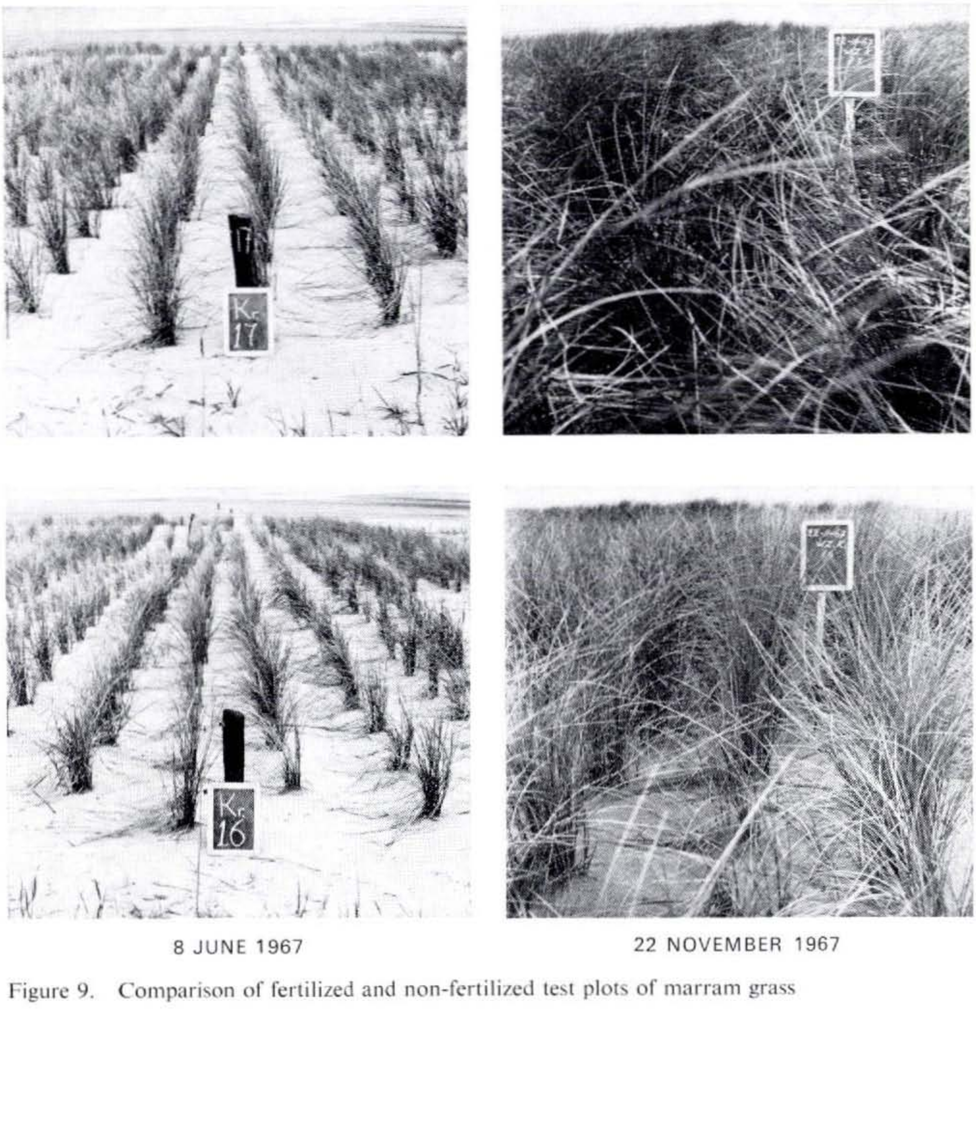


Figure 8. Effect of various fertilizers on the growth of marram grass

MARRAM GRASS

FERTILIZED

NON FERTILIZED



8 JUNE 1967 22 NOVEMBER 1967

Figure 9. Comparison of fertilized and non-fertilized test plots of marram grass

Baltic Marram grass – *Ammocalamagrostis baltica*

Fertilization with N-80 and N-80, P-20 and N-80, P-20, K-20 on plots planted with Baltic marram grass has a clearly favourable effect on the growth of the plant (figure 10). The P-20 dosage gives no better and sometimes even worse results. It was also found that N-80, P-20, K-20 has less effect than the N-80, P-20 dosage (table 4b).

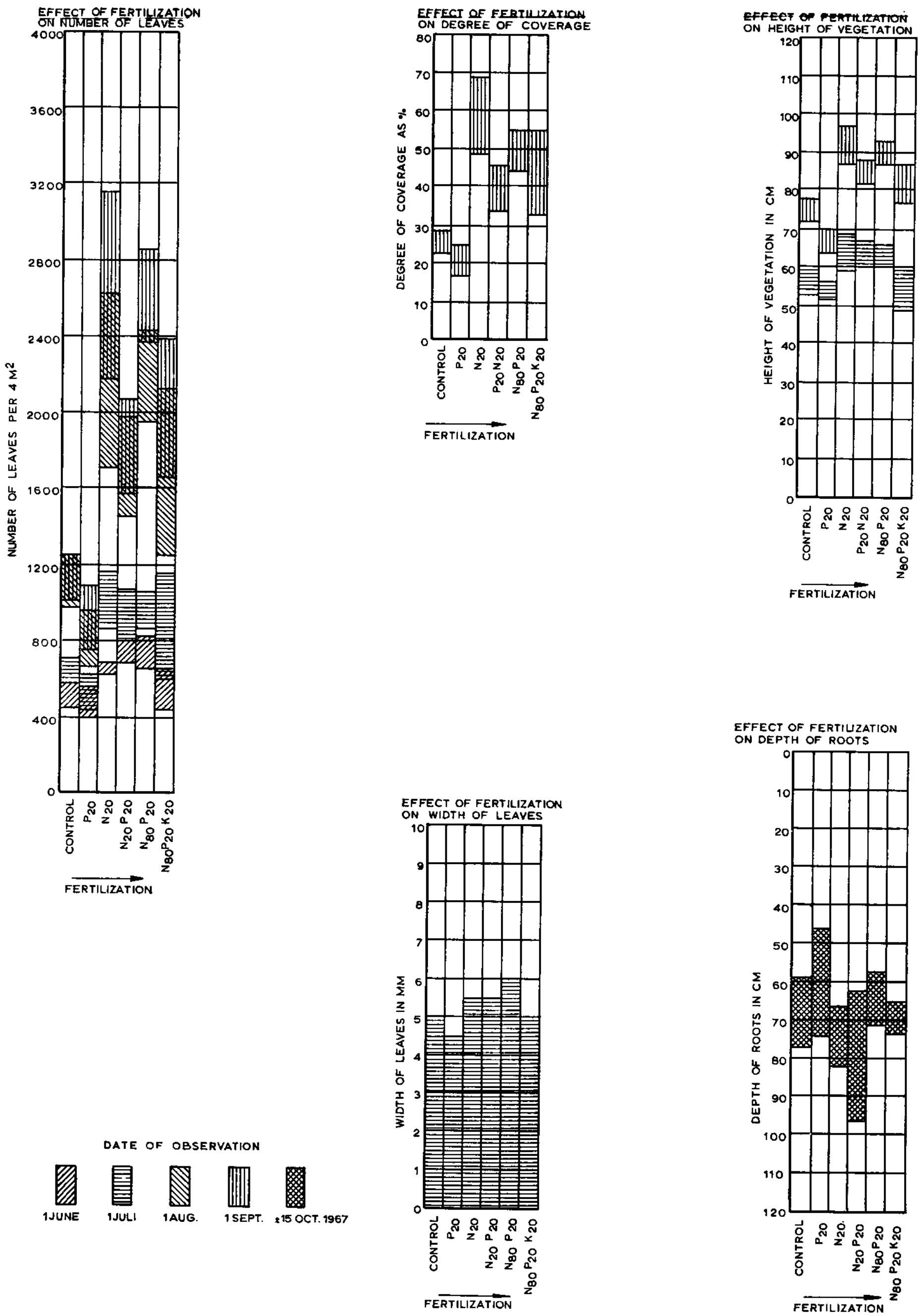
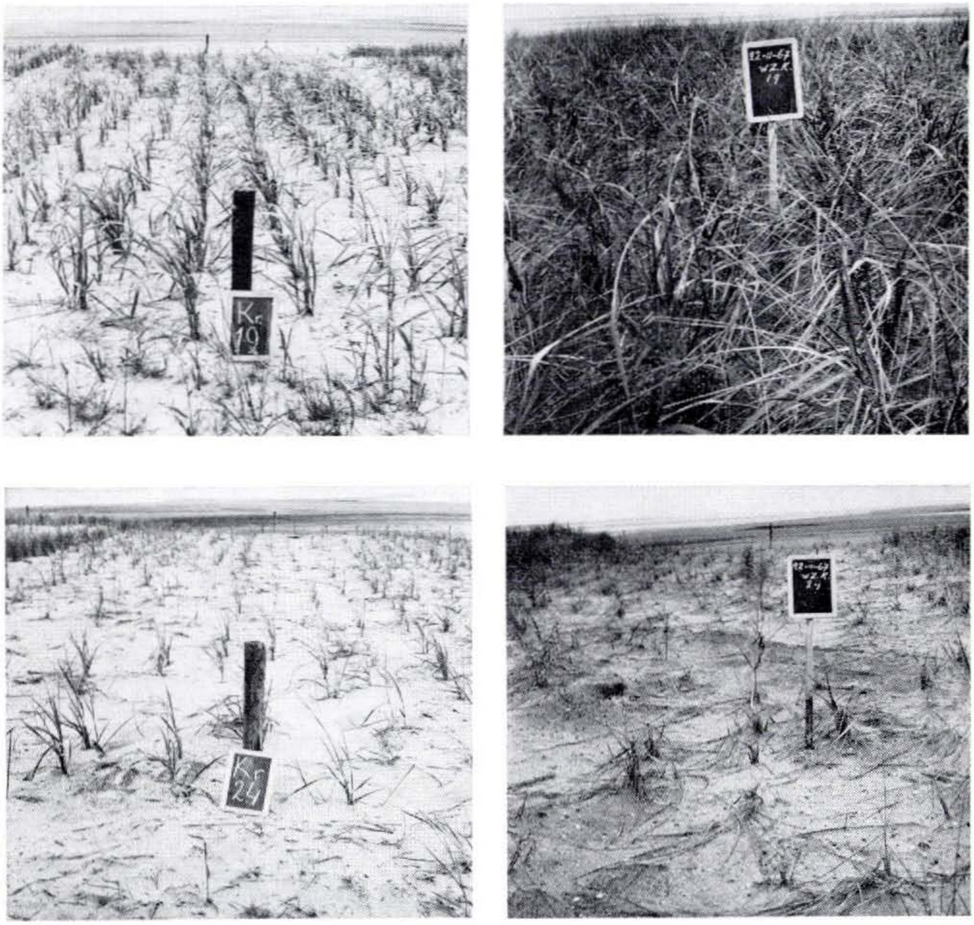


Figure 10. Effect of various fertilizers on the growth of Baltic marram grass

LYME GRASS

FERTILIZED

NON FERTILIZED



8 JUNE 1967 | 22 NOVEMBER 1967

Figure 11. Comparison of fertilized and non-fertilized test plots of lyme grass

Lyme grass – *Elymus arenarius*

Figures 11 and 12 show that fertilization with nitrogen has a stimulating effect on the growth of lyme grass plants. The effect of N-80 is greater than that of N-20. A P-20 dosage has no stimulating effect.

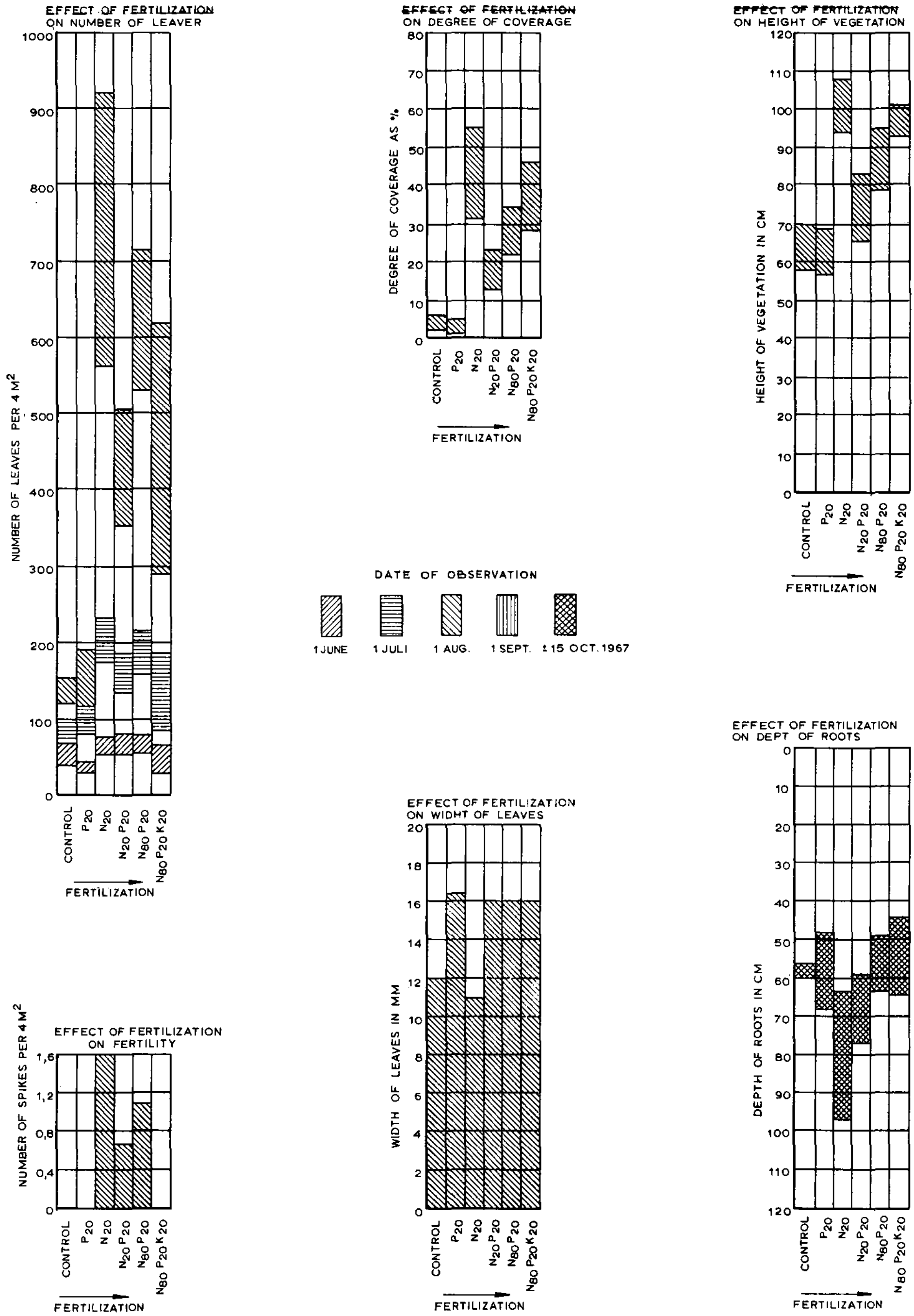


Figure 12. Effect of various fertilizers on the growth of lyme grass

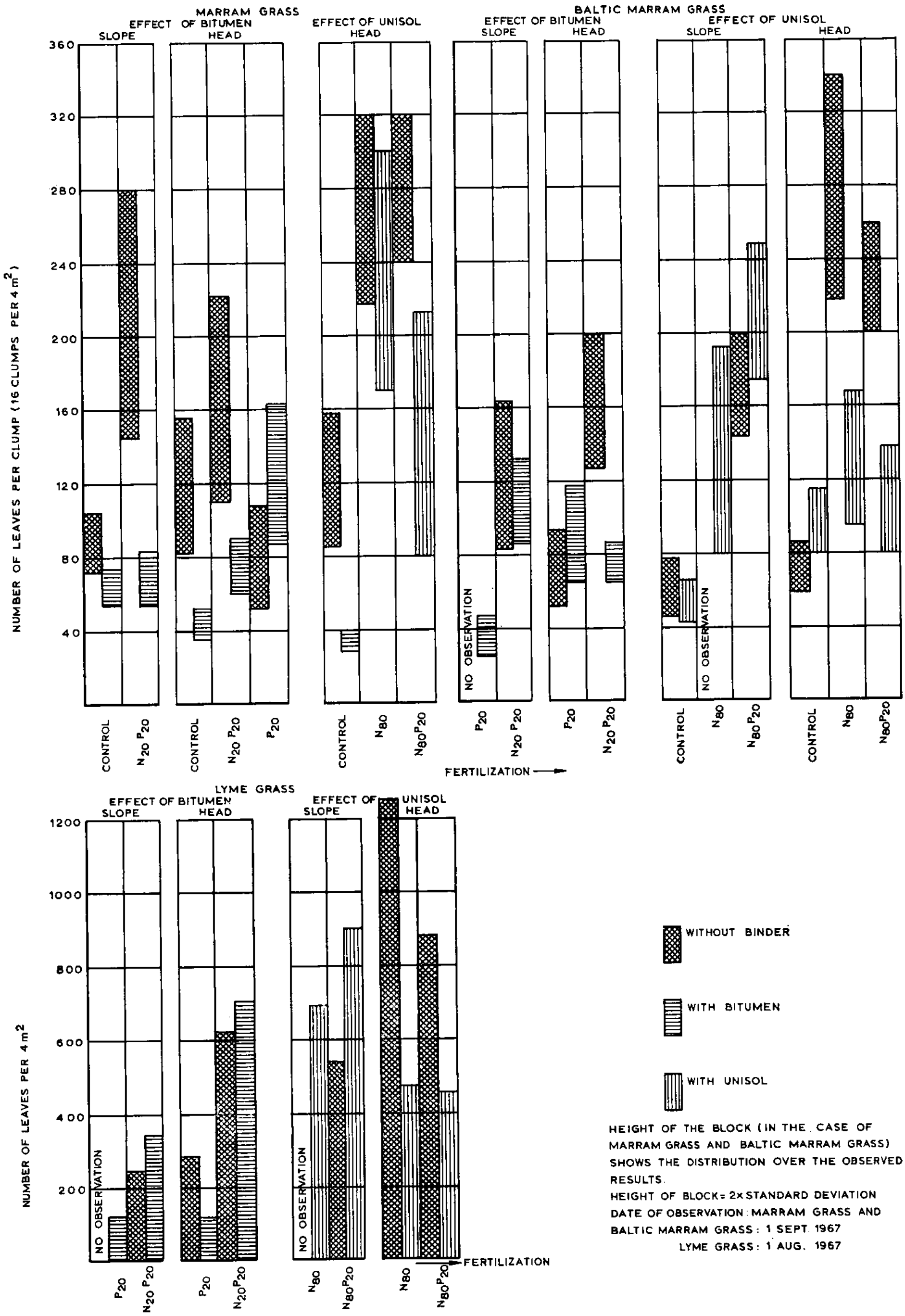


Figure 13. Effect of bitumen and unisol on the growth of marram grass and lyme grass on the sea shore

BINDERS

All binders were successful in stabilizing sand. Figure 13 and table 5 show that the binders had no clearly positive effect on the growth of both Marram grass and Baltic marram grass, but rather a negative effect.

		Marram grass		Baltic Marram grass	
		bitumen compounds	unisol	bitumen compounds	unisol
Control	Slope	–	*	*	o
	Top	–	–	*	+
P-20	Slope	*	*	*	*
	Top	o	*	o	*
N-80	Slope	*	*	*	*
	Top	*	o	*	–
N-20, P-20	Slope	–	*	o	*
	Top	–	*	–	*
N-80, P-20	Slope	*	*	*	o
	Top	*	–	*	–

Note: For an explanation of the symbols see table 4

Table 5. *The effect of binders*

3.4. Stimulation of an existing, stunted dune grass vegetation

An impoverished vegetation of the fore dunes can be encouraged by fertilization with nitrogen (N-40). The optimum 'ime during which the fertilization should be applied is 1 to 2 years. If fertilization is applied for longer, the marram grass vegetation will become too thick.

Mowing of old, withered marram grass vegetation

A test strip covered with old, withered marram grass was mown to see how long it would take for new shoots to appear on the mown ground. Mowing by hand turned out to be difficult, because the marram grass was very dry at the time.
Mowing took place before the growing season. The total volume of dry material after mowing was about 8,600 kg/ha. After six months the mown marram grass had completely regrown; the shoots were about 50 cm high and the plants looked healthy. No fertilization was applied to this strip.

3.5. The cost of sowing, planting and fertilizing of the dunes

This depends very much on local factors. For example, the cost of taking material and plants to the area in question can vary very much; the quality of the plants and the size of the seed harvest can also be very different.
Table 6 shows only the number of man hours needed for the various stages of the work. The cost of materials (fertilizers, binders) and transport (of material and equipment) have not been taken into consideration.
A distinction has been made between work in rough terrain, where most of the work has to be done by hand, and fairly even terrain where it can be done mechanically.

Description	Manual*		Mechanical**
	Hours/ha	Hours/kg	Hours/ha
Sowing/Harvesting		2	
Marram grass panicles			
– threshing marram grass or sand twitch		0.3	
– preparing the ground for sowing	10		4
– sowing	8		2
Planting – taking cuttings from the plants and planting them out	2000		
Fertilizing	4		1
Application of binders			1

* In rough terrain
** In fairly even terrain

Table 6. *A rough estimate of the number of man hours required for various sand stabilization activities*

Summary

A dosage of N-80 proved to encourage growth in all the crops investigated. This dosage was least effective in sand twitch. The impression was gained that a supply of fresh wind-blown sand was more important to the vitality of the plant than fertilization. In sand twitch only, P-20 in combination with N-80 encouraged growth very clearly. Fertilization with potassium produced no effect.
Both bitumen and Unisol proved in most cases to have an unfavourable effect on the growth of the crops investigated.

4. Sowing and planting dune vegetations

4.1. Sowing marram grass and sand twitch

The best time for sowing is from the middle of March to the end of April, but it can be done with success in the summer and even early autumn. Both for marram grass and sand twitch a density of 100 fertile seeds per m^2 is sufficient.
The conversion of this number of seeds to the weight of the number of seeds per ha can be done by means of the following formula:

$$A = \frac{100}{Z} \cdot \frac{100}{K} \cdot 10^3 \text{ DKG}$$

where A = the weight of seed in kg/ha
Z = the seed content as a percentage
K = the fertility as a percentage
DKG = the weight of a thousand seeds (for marram grass the DKG = 4 grams; for sand twitch the DKG = 25 grams).

For practical reasons it is not possible to sow less than 20 kg/ha mechanically. If less is required, the quantity should be made up to 20 kg by mixing with non-fertile seed (heated to 100 or 120°) of the same DKG. It is possible to have the seed content and the fertility tested (In the Netherlands, at the State Seed Testing Station at Wageningen).
The nature of sand twitch seed is such that it can only be sown by hand. Marram grass is suitable for mechanical sowing, provided the ground is suitable (there must be no transverse slopes steeper thans 1 : 5).
Both marram grass and sand twitch germinate in the dark. After sowing, the seed has to be covered by a layer of soil of 2-3 cm thick. If the sowing is done mechanically grooved rollers, known as Cambridge rollers, can be used for this and are fitted to the sowing-machine. The rollers press the seed into the soil. If sowing is done by hand, the ground can be forked over, harrowed or raked. If the ground is hard it is a good idea to harrow before sowing.
Sowing can only be successful if the sand is not blown away within the first 6 months, and also if there is no drifting of any significance, and no flooding. The soil can be stabilized by the application of binders to prevent erosion; or by harrowing in straw (in flat ground) or sticking straw or canes vertically into the ground (in sloping or undulating ground); or by placing fences or covering with twigs.

The seed-bed can be protected from drifting sand by placing fences or bundles of straw to catch the sand outside the bed. Tests are being made with this method at the moment.
Another way of encouraging the growth of the seedling is to improve the environmental conditions. The drying out of the soil and the crop can be reduced by harrowing in straw or sowing ground cover at the same time. Ground cover is a crop that germinates more quickly and earlier than the permanent plant and protects it in the first stage of its development. In addition, soil tests should be carried out before sowing, in order to establish whether fertilizers should be applied, and if so what fertilizers and in what quantities.

4.2. Harvesting

The best time for harvesting marram grass seed is from mid-July to mid-August. The ripeness of the seed for harvesting can be established by picking a handful of flower spikes and beating them. If the spikes are ripe a little of the seed will fall out. Immature seed must not be harvested as it has too little germinating power. In the other hand, if you wait too long much of the seed can be blown away in high winds.
Harvesting is done by cutting off the spikes with a knife and collecting them in baskets or sacks. The spikes must then be allowed to dry in a well-ventilated room and then threshed with a threshing-machine such as is used for flower-seeds. The seed can then be mechanically cleaned if necessary. Marram grass seed obtained in this way can be sown very successfully with a grass-sowing machine.
The amount of harvestable marram grass spikes is of the order of 250 l/ha. After threshing and cleaning this produces approximately 8 kg of seed.
Sand twitch spikes are ripe at about the same time as those of marram grass (mid-July-mid-August). The seeds are then hard.
These spikes do not lose their seed in the ordinary way, but the spikes become brittle so that they finally break through the action of the wind or if they are touched. The seed still clinging to the pieces that break off thus reaches the ground.
Sand twitch seed also has to be dried and threshed after harvesting. However, it has not proved possible to separate the seed from the other parts of the spike in threshing. The spike crumbles up into uneven pieces, from which the seeds do not become loose. Because of the irregular size of the pieces, it is best to sow this seed by hand, possibly using a dispenser to distribute it evenly.
Sand twitch could also be chopped, so that the spikes would be chopped into smaller pieces. Sowing the chopped material has the advantage that there are no larger pieces to blow away. Chopping can be done mechanically. However, care should be taken to select a chopping machine that will not damage the seeds.
Chopping marram grass is not recommended, since the seed falls out if the spikes are ripe.

The yield of the sand twitch harvest is approximately the same as that of marram grass. The cost of obtaining 1 kg seed is dependent on the quantity of seed produced, which may vary from year to year.

4.3. Planting out

It is common practice in Dutch coastal management to take cuttings from clusters of dune grasses in areas where there is sufficient vegetation, and plant them out elsewhere where the vegetation is scant.
Dune grasses should preferably be planted out in March or April, but otherwise at any time when there is an R in the month. In the summer months the cuttings should if possible be taken and planted out on the same day, and the cuttings should be covered to protect them from the sun in the interval between splitting and planting out. If the plants have to remain out of the soil longer than a few hours, it is as well to cover the roots with damp sand.
Planting can best be done diagonally. Marram grass, Baltic marram grass and sand twitch should be planted at intervals of 50 × 50 cm and lyme grass at intervals of 25 × 25 cm. It is recommended that lyme grass should not be planted separately but amongst marram grass or sand twitch. The reason is that lyme grass loses its leaves in the winter and therefore offers little resistance to sand erosion. Another drawback of lyme grass is that it is very liable to damage by rabbits, and one wonders whether it is in fact suitable for use in coastal management at all.
Every cutting should have at least six shoots, each with two growing points at the lower end. The plants are inserted in the soil at a depth of 15-20 cm.
The lower limit for planting should be set at about 2 or 3 metres above mean high water level. If the lower limit is set higher, drifting sand will be trapped on the upper part of the slope only. As a result, the top of the slope thickens and a steep incline is produced, on which it is difficult for vegetation to survive.
A slope of 1 : 2 or 1 : 3 is suitable for marram grass.
There are advantages in planting sand twitch on the lower part of the shifting dunes because of its greater salt resistance.
Dune shrubs (sea buckthorn, burnet rose, elder, etc.) should preferably be planted in February or March, but can be planted at all times when there is an R in the month. In order to protect the soil from erosion, it is important for a covering of shrubs to be produced which will tolerate undergrowth, and it is therefore best to place the shrubs about 10 metres apart. Plants of sea buckthorn should have a good root system and must be split and planted out on the same day (planting depth about 25 cm). Cuttings of burnet rose and elder may be about 1 m long (planting depth 0.5 m). Rooted runners of sea buckthorn should be used and the roots should be placed about 25-40 cm deep according to the dampness of the soil. It is recommended that sea

buckthorn should be sown in places with a great deal of shifting sand. Sea buckthorn can only be planted after a vegetation of grass or marram grass has stabilized the sand. Good results have been obtained from sowing sea buckthorn in more sheltered places where the sand is disturbed little, if at all.

5. Protective fences and dykes of wind-borne sand

5.1. Introduction

Sand fences are used in areas where the quantity of windblown sand is so great that it cannot be stabilized by vegetation and in areas where a rapid accumulation of wind-blown sand is desired along a predetermined line, for instance where sand dykes are to be built.
In the first case, the sand fences are used to reduce the quantity of sand blowing over sufficiently for the vegetation behind them to keep pace with it.
In the case of sand-dykes, the purpose of sand fences is to trap and hold as much as possible of the drifting sand.

5.2. The effect of sand fences

Some laboratory experiments were made by MANOHAR AND BRUUN, (1970) to investigate the braking of the wind force under the influence of sand fences. Figure 14 is derived from their research, and shows the decrease in wind velocity in front of and behind the wind break.
The slowing down of the wind in front of a sand fence causes the wind-blown sand to settle. This creates a windward slope on the ground in front of the fence. The magnitude of the windward slope decreases as wind velocity increases. Immediately in front of the fence part of the air-stream is deflected upwards and downwards, which gives rise to extra turbulence and therefore reduced sedimentation, so that sometimes there

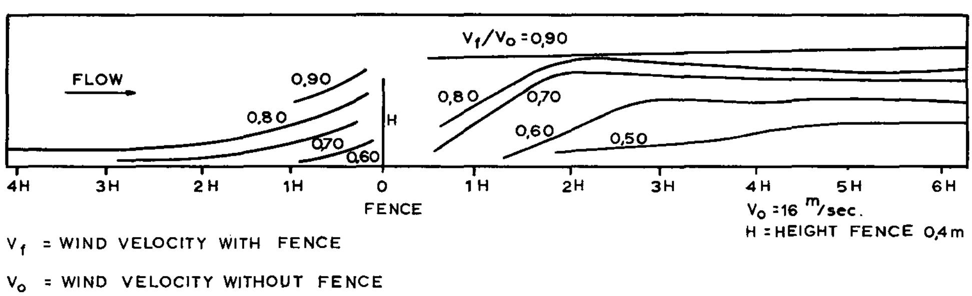


Figure 14. Braking effect on the wind in front of and behind a sand fence (according to MANOHAR AND BRUUN, 1970)

is even erosion in the immediate vicinity of the fence and a V-shaped hollow is formed.

The grains of sand passing over and through the fence may be deposited in the area of reduced wind velocity behind it. A ridge is formed here too, but in this case the slope becomes steeper as wind velocity increases. This is attributable to the fact that with increasing wind velocity the area within which the force of the wind is slowed down behind the fence becomes smaller. A V-shaped profile is produced on either side of the fence.

If the wind velocity remains constant for a long time, a state of equilibrium will gradually be reached around the fence, with a stable windward slope; there will also be a V-shaped profile of regular depth round the fence and a very shallow leeward slope. The sedimentation on the leeward side reaches approximately the height of the fence.

Manohar and Bruun's tests also showed that the area affected by a fence of a height H in the path of the wind extended approximately to a distance of 2 H on both sides of the fence.

It can be deduced from the above that the capacity of a fence to trap sand depends on:

- the quantity of sand blowing up from the beach. This is determined by the wind velocity, the grain-diameter of the sand and the water-content of the sand,
- the size of the area in which the wind velocity is reduced,
- the porosity of the fence and the accompanying degree of turbulence of the air on both sides of the fence,
- the fall-velocity of the transported sand.

5.3. Practical experience

Various arrangements have been tried for the placing of sand fences [BOESCHOTEN, 1954]. Generally speaking, the best results are obtained with parallel rows of straight fences, at a distance of 5 to a maximum of 10 metres from each other.

Other fences can be placed at right angles between the rows 5 to 10 metres apart, to prevent the accumulated sand dispersing if the wind blows parallel to the longitudal rows of fences. MANOHAR AND BRUUN, (1970) came to the conclusion, as a result of wind-tunnel tests, that the optimum distance between the fences is about 4 times the height.

The material used can be osier or reeds which are inserted 0.25 to 0.50 metres into the ground. The top of the fence must be straight and horizontal if the dyke is to be the same height all the way along.

Plastic fencing with perforations of various sizes can also be used with success [SAVAGE AND WOODHOUSE, 1968, ERCHINGER, 1972].

The fence should let through about 50% of the wind, as has been shown by measure-

ments in wind tunnels [MANOHAR AND BRUUN, 1970] and experience in the field [BLUMENTHAL, 1964, SAVAGE AND WOODHOUSE, 1968].
The minimum height at which the first fence can be placed is about MHW (mean high water line) + 1 metre. Fences will often be placed higher, however (MHW + 2 m), to keep damage from storms and high tides to a minimum.
Both the line of the fence and the way the fences are placed may differ according to the purpose they are to serve.
If they are being used for stabilizing sand only, the line of the fence is not so important. It will usually be possible to place the fences fairly high (MHW + 2 m) so that damage by storms and high tides will be kept minimal. It will also often be possible to use cheaper materials, and the fences need not be so high.

5.4. Sand dykes

The selection of the line of the fences is extremely important where the sand is being used to form a dyke.
Although local conditions may considerably affect the choice of the line of the fence, there are nevertheless a number of points which should always be taken into account if at all possible (see also BLUMENTHAL, 1964). It is recommended that the line should run more or less at right angles to the winds which can be expected to bring in the largest quantities of sand. These winds can be estimated by the method described in the Appendix. It is worth noting that on the Dutch coast strong southwest-west-northwest winds are often accompanied by precipitation and increased water levels along the coast. Both these factors restrict the amount of sand carried by the wind to a greater or lesser degree.
The line of the embankment should not be too far from the MHW-line. If so, sand twitch may appear spontaneously on the beach below it which will then stop a lot of the sand that would have helped to build up the dyke.
The minimum distance between the mean high-water line and the embankment was put by VAN DER STEGE, (1965) at 200 metres, a figure based on a number of cases in practice. BLUMENTHAL, (1964) recommends that an even greater distance be allowed, so that any shift inland of the mean high-water line will not immediately result in a too narrow strip of foreshore, and because it is best for the dyke to be widened on the seaward side.
Damp depressions (creeks and layers of shells) on the beach restrict the amount of loose sand considerably. The sand embankment should be at some distance from zones of this kind.
The height of the fences and the sequence in which they are placed for building a sand dyke depends on the aim in view [BLUMENTHAL, 1964]. In the first stage the aim should be to achieve breadth. For this it is preferable to use low fences (about one metre in

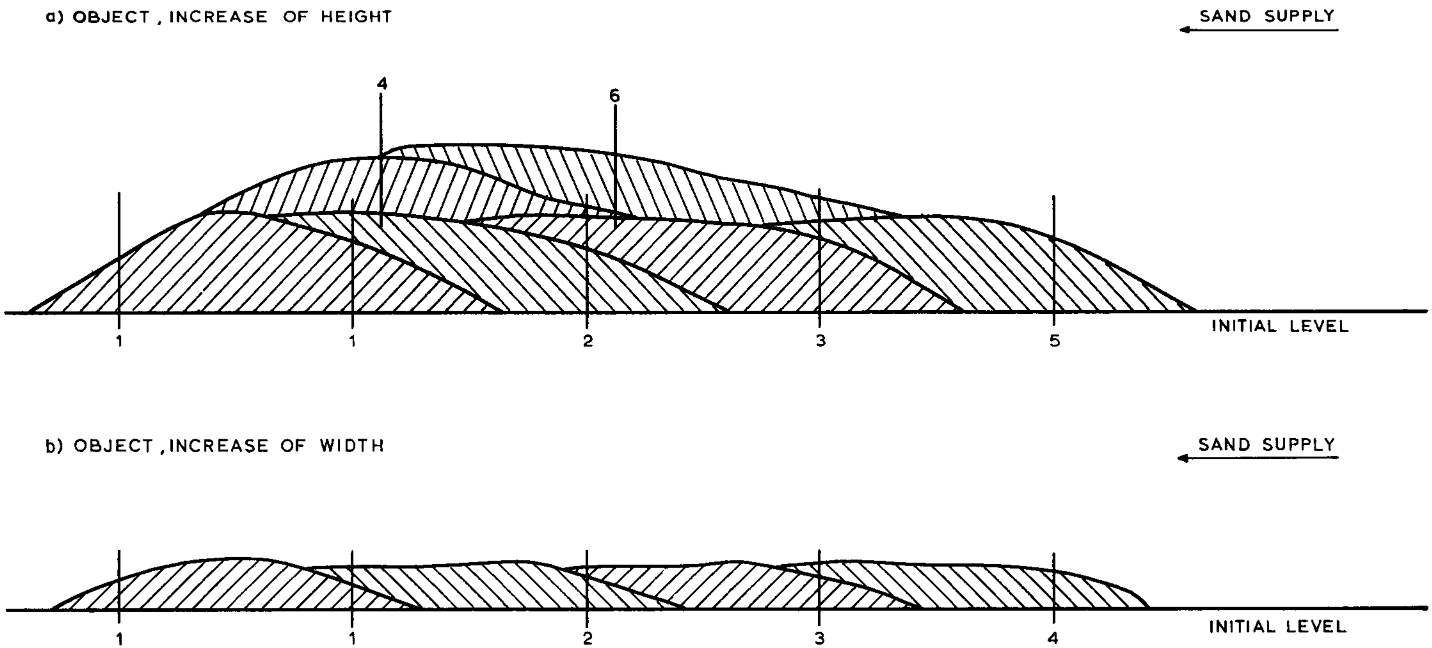


Figure 15. Principle of placing sand fences (according to BLUMENTHAL, 1964)

height). At a later stage, when the aim is to gain height, it is better to use tall fences (about two metres). In any case, broadening of the profile of the dyke is best obtained if the second and subsequent rows of fences are placed in the direction from which the sand is blown (figure 15).
It is recommended that the inner slope of the dyke be held in place by means of marram grass vegetation. Sand stabilization can also be achieved temporarily by spreading straw.

6. Planting dredged sand elevations

The first measures to be taken to prevent the dispersal of dredged sand vary according to whether the sand originally came from salt or fresh water. They also depend on the season of the year at which the work was carried out and the ultimate purpose for which the dredged sand elevation is to be used.

Later measures are the same whether the sand came from salt water or fresh.

Elevations of salt-water sand include those created by suction dredgers and presses, where the sand was obtained from the seabed or estuaries. Examples are works for the improvement of crumbling dune ridges – artificial dunes in fact –, sand dams built out to sea, such as the Southern Harbour Mole of Europoort, or dams built round sunken pits for engineering works. In all these cases the problem is to give immediate protection to the sand surfaces to prevent dispersal, irrespective of the season.

If the surfaces are small and the slopes steeper than one in four protection can be given by planting with marram grass, which can be done at any time of year. In the summer (April to September), planting with marram grass should be preferred to inserting reeds or straw, partly in view of the cost. Admittedly, marram grass planted in the summer grows less quickly, but experience has shown that a great many of the plants put in in the summer will take, at least if they have living roots or root nodes. Larger surfaces and shallow slopes can also be planted with marram grass, but this is expensive.

A cheaper method is to sow grasses. But this is not possible until the salt sand has become desalinated. This is the case when about six cm of precipitation has fallen on the sand. So there is a certain lapse of time between the sand elevation being finished and the time when sowing can be done. Measures will need to be taken in this interval to prevent the sand blowing away. The following method produced good results in the case of the Southern Harbour Mole of Europoort.

Five to six thousand kilograms of straw per hectare were harrowed into the head of the dam. When the top layer was sufficiently desalinated the dam was sown with seed. It was decided to use rye (60 kg per ha) as a cover crop because the plant can withstand salt well. In addition, rye grass (10 kg per ha) and Westerwolde rye grass (10 kg per ha) were used. These grasses grow quickly and produce a generous amount of new seed so that they perpetuate themselves. However they do need fertilizing. Twenty kg per ha of creeping fescue and also common fescue were added to the mixture. This species is resistant to salt but a slow grower. Fertilization is not necessary for this plant Ten kg per ha of meadow grass seed was added because of its high drought resistance. For sowing on the seaward side of the dam, marram grass seed (25 to 30 kg per ha) was added to the mixture.

If sowing is done in the spring and summer, Westerwolde rye grass can be used as a cover crop (20 kg per ha).

Simultaneously with sowing, fertilization with 300 kgs per ha of NPK 17-17-17 compound fertilizer was applied. If sowing is done in the spring, it is recommended that further fertilization with 200 kgs per ha of nitrogen (saltpetre) (23% N) be applied. Since it is not usually intended that the grass should be mown but that a sturdy covering of grass and a healthy, rather open, marram grass vegetation be obtained, it is advisable to restrict the additional fertilization to a minimum.

No universal rules can be given regarding the choice of grass species and fertilizers. It is recommended that expert advice be sought.

To prevent the new grass being buried by sand drifting from the beach and the slopes of the dam, marram grass was planted on the slopes and on a strip about five metres wide along the outer edge of the head. In the area immediately adjoining this, marram grass was sown along with the grasses and cover crops. In this way, a gradual transition was obtained from the vegetation of the beach to that of the sand dam. Once grass has become established, attempts can be made to create a 'natural' dune vegetation of, for example, sea buckthorn, burnet rose, elder and hawthorn (provided the ground water conditions are suitable). It may therefore be worthwhile to plant these shrubs. It is recommended that they be planted in groups and not individually, since they then derive some support from each other and offer more resistance to the wind.

If the elevation is formed of fresh-water sand, for example if the sand has been obtained from neighbouring dunes to strengthen weak places, or in the case of industrial areas made of dredged sand, etc, a start can be made with sowing and/or fertilizing immediately after the elevation is finished. However, if the work is finished in the autumn or winter, it is recommended that sowing be delayed until the following spring. The sand terrain can then be protected from erosion by harrowing in straw or spraying it with binder. The latter method is not only more expensive but has other disadvantages as well. People cannot be allowed to walk or drive on the land, since this would disturb the thin layer of binder on the surface of the sand and worse drifting than before would take place. Another disadvantage is that the new grass emerging through the layer of binder could easily be destroyed by sand drifting from nearby untreated areas, which in fact happened in tests in the Europoort area. Protecting sand flats consisting of salt-water sand with a bitumen binder has little point if it is desired to cultivate a covering of grass. The layer of bitumen prevents the infiltration of rainwater and therefore delays the desalination of sand, thereby hampering the growth of the grass.

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Appendix

Rough calculation of quantities of drifting sand

Before embarking on measures for sand stabilization it may be desirable to have a rough idea of the quantities of wind-blown sand that can drift annually in a particular area. This information is also valuable in deciding on the line of sand dykes or artificial dunes.

There are three ways in which sand can be transported by the wind. These are bed load, saltation load and suspension load.

Observations have shown that only dust and very fine sand are transported as suspension load and that the contribution of suspension load to the total load of sand transported over the beach is negligible.

BAGNOLD, (1941) found both from wind-tunnel and field tests that in non-cohesive sand there is a fixed relationship between the quantity of bed load and the quantity of saltation load, namely 1 to 3. If one or the other is known, the total load can be calculated. The saltation load is the easiest to estimate. In the wind-tunnel, it was found that the sand grains in the saltation load followed paths which were of the order of decimeters in height and a number of decimeters in length depending on wind velocity [BAGNOLD, 1941].

The grains in the saltation load are accelerated by the wind to such an extent that the speed with which they hit the ground is appoximately the same as the wind velocity at the highest point of the path. The impact of the grains of sand is so great that at the point where they touch the ground a number of other grains may bounce or roll away. The increase in the momentum of the grains in the suspension load accompanies a drop in the momentum of the wind. The wind is slowed down and a vertical velocity gradient arises, which is a meausre of the shear stress. The latter can be described as the transfer of energy from the wind to the grains of sand per unit of time and per unit of surface.

Bagnold related the total impulse of the falling sand grains per unit of surface and per unit of time to the shear stress of the wind, starting from the kinematica of the springing grains. He found the following formula for saltation load:

$$q_s = C_1 \sqrt{\frac{d}{D}} \quad \frac{\rho_a}{g} U_*^3 \tag{1}$$

where

q_s = the weight of the salatation load per unit of time per running metre of wind path in kgs/sec per metre

C_1	= constant	
d	= mean grain diameter of the sand	m
D	= reference grain diameter of $250 \cdot 10^{-6}$ m	m
ρ_a	= density of the air (1.22 kg/m^3)	kg/m^3
g	= gravity acceleration	m/sec^2
U_*	= shear velocity; $U_* = \sqrt{\frac{\tau_0}{\rho_a}}$	m/sec
τ_0	= shear stress	N/m^2

If the above relationship between bed load and salatation load is introduced, the total quantity of sand transported by the wind (q) is represented by:

$$q = C \sqrt{\frac{d}{D}} \; \frac{\rho_a}{g} \; U_*^3 \tag{2}$$

The constant, C was found to have a value of 1.5 for sand of approximately uniform diameter; 1.8 for dunc sand and 2.8 for sand with grains of various sizes. Obviously, Bagnold's formula is valid if the shear velocity (U_*) is greater than the critical value for the sand movement (U_{*c}).

Bagnold found that for non-cohesive sand U_{*c} can be determined in accordance with:

$$U_{*c} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} \, gd} \tag{3}$$

Here, ρ_s is the density of the sand grains; for an explanation of the other symbols see above.

The proportionality factor $A = 0.1$ for sand with a diameter greater than 200 μ. On the beach, the value of U_{*c} may be greater than that for non-cohesive sand due to the sand grains being bound by salts, calcium and iron and due to capillary forces in the damp surface layers.

The increase of U_{*c} under the influence of binding is only slight. After all, if sand is blown about elsewhere on the beach, the impact of the grains in the saltation load will easily disturb the thin bound layer.

The effect of the capillary forces near the surface of the sand on the value of U_{*c} is more significant, as is shown in figure 16 [SVASEK AND TERWINDT, 1974].

The value of the shear velocity U_* can be determined from the vertical wind speed distribution in accordance with:

$$U_z = 5{,}75 \, U_* \log \frac{z}{z_0} \tag{4}$$

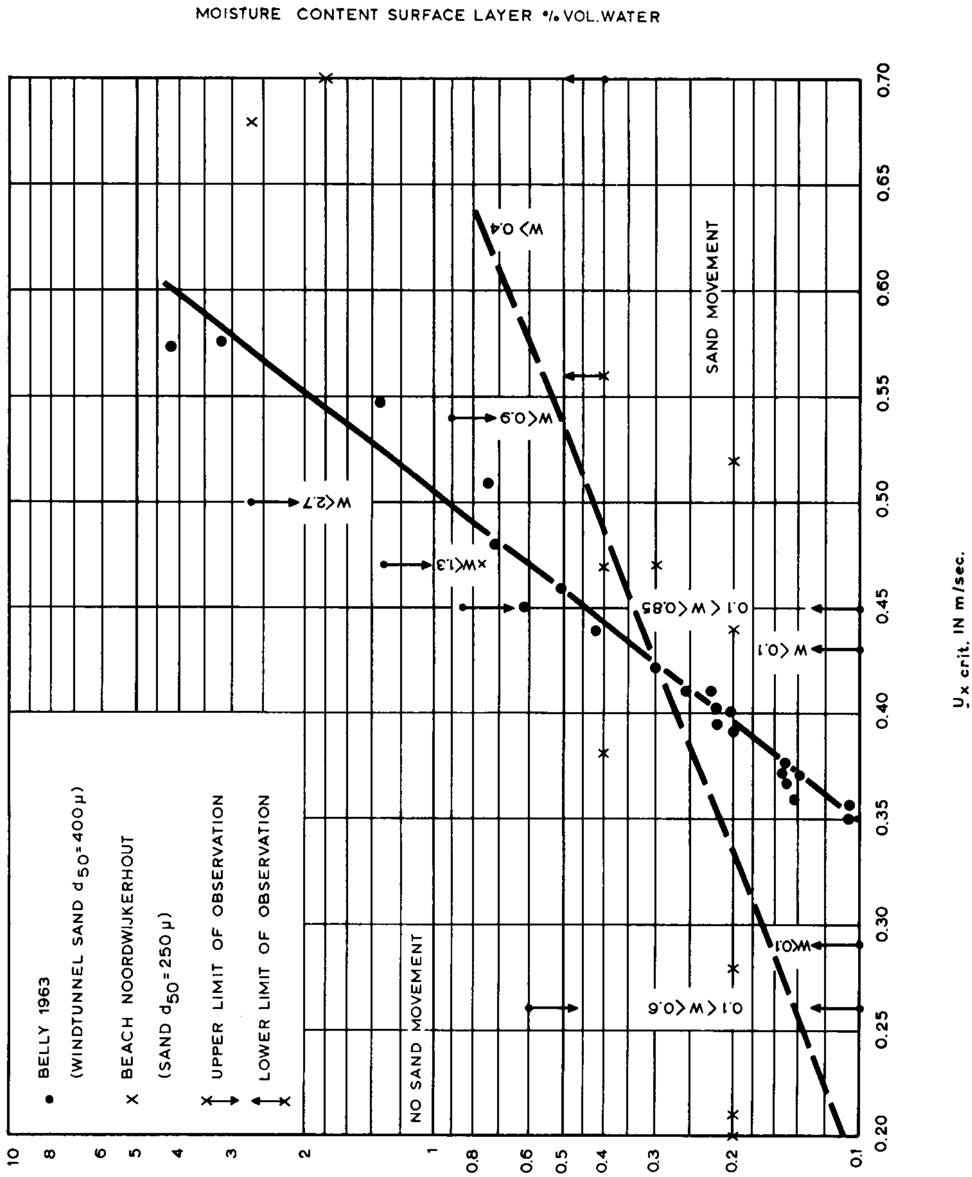

Figure 16. Relation between the moisture content of the surface sand and the critical shear velocity U_{*_c} (according to SVASEK AND TERWINDT, 1974)

where

U_z = wind velocity at height z m/sec

U_* = shear velocity m/sec

z_0 = height (m) above the ground at which the velocity = 0.

Bagnold found that $z_0 = \frac{1}{33} k$, where k is the measure of the unevenness of the ground, or the ground roughness factor (in m).

Formula 4 now becomes:

$$U_z = 5{,}75\ U_* \log \frac{33z}{k} \tag{4a}$$

On the basis on this formula the measured wind velocities above he ground can be plotted against the logarithm of the height at which they are measured. A straight line can be drawn through the points in the graph thus obtained. The steepness of the line is a measure for U_*.

A useful method for determining U_* is to read off U_z at two points on the line, in such a way that $z_1 = 10z_2$.

It then follows from formula 4a that:

$$U_{z_1} = 5{,}75\ U_* \log \frac{33z_1}{k}$$

$$U_{z_2} = 5{,}75\ U_* \log \frac{33z_2}{k}$$

$$U_{z_1} - U_{z_2} = 5{,}75\ U_* \left(\log \frac{33z_1}{33z_2} \right) = 5{,}75 U_*$$

$$U_* = \frac{U_{z_1} - U_{z_2}}{5{,}75} \tag{5}$$

The relationship between the wind force and the values of U_* occurring on the beach can be determined from speed measurements made on the beach at various wind forces (registered at a registration station in the vicinity) and from these the quantity of sand, q. Table 7 shows the connection between wind force and quantity of sand transported on the beach, based on measurements on the Dutch coast [SVASEK AND TERWINDT, 1974]. It is worth noting that no sand is blown by the wind if the force is less than 3 on the Beaufort scale. The figures in the table are of course only valid for averate grain sizes found on Dutch beaches, which are approximately between 150 and 200 μ.

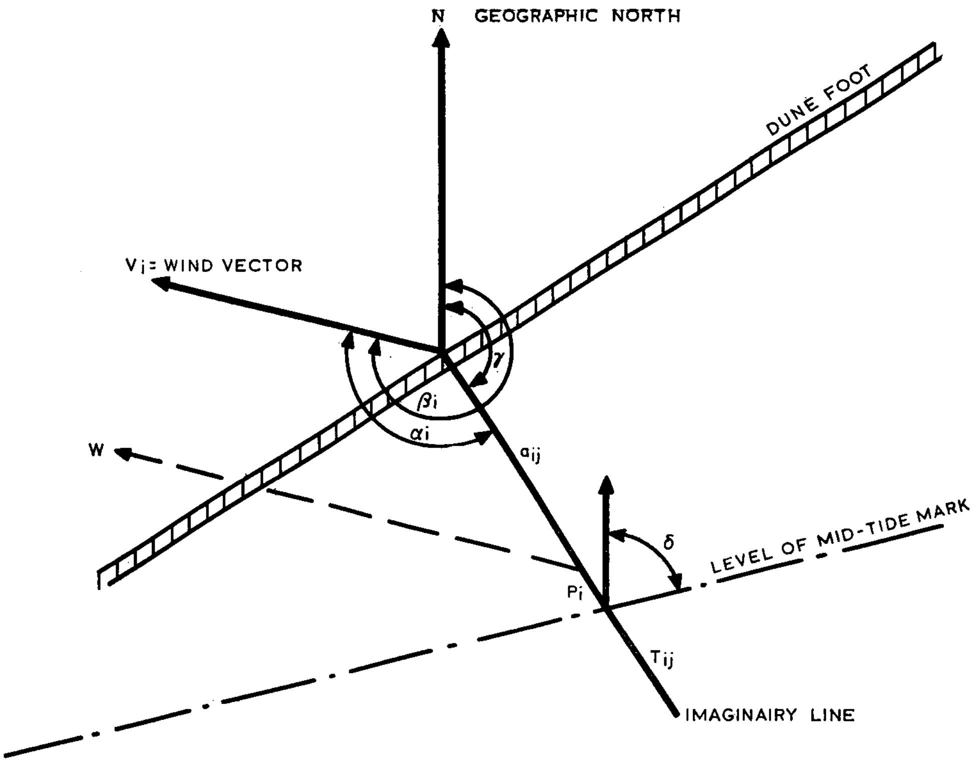

Figure 17. Sketch explaining the calculation of the total quantity of sand transported by the wind over an imaginary line

If the frequency of occurrence of the wind forces (in degrees on the Beaufort scale) as a function of the wind direction over a certain period is known, the total quantity of sand transported by the wind through an imaginary line at right angles to the wind during the period in question can be calculated as follows (see figure 17).

$$q_t = \sum_{i=0^\circ}^{360^\circ} \sum_{j=4}^{12^\circ\,\mathrm{B}} f_{ij} q_j a_{ij} \sin \alpha_i \tag{6}$$

q_t = the total quantity of sand transported by the wind over the line (kg/period)
f_{ij} = frequency of occurrence of wind forces j (sec) in the wind direction i
q_j = sand transported with wind force j (kg/sec/m^1 wind path)
a_{ij} = effective length of the line through which the sand transport occurs (metres)
α_i = angle of wind direction i to the direction of the line

Wind force in °Beaufort scale	q_j in 10^{-6} $m^3/sec/m^1$ wind path
4	–
4	1
5	3
6	14
7	13
8	86
9	165
10	310
11	408
12	not measured

Table 7. Sand transported by the wind at various forces

q_j is of course expressed in kgs/sec/m′ of wind path or per m′ perpendicular to the direction of the wind. In order to define the angle α_i unequivocally we assume: (see figure 17)

$$\alpha_i = \beta_i - \gamma$$

where

β_i = the angle between the geographic North and the direction in which the wind is blowing

γ = angle between the geographic North and the direction of the line.

The effective length of the line a_{ij} is taken as that part of the line where sand transport by the wind takes place. Various factors influence the magnitude of a_{ij}. It changes, for example, with variations in the water level under the influence of the tide. The mid-tide mark (M_0) can be taken as an average for these variations. The mid-tide mark varies due to the effect of the wind. If this effect is to be introduced into the calculations, the average variations in the height of the mid-tide mark as a function of wind direction and wind force (W_{ij}) should be known. This has been determined by NIJHOF, (1965) for the Hook of Holland weatherstation. The average water level on the beach for various wind directions and wind force (T_{ij}) now becomes:

$$T_{ij} = W_{ij} + M_0 \tag{7}$$

The magnitude of a_{ij} is determined not only by T_{ij}, but also by the phenomenon that winds blowing off the sea need some little distance along the beach before their capacity to carry sand reaches saturation point. The distance varies with the wind force.

Observations have shown that with high winds, when considerable quantities of sand are transported, the distance in the direction of the wind can be put at about 20 metres. As a result of this phenomenon, the reduction P_i of the effective line-length a_{ij} is as follows (figure 18).

$$p_i = \frac{20 \sin (360 - \beta + \delta)}{\sin (\gamma - \delta)} \tag{8}$$

where δ is the angle between the mid-tide line and the geographic North.
It should be noted that this reduction is only applied in the case of onshore winds.
The effective length of the line now becomes:

$$a_{ij} = M_{ij} - | p_i | \tag{9}$$

in which M_{ij} is the distance from a certain point (for example the foot of the dunes) as along an imaginary line over the beach perpendicular to the line of the dunefoot, to the mid-tide line.
If $a_{ij} = 0$, it is assumed that no sand drifting due to the wind is taking place on the beach.
The length of a_{ij} can now be obtained from the profile data. The profile data of the

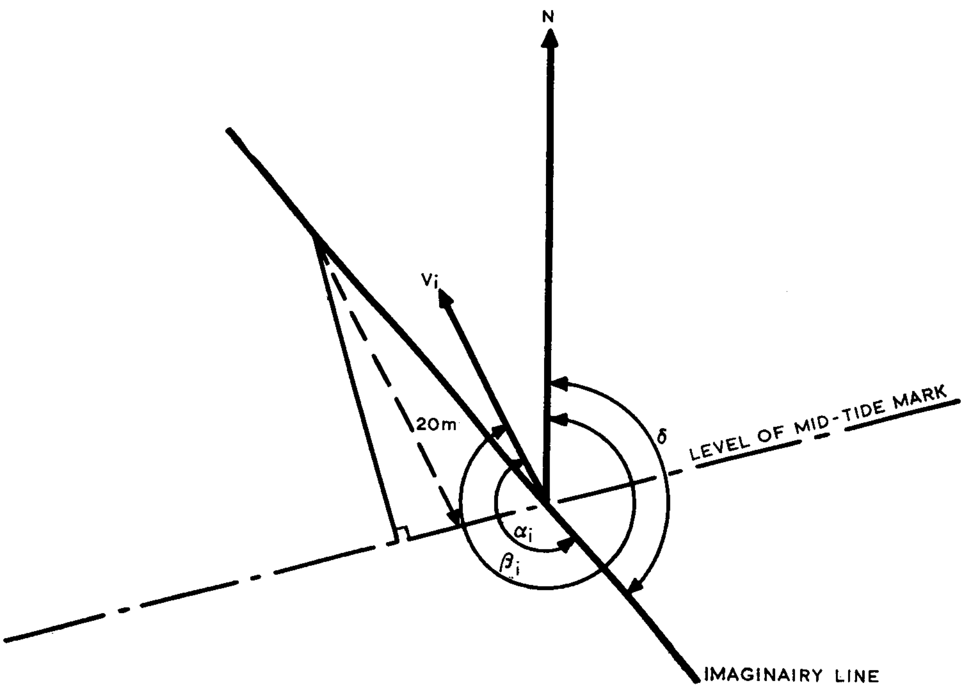

Figure 18. For explanation see text

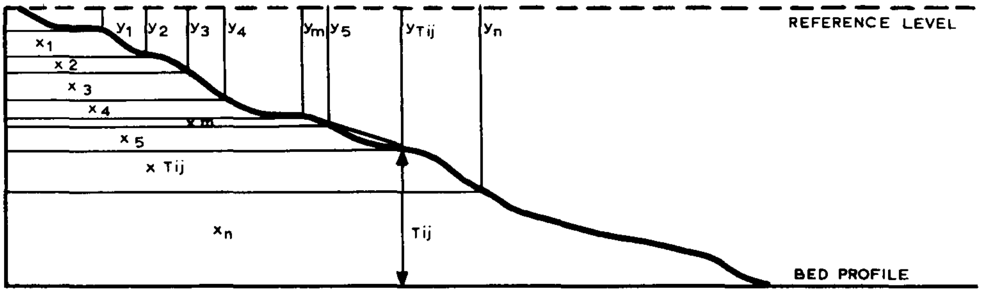

Figure 19. For explanation see text

measurement line consist of n pairs of data (x_n, y_n), where x_n is the horizontal distance from a fixed point and y_n the vertical distance from a line of reference to ground level (figure 19).

The number of pairs (n) selected should be such that a good approximation of the bottom profile is obtained by linear interpolation between a previous and a subsequent value of y.

The level of the mid-tide line T_{ij} $(y_{T_{ij}})$ in the profile is known. The corresponding value $x_{T_{ij}}$ can be found from the profile data by interpolation.

In addition, we know the distance p_i along the profile. The coordinates of x_{p_i} and y_{pi} can be found, starting from the point $x_{T_{ij}}$, $y_{T_{ij}}$. The coordinates determine the seaward limit of a_{ij}.

Let us suppose that the coordinates are $x_{p_i} = x_m$ and $y_{p_i} = y_m$, where m is equal to the nearest value of n to seaward of x_{p_i}.

The effective length of the line a_{ij} now becomes:

$$a_{ij} = \sum_{n=0}^{n=m} \sqrt{(y_{n+1} - y_n)^2 + (x_{n+1} - x_n)^2} \tag{10}$$

It may be desirable to know the components of the sand transport vector parallel to and vertical to the line, as well as the total quantity of sand passing over the line (which can be calculated by the aid of formula 6). It should be noted that in analysing the sand transport vector per wind direction, the distance over which the transport takes place must also be analysed. The total component perpendicular to the line is then:

$$q_{tot,nor} = \sum_{i=0}^{360} q_i \sin^2 \alpha_i \tag{11}$$

in which $q_i = \sum_{j=4}^{12^\circ B} f_{ij} q_j a_{ij} \sin \alpha_i$

The total component parallel to the line is:

$$q_{tot,\,par} = \sum_{i=0}^{360} q_i \cos^2 \alpha_i \tag{12}$$

In deciding on the line of a sand dyke it may be desirable to know the quantity of sand that crosses a certain line per running metre q_r and can be retained. The values of a_{ij} along a number of lines perpendicular to the line concerned are calculated in accordance with the above procedure. Where a_{ij} is greater than o the following applies (see figure 20):

$$q_{ri} = -\cos \alpha_i \sum_{j=4}^{12°B} f_{ij} \cdot q_j \tag{13}$$

$$q_{r\,tot} = \sum_{i=0}^{360} q_{ri} \tag{14}$$

Obviously, by the method of calculating described above it is not possible to obtain more than a rough idea of the quantity of sand transported by the wind. In the first place, there is a clear variation in the points in the graphs showing the relation between U_* and q and U_* and wind force.

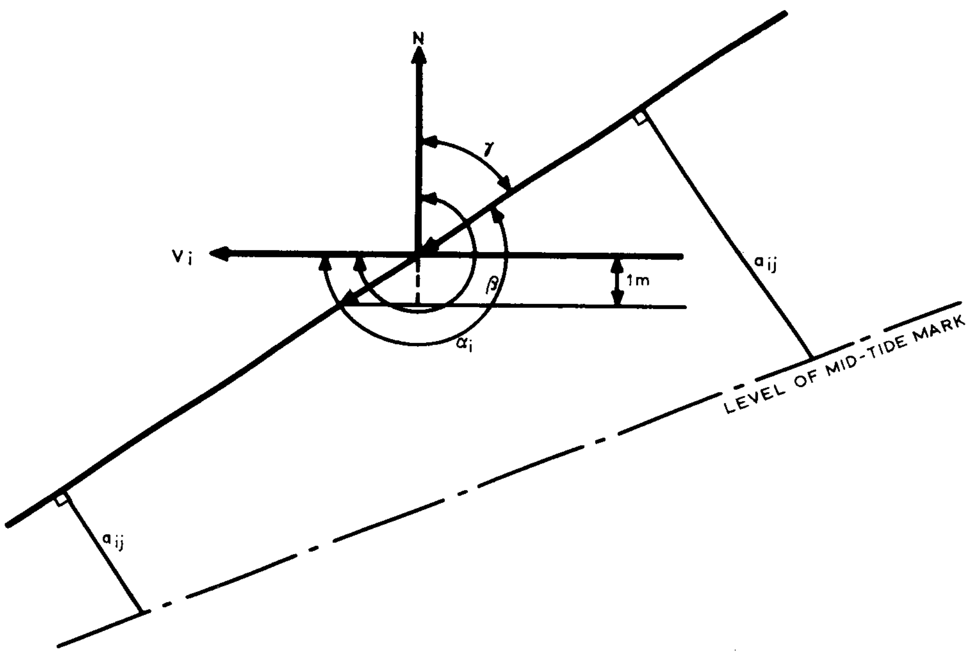

Figure 20. For explanation see text

The sheltering effect of the ridge of dunes in the case of offshore winds and the consequent reduction in wind velocities over the beach have not been taken into consideration. This is due to the fact that at present there are insufficient reliable data available on the reduction in the amount of sand transported by offshore winds compared with that transported by onshore winds of the same force.
Finally, the net sedimentation at a particular spot is often not only dependent on wind blown sand, but also on the amount of sand brought in by the waves under storm conditions.
A number of practical applications have shown however that useful data can be obtained by the method described above if a certain degree of uncertainty is accepted.

In the series of Rijkswaterstaat Communications the following numbers have been published before:

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Dr. J. J. Dronkers† and prof. dr. ir. J. C. Schönfeld
Report on Hydrostatic Levelling across the Westerschelde
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