The role of beach nourishment in altering phosphorus availability in Dutch sand dune ecosystems

Utrecht University
Faculty of Geosciences
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Author: **T. E. Mason BSc**
Email: t.e.mason@students.uu.nl
Student Number: 4046110

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Supervisors: dr. J. van Dijk
I. Pit MSc
Second Reader: prof. dr. Jasper Griffioen
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Utrecht University

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Abstract

Beach-nourishment is becoming more popular as a method to fight coastal erosion (Speybroeck *et al,* 2004a). A new form of beach-nourishment, the mega-nourishment is being trialled in the Netherlands as an alternate form of nourishment using the power of nature to defend against coastal erosion (De Zandmotor, 2014). However no research has of yet analysed the role of beach-nourishments in potentially altering the P-availability in a sand dune ecosystem. This paper aims to compare the effects of a mega-nourishment and traditional-nourishment site against a reference site (non-nourishment) to see analyse the effects of differing nourishment techniques on sand dune ecosystem P-availability. Extensive field work and lab analysis of sediment samples collected from sandpits and sand traps revealed the three following major findings: 1) Both mega- and traditional-nourishments can become a potential new source of P when compared to non-nourishment site. At the beach on the non-nourishment site only 0.07 µmol g/ P more Tot-P was found when compared to the established dunes, however at the mega-nourishment and traditional-nourishment site this figure was 9.37 µmol g/ P and 2.54 µmol g/ P more. Secondly it was also found that through the mean of aeolian transportation, high concentrations of P, predominantly in the form of Fe-P, were being transported to the established dunes beach-nourishment sites. Thirdly it was found that the concentration of Fe-P at beach-nourishment sites was strongly related to the proportion of fine grain sediment in the sample, meaning that nourishment samples containing a higher proportion of fine-grain sediment are more likely to alter P-availability at sand dune ecosystems in the future. More research is required to ascertain how this change in P-availability could affect the sand dune ecosystem over time.

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1. Introduction

At present, the Dutch coastline is being plagued by erosion and subsidence (Ramaekers, 2015). This is a problem that may get worse as global environmental change continues. As sea levels rise and the magnitude and quantity of storm events increase erosion is expected to become a pressing issue for the Dutch coastline in the forthcoming century (Giardino *et al*., 2013). There are currently a multitude of measures that can be implemented to reduce coastal erosion, ranging from breakwaters, groynes and seawalls to dykes, walls and boulders, as well as beach nourishment techniques (Arens *et al*., 2013; Airoldi *et al*., 2005).

Beach nourishment currently plays an important role in the Dutch coastal management plan, with beach nourishments constantly increasing every year in the Netherlands (Hanson *et al*., 2002). Giardino *et al*. (2011) states that as time progresses and as sea levels rise and storm events increase as predicted, the yields of sand required for sand nourishment will also have to increase. Today, beach nourishment is considered better than traditional hard defences, with much research looking into the effects of beach nourishment on erosion (Brown & McLachlan, 2002; Hamm *et al*., 2002, Hanson *et al*., 2002, Greene, 2002, Finkl, 2002). However, little work has examined the effects of beach nourishment on the geochemistry of the deposition sites, nor the subsequent effects on the ecology. This is an important oversight as the addition of sand from another location may contain many different properties, such as; grain size, sediment composition and pH. These alternate properties, amongst others, may affect the geochemistry at the nourishment site (Speybroeck *et al*., 2006). For example, finer grain sediment contains higher concentrations of Fe/Al-bound phosphate (Fe-Al-P) than coarser grains (Andrieux-Loyer & Aminot, 2001), and it has been found that beach nourishments often consist of finer grain material (Greene, 2002; Hamm *et al.,* 2002) Continuing, beach nourishments that for example are enriched with more shells would contain a higher proportion of Calcium-bound phosphate (Ca-P) (Slomp & van Cappellen, 2007), whilst a sediment with a lower pH would cause the dissolution of Ca-P into organic-bound phosphates (Org-P), which are more easily accessible for vegetation and micro-organisms (Kooijman *et al*., 1998). It is therefore important to consider the effects of the properties of new sediment used for beach nourishment on the geochemistry.

Currently, in the lime-rich soils in the south-west (Renodunaal district) of the Netherlands both N and P play significant roles in ecological succession in the sand dune ecosystem. In the Renodunaal district P-availability is the regulating nutrient, limiting the biomass production as it is found in lower quantities than in nitrogen (N). However, the N:P ratio is liable to change in response to how calcareous the soils are. In calcareous soils N and P co-limit one another, in partly decalcified soils N and P can be found highly available and in decalcified soils P can be found in decreased availability (Kooijman & Besse, 2002). Kooijman & Besse (2002) found that the high nutrient availability in partly decalcified soils of the Renodunaal district was correlated with a peak in above-ground biomass. Subsequently, Kooijman and Besse (2002) state that the above-ground biomass is due to the peak in P availability, found in the partly decalcified soils, as P is generally more soluble at this pH and less likely to become fixed to either calcium, iron or aluminium phosphates. Nitrogen, on the other hand, shows no relationship. As a result of this, P-availability in sand dune ecosystems must be a key consideration when work, such as beach nourishments, may affect its availability.

In the lime-rich Renodunaal district of the Netherlands biomass production is predominantly regulated by P-availability (Kooijman, 2004). Therefore any changes to the total phosphorus (Tot-P) or the individual fractions of the phosphorus (P) may have consequential effects for both the biomass production and N-availability. Continuing, when one consider that the sand dune coastal zones along the Dutch coastline is home to 70% of the plant species found in the Netherlands (Veer & Kooijman, 1997), any changes in the P-availability could have serious consequences for the vegetation that grows there and the ecosystem that exists.

This paper investigates the relationship between beach nourishments and P-availability, examining whether the use of two types of beach nourishments can affect the availability of individual fractions of P, the Tot-P and whether these changes in P-availability could affect the vegetation in the future. The research consists of fieldwork, where data was collected from 3 different sites, and lab-analysis to analyse the P-fractions and Tot-P found in the sediment at the different sites. The results from the lab analysis will then be statistically analysed. Firstly, this paper will examine the forms of beach nourishment, before providing a literature review and then generating aims and hypotheses. The field site locations and methods shall then be summarised, wherefore a detailed description of the results and discussion is given.

1.1 Background Information

1.1.1 Forms of Beach Nourishment

This paper will examine two types of beach nourishment: mega-nourishment and traditional-nourishment. Both forms of nourishment can be described using the same terms:

"*… an artificial addition of suitable quality of sediment to a beach area that has a sediment deficiency in order to rebuild and maintain that beach at a width that provides storm protection and a recreation area"* (Davison, *et al.*, 1992).

Beach nourishment addresses the issue of rebuilding and then maintaining a beach, by firstly being a source of restoration, by providing a large initial supply of sediment, and then by renourishing the coastline over time by smaller periodic contributions over time (Davison, Nicholls & Leatherman, 1992). The main difference between the application of a mega-nourishment and traditional-nourishment is the scale. Mega-nourishment projects are much larger than traditional-nourishment projects, consisting of a much higher quantity of sand and a larger target area for restoration and re-nourishment. Mega-nourishments are expected to have a series of advantages over traditional-nourishments being more economical, efficient and more environmentally friendly than their traditional-nourishment counterparts (Van Slobbe *et al.*, 2013).

Fig.1.1 – A photograph showing the full extent of the sand motor after it was initially deposited in 2011. Source: Dutch Water Sector (2011).

The Sand Motor, a pilot project of building with nature on a large scale, was created in 2011 and is an example of mega-nourishment, much larger than traditional-nourishment methods. It is the first example of mega-nourishment worldwide and a substantial 21.5 million cubic metres of sand has been deposited at the site (fig.1.1), which can be found on the coastline 7km south of The Hague (De Zand Motor, 2014; 2013a, 2013b, 2013c). The mega-nourishment was deposited along 2.4km along of the coastline and extended 1km out to see at its furthest point and take the shape of a hooked peninsula (Stive *et al.,* 2013). It is expected that the Sand motor will nourish a 10km section of coastline over the next 20 years (Stive *et al*., 2013). The Sand Motor uses nature, such as tidal and aeolian forces to transport sand from the deposition site up and along the South Dutch coast in order to supplement and form new beaches and sand dunes (De Zand Motor, 2014; 2013a, 2013b, 2013c). It is expected that 60% of the nourishment will nourish the coastline north of the sand motor, whilst 40% will nourish the coastline to the south of the sand motor. In short the three main purposes of the Sand Motor are as follows (De Zand Motor, 2013a, 2013b, 2013c, 2014):

- To provide long-term protection and enhancement of the coastline
- To widen beaches and dunes in order to increase natural and recreational development
- To develop knowledge and innovation in coastal reinforcement and management.

The expected development of the Sand Motor is portrayed in Fig.1.2 and its location is shown in Fig.2.

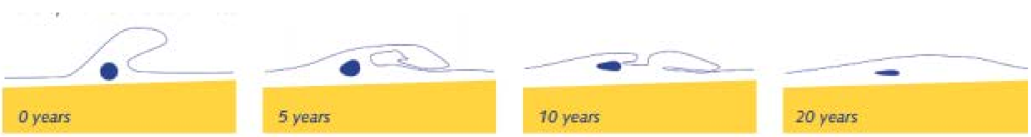


Fig.1.2. A diagram showing the expected development of the sand motor over time, as sand is transported away from the deposition site via tidal and Aeolian transport. Diagram from De Zand Motor, 2012, p 1.

Traditional nourishments, which are smaller in scale than mega-nourishments, rely on the same principles as the mega-nourishment, but generally involve much smaller quantities of sand and target specific areas where there was no beach before, or only a very narrow beach (Speybroeck *et al*., 2006a). Mega nourishment projects, are exceptionally rare, with the Sand Motor being the first of its kind, however traditional nourishment projects are much more numerous with over 600 individual projects being completed in Europe between 1997 and 2002 (Speybroeck *et al*., 2006a). Furthermore, 200 of those traditional-nourishment projects were implemented in the Netherlands alone (Speybroeck *et al*., 2006a).

In this sub-chapter an examination of past literature and research into the effects of beach-nourishment on the local environment will be covered. This will examine the known effects of beach-nourishments on erosion, geomorphology, geochemistry, ecology, pH and sediment size. Subsequently, an overview of the different types of beach-nourishments will be given, including an in-depth analysis of a new form of beach-nourishment; mega-nourishments. From this literature review, a gap in the research was identified.

1.1.2 Previous Research of the Effects of Beach Nourishment

As beach nourishment projects become more wide-spread, with 600 projects in Europe being implemented in Europe alone between 1997 and 2002 (Speybroeck *et al*., 2006a), there has been an increase in research on the subsequent effects of beach-nourishment on erosion, geomorphology, ecology and geochemistry. It is worth noting that the majority of research is based on traditional-nourishments, as mega-nourishments are much more recent and there has been less time to examine their effects on the environment and ecology.

Erosion and Geomorphology

The impacts of beach nourishment on erosion and geomorphology of the area is heavily researched. Van der Meulen *et al*. (2014) examined the development of new dunes along the Delfland Coast, the Netherlands, which were created via beach and foreshore nourishments, a form of traditional-nourishment. It was found that 4 years after dredging sand from 10km off the coastline and then transporting it onshore that the geomorphological changes were quite dynamic. In those 4 years a substantial quantity of sand was transported away from the beach and the valley to the established dunes, with grasses also trapping a sizeable quantity of sand in the fore dunes (van der Meulen *et al.,* 2014). Aeolian transport was responsible for the these changes in geomorphology.

The research of Roelse (1996) took more of an overview to the work of Van der Meulen *et al.,* 2014), examining not only the effects of beach-nourishments on erosion and geomorphology, but also flood protection and recreation, amongst other issues. Traditional-nourishments along the Dutch coastline which were located at the following location were examined: Ameland, Texel, North-

Holland, Schouwen and Walcheren. Roelse (1996) found that in the majority of cases that traditional-nourishment was an effective way in reducing the amount of erosion that occurred at the targeted site. The only site were traditional-nourishment was deemed ineffective was at Texel, were it was also decided to build other hard coastal defences as it would theoretically prove cheaper over time.

Giardino *et al*., (2011) took another approach from the work of Van der Meulen *et al.,* (2014) and Roelse (1996) and created a numerical model to analyse sand volumes and sediment transportation along the Dutch coastline to use as a tool for beach-nourishment assessment. This mathematical model allowed an analysis over a much longer period of time, looking at more lasting effects of beach-nourishments. Giardino *et al*., (2011) assessed two scenarios based on two different data sets, data from 1964-1990 (scenario 1) and data from 1990-2006 (scenario 2). Scenario 1, where beach-nourishment was quite rare, revealed that most of the Dutch coastline suffered some form of structural erosion. On the other hand, their analysis of scenario 2 (where beach-nourishment is more common) alongside a long-term prediction based on a numerical model suggests that beach-nourishment is successfully mitigating erosion issues (Giardino *et al.,* 2011).

Greene (2002) and Hamm *et al.,* (2002) analysed the movement of sediment at beach-nourishment site, assessing the physical changes on the site. For example, the sand at the targeted beach is much more compacted and also with a range of 3-4 times higher than previously. Greene (2002) also found that bordering beaches would benefit from longshore drift, as sand would be transported from the nourished site along the coast, thus reducing overall erosion along the coastline. Hamm *et al.,* (2002) found that the transport of sediment from the beach-nourishment site was inevitable. However, they noted that this was a complex process as the transportation of sediment was dependent on many factors. The location of the beach-nourishment may affect the prominence of either long or cross-shore drift, thus effecting the transportation and effectiveness of reducing erosion in adjacent beaches. Hamm *et al*., (2002) also stated that finer material, was more easily transported, thus meaning that beach-nourishments of finer material would be more quickly transported to counter erosion issues. However, one may speculate that if this is the case, that the beach-nourishment would also have a shorter life span than a beach-nourishment made or more coarse material. Another complication is that other time (e.g. decades) tidal patterns can change, meaning that the distribution of material can also change, thus affecting the geomorphology and effectiveness against erosion (Hamm *et al*., 2002).

In summary, there has been ample research into the effects of beach-nourishment onto geomorphology and erosion in the local area. It has been found in all but one of the cases, that beach-nourishment significantly reduces erosion in the local coastline, with the one exception being on Texel (Roeles, 1996). These findings are further strengthened by the modelling work of Giardiono *et al.,* (2011) and the analysis of Greene (2002). Furthermore, van der Meulen *et al*., (2014) also found that there is significant transportation of sediment from the beach to fore and established dunes, as well as discovering that sediment from the valley is also transported to the established dunes. Hamm *et al*., (2002) adds more to this field, by stating that beach-nourishments that consist of finer sediment will be more easily transported.

Beach-Nourishment Sediment P-binding

Whilst there has been much research into the effects of beach-nourishment onto the local geomorphology and erosion, there has been little research into how the addition of borrow sediment onto the beach may affect the local sediment chemistry. The work of Stufyzand *et al*., (2012; Stufyzand *et al.,* 2010) did perform an in-depth analysis of the effects of beach-nourishment on the Dutch coastline. Their work revealed that on average the content of lime, iron (Fe), phosphorus (P), arsenic (As), barium (Ba), cobalt (Co), caesium (Cs), nickel (Ni) and zinc (Zn) were significantly higher in sand that contained nourished sediment than sand were no beach-nourishment had occurred (Stufyzand *et al.,* 2012). Whilst this research did reveal higher concentrations of P found in the sand containing nourished material, it did not provide a further analysis of how this P was bound to other material. Whilst there has been some research into the area, it is difficult to apply the findings directly to beach-nourishment sites in the Netherlands. For example Rasheed *et al*., (2009) examined the chemical composition of sediment from four potential borrowing sites with that of the intended deposition site for the beach nourishment. It was found that the contents of the organic carbon (C), total nitrogen (N), total P, inorganic N, inorganic P, inorganic P, cadmium (Cd), Co, copper (Cu), lead (Pb), Zn and magnesium (Mn) in the sediment from the potential borrowing sites were generally within a similar range or slightly less that the concentrations of the marine sediments found in local area. However, it is difficult to directly apply these findings to beach-nourishment sites in the Netherlands for a number of reasons. Firstly, this research was conducted in the Gulf of Aqaba and the Red Sea, a completely different biome from the Dutch coastline with different sedimental and geochemical properties. Secondly, the sediment selected as borrowing sites were predominantly terrestrial sites, with only a one site consisting of sediment dredged from the sea floor. Thirdly, the research is predominantly concerned with examining the possibility of leeching of chemicals from the sediment applied to the beach-nourishment site into the ocean, rather than examining the potential effects on the local vegetation. Therefore, it is difficult to extrapolate the findings of Rasheed *et al*., (2009) to the Dutch coastline, as Dutch beach-nourishments generally consists of sand being dredged from only the seafloor, not terrestrial sites. Also, in the Netherlands as the sand for the beach-nourishment is dredged off the seafloor, there is no worry of it leeching back into the sea and potentially causing a significant change in the chemical concentrations found there.

Another limited aspect of relevant beach nourishment research is the work of Greene (2002). Greene (2002) found that sediment containing high quantities of shell content could cause long-term issues. Unlike finer material, such as sands and silts which are transported away from the nourishment site, the shell content tends to remain due its heavier weight. Whilst Greene (2002) does not make the following statement, it would be logical to believe then to find higher contents of Ca-P at the beach nourishment site than the fore dunes, established dunes or further along the coast.

Marine Sediment P-binding and grain size

The grain size found in beach-nourishments may differ due to the depth the sediment was dredged from. Van Duin *et al*. (2012) states that usually nourishments only dredge up sediment from the Holocene epoch, however when larger beach-nourishments are required sediment can also be dredged up from the Pleistocene epoch. This difference in sediment is important as it could equate to different sediment properties, such as grain size.

Whilst there are no other papers that the author could find that analysed the specific P-binding of sediment used in beach-nourishments, there are still further insights to be gained from other related literature. For example, there has been ample research into phosphorus concentrations in iron oxide marine sediments. Slomp *et al*., (1996) analysed the role of iron oxides in binding to P in North Sea sediments at depths up to 12cm below the seafloor and found that in fine sediment fractions (<10μm) of surface samples iron-oxides played a dominant role in P-binding. Furthermore, it was found that the iron-oxides that the P binded to was found at all depths measured, suggesting that these iron-oxides could act as both a temporary and permanent sink for P in these marine sediments (Slomp *et al*., 1996). This is an important point to consider as the sand that is dredged up for beach-nourishment along the Dutch coastline is from these areas in the North Sea, so may contain the same P-binded iron-oxides. Examining other forms of P-fractions, Caraco *et al.,* (1990) examined the role of P released by decomposition in sediments. It was found that, unlike Fe-P, that P released by decomposition (Organic-P) was not permanently stored in the marine sediments, but rather released into the ocean water.

Bramha *et al*., (2014) conducted an in-depth analysis of the distribution of P-fractions in surface marine sediment (0-5cm) off the Kalpakkam coast, India. Whilst the location of this research is a large distance away from the Dutch coastline, useful conclusions can still be drawn from this research. Bramha *et al*., (2014) found Calcium-P (Ca-P), Fe-P, Aluminium-P (Al-P), Organic-P (Org-P) and loosely-P (Lo-P) all present in the sediment. Of particular note is that it was found that Ca-P was the largest fraction (68.7%) present, followed by the Org-P (16.4%). Moreover, the concentrations of Fe-P and Al-P were directly related to the quantity of fine sediment found in the sample.

Further support to the findings of Bramha *et al*., (2014), Andrieux-Loyer & Aminot, 2001) found that Fe-P, Al-P and exchangeable (exch-P) are all significantly related to the proportion of fine fraction (<63μm) sediment. They studied marine sediment collected from the Bay of Seine, amongst other areas along the French coastline and found that Fe-P and Al-P was positively correlated against the amount of finer grain size sediment. Furthermore, they also found that the source of Ca-P was likely to be of shell or metamorphic continental origin, rather than of sedimentary origin (Andrieux-Loyer & Aminot, 2001). Closer to the Dutch coastline, Eisma & Kalf (1979) and Eisma (1968) found that Belgian-Dutch coastal water generally consisted of finer suspended particles, which was most likely due to a shoreward displacement of near-coastal bottom water. It is therefore important to consider the amount of fine grain size sediment being dredged up and being used in beach-nourishments. Greene (2002) and Hamm *et al.,* (2002) both found that beach-nourishments sourced from marine sediments usually consist of a higher proportion fine grain size sediment then the non-nourished sand it is about to supplement. This fine grain material is more easily transported by aeolian processes, meaning that it could be easily transported into the established sand dunes (Hamm *et al.,* 2002). As a result of this more Al-P and Fe-P could enter the sand dune ecosystem. This potentially could be an issue as in established sand dunes in the as the top layer of sediment can be partly decalcified or decalcified (Kooijman, 2004). Therefore the solubility of the Fe-P and Al-P increases, making the P bounded to them more accessible to the vegetation (Shen *et al.,* 2011).

Riverine Sources of Phosphorus

An important source of P to the oceans come from river water (Grizzetti *et al.,* 2012), so therefore it is important to consider how this may influence sediment being dredged up for beach-nourishments. Van der Zee *et al.* (2007) examined phosphorus retention, transformation into other P-fractions at the Scheldt estuary (Belgium/Netherlands). They argued that estuaries are key sites where biogeochemical processes can alter fluxes from land to the oceans. This is important to consider, as sewage is still a large source of P in river water (Jickells, 2005). The research of Van der Zee *et al*., (2007) found that the rivers Sheldt and Zenne were key suppliers of P to the estuary, with inorganic-P being more common than organic-P. Furthermore they found that the Scheldt sub-basin was a source of particulate inorganic phosphorus (PIP) and to the estuary during the productive time of the year (May-September) (Van der Zee *et al*., 2007). Continuing Van der Zee *et al*., (2007) found that P transformed into new fractions in the Scheldt estuary, which subsequently led to the estuary acting as a source of PO_4 to the coastal area. These findings are further reinforced by the work of Grizzetti *et al.* (2012) whose work analysed the N and P loads discharged from rivers to coastal European seas. Their results found whilst P loads into the North Sea has been decreasing over the last 20 years, the P influx into the North Sea is still a substantial 6000 ton P per year. Adding, further relevance to the above work, Van Beusekom and De Jonge (1998) found that in the Ems estuary 60% of the total P was transported out to the North Sea, with the remaining 40% being trapped in the estuary's sediments.

Previous research has shown that P from the North Sea is generally exported to the North Atlantic at a rate of 4 – 52kT P per year^{-1}, which is a substantial rate, however thus includes other P inputs such as the NW & NE Atlantic, E Skagerrak and Southern Channel (Brion *et al*., 2004). However, Brion *et al*., (2004) also found that the amount of P being buried in sediments in the North Sea varies hugely from -10 ± 9 TP kT year^{-1}. With such a substantial quantity of P being transported to the coastal zone of the North Sea it is an intriguing question on how this stored P in the marine sediment may affect P-availability in sand dune ecosystems when it is dredged up for beach-nourishment purposes.

Sand Dune Sediment Chemical Composition

The chemical composition of the sand is a key consideration for many reasons, but it is especially meaningful when analysed in the context of its relationship with the ecology that is reliant on it for an influx of nutrients. Nitrogen (N) and phosphorus (P) are extremely important for plant growth (Neset & Cordell, 2011), with a substantial amount of research examining their roles in sand dune ecology (Jones *et al*., 2004; Kooijman & Besse, 2002, Kooijman *et al*., 1998, Oliff *et al*., 1993, Kachi & Hirose, 1983). One of the most significant findings in Dutch sand dune ecosystems is that in most cases phosphorus limitation is prevalent, due to the high levels of N deposition (Kooijman & Besse, 2002; Kooijman *et al*., 1998). Furthermore, Bakker *et al.* (2005) states the form of P-fraction is extremely important for plant uptake. Not all P is available to plants, however sand dune ecosystems are an example of early successional vegetation that can persist on low P-availability. (Bakker *et al.,* (2005). P-availability in sand dune ecosystems largely depends on the precipitation and adsorption of inorganic P, specifically Ca-P and Fe-P. Whether the phosphorus is precipitated or adsorbed by the Ca and Fe depends on the soil pH. Bakker *et al* ., (2005) found that in calcareous dunes (pH above .3)

Ca- and Fe- rich soils can reduce the P-availability of the soil by adsorping the P, meaning that over time the soil will become more suitable for early successional vegetation. However if the pH of the soil becomes more acidic, the Ca-P and Fe-P become more soluble, releasing the P into the soil and increasing the P-availability for the vegetation. This means that the Dutch sand dune ecosystems may be vulnerable to changes in the P-availability as well as the concentrations of Fe-P and Ca-P of the sediment.

1.2 Research Problem

As of yet, no research has examined whether beach nourishment in the Netherlands may alter the P-availability for the sand dune ecosystem. I would expect to see some significant differences in P-fractions and perhaps total-P between sites where beach-nourishments have occurred and where beach-nourishments have not occurred. I believe these differences will occur due to higher quantities of finer grain sediment and associated Fe-P at the sites where beach nourishment occurred. Furthermore, there may be differences in the P concentrations of the two beach-nourishment techniques as the sediment was dredged from different depths under the seafloor, may contain different quantities of marine shells and Fe-P and properties such as grain size.

Furthermore, I also expect there to be significant differences in P-fractions and total-P between the beach where the nourishment is deposited and further inland at the established dunes. Firstly I believe that there will be a higher concentration of Ca-P on the beaches than in the established dunes. This is due to the high quantities of sea shells dredged up in the beach-nourishment process that cannot be transported away from the deposition site by aeolian transport. Furthermore, I expect to find higher concentrations of Fe-P being transported from the beach to the established dunes, due to its associated grain size being more easily transported by aeolian transport. Again, I would expect there to be a scaler effect in the differences, with a great difference observed between the beach and the established dunes at a site of Mega-nourishment, than a site of traditional-nourishment and also a site of non-nourishment.

1.3 Research Aim

The aim of this research is to examine how beach-nourishments affect the P-availability in Dutch sand dune ecosystems. This paper aims to examine the differences over two spatial scales, that of inter-site differences (e.g. difference in Total-P between a site of mega-nourishment and non-nourishment), and of intra-site differences (e.g. difference in Total-P between beach and established dunes). This paper aims to examine the difference in not only Total-P, but also the differences in P-fractions over these two scales.

1.4 Research Questions

The overarching research question of the project is:

- Can beach-nourishments cause substantial differences in p-availability in sand dune ecosystems when compared to non-nourishment sites?

The sub-research questions are as follows:

- **R.Q.1:** Are mega- and traditional-nourishments potential major sources of phosphorus, and do the two nourishment techniques differ from one another in the quantity of phosphorus they provide?
- **R.Q.2:** What forms and amounts of P-fractions are transported to the established dunes via aeolian transport and are they significantly different from identified potential major sources?
- **R.Q.3:** What important differences are there in the P-fractions, particularly Fe-P and Ca-P, between aeolian transported sand at the beach-nourishment sites and non-nourishment sites?
- **R.Q.4:** Can grain size of the imported sediment play a significant role in the phosphorus availability at mega- and traditional-nourishment sites?

This research will collect soil and windblown sediment samples from a mega-nourishment site, traditional-nourishment site and non-nourishment site. These samples will then be analysed for total P availability and its composition of P-fractions.

1.5 Relevance of Research

1.5.1 The scientific relevance of the proposed research

Whilst there has been much research into sand nourishment, none has yet analysed the roles of both mega and traditional nourishment in altering the available phosphorus in the local sand dune ecosystems. The current research has predominantly addressed issues with erosion and changes in morphology of the beaches and sand dunes, but little as examined the role beach-nourishments in effect P-availability. The research proposed in this document aims to fill the gap in literature with regards to the role beach nourishment plays in potentially altering the phosphorus availability in sand dune ecosystems in the Netherlands.

Whilst there has been research into the various forms of P-speciation and P-binding ; Bramha *et al.*, 2014; Wang *et al.,* 2013; Slomp *et al.*, 1996), there has been no research that examines the role of P-speciation and P-binding in beach nourishment and the subsequent effects on the local sand dune ecosystem. Again, the research proposed in this paper will help to address this gap in the literature.

1.5.2 The social relevance of the proposed research

This is an extremely important point, as beach nourishment plays an important role in Dutch coastal defences and at present looks only likely to become more crucial role in the future of Dutch coastal defence (Giardino *et al.*, 2011). With more of the Dutch coastline potentially be exposed to beach nourishment projects, large swathes of sand dune ecosystems could be affected. As phosphorus availability governs plant productivity (Kooijman & Besse, 2002) and beach nourishment projects potentially being a new source of phosphorus to the local sand dune ecosystems, the local ecosystem could potentially change as more phosphorus become available. This could threaten the high biodiversity that is found in the Dutch sand dunes (Grootjans *et al*., 2002). With academics stating that anthropocentric activities are causing large scale habitat loss and extinctions over the planet, we should strive to be more aware about how our activities may cause damage to and in extreme causes cause species to go extinct (Rockstrom *et al*., 2009).

2. Research Design

The research design is composed of the following sections:

- Study area:
  - Mega-nourishment site
  - Traditional-nourishment site
  - Non-nourishment site
- Areas of research:
  - Collection of sand pit sediment
  - Collection of sand trap sediment
  - Chemical and grain size analysis of sediment
- Statistical analysis

2.1 Study Area

The sediment samples for laboratory analysis were collected between March and May 2015 from 3 different sites along the Dutch coastline. All 3 sites that were selected are found south of the calcium boundary found at Bergen-aan-Zee (52.661520 N, 4.632103 E). The calcium boundary found at Bergen-aan-Zee is an important boundary to consider (Fig.2.1). To the north of this boundary is the Wadden district with coastal dunes that were initially low in calcium content, whilst to the south of the calcium boundary the Renodunaal district is located, an area of coastal dunes with initially high calcium content, (Kooijman, 2004; Kooijman *et al.*, 1998).

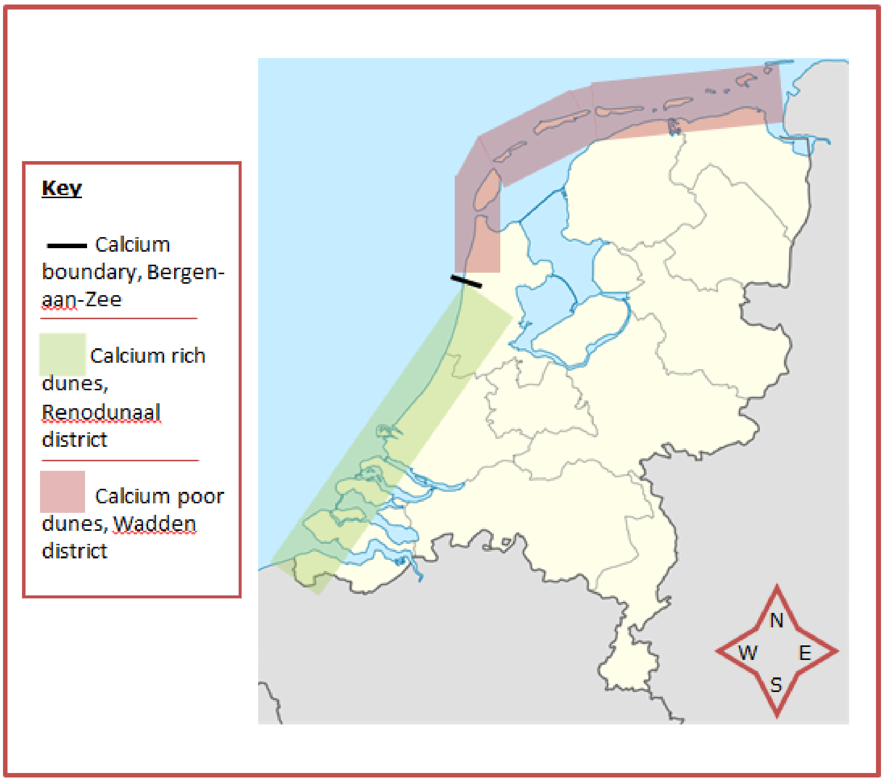


Fig.2.1 A map depicting the differing calcium zones of the Dutch coastline

Whilst it would be ideal to be able compare and analyse sites along the entire Dutch coastline this is not possible due to the differing calcium content zones of the sand dunes. Due to these fundamental differences in the calcium content of the soils and how it affects the sites chosen for study were all located in the Renodunaal district. Here, in the Renodunaal district contain high quantities of calcium phosphates such as dicalcium phosphate and hydroxyl apatite, resulting in more phosphorus readily available for vegetation uptake. Conversely, in the Wadden district, where the coastal dunes are now nearly completely decalcified, these calcium phosphates are much rarer, with thus much less phosphorus available for vegetation uptake (Kooijman *et al.*, 1998). Because of these fundamental differences in phosphorus availability in the soils of the Wadden and Renodunaal district it makes it illogical and difficult to analyse and compare sites from both districts in the same study.

In the Renodunaal district 3 different types of soil can be found (Kooijman, 2004):

1) Calcerous soils where a high pH is present
2) Soils were the topsoil has decalcified, though the root zone is still calcified
3) Soils were the top 1m has become decalcified and acidic.

These changes in the soil are caused by the evolution of successional stages in vegetation, with the successional stages progressing causing a decrease in the pH and calcium content. As pH decreases calcium phosphates dissolve quickly, allowing the incorporation of the phosphorus into organic matter by vegetation and micro-organisms (Kooijman *et al*., 1998).

The dunes of the Renodunaal district composed of sand that was deposited during the late Pleistocene and early Holocene. The source of this sand is from the rivers Maas, Rijn and Schelde and contains high concentrations of nutrients and calcium (Ecomare, 2015; Eisma, 1968).

The field sites selected are described below, with a map (Fig.2.2) showing the location of the field site locations.

2.1.1 Mega-nourishment site

The site chosen to study the effects of mega-nourishment on p-availability is located south of Den Haag at the following co-ordinates: 52° 3'5.04"N, 4°11'5.10"E. The mega-nourishment there is known as the sand motor and is the main study site of the research. The Sand Motor was created in 2011 and contains 21.5 cubic million metres of sand. (De Zand Motor, 2014; 2013a, 2013b, 2013c). The distance from the far edge of the nourishment site to the dunes is currently 1km, whilst the length of the deposition site along the coastline is currently 3.7km. The beach is very popular with leisure-goers, particularly with kite-surfers, although the sand dunes themselves are protected and off limits to the public.

2.1.2 Traditional-nourishment site

The site chosen to study the effects of traditional-nourishment on p-availability is located at the Zoutelande, Zeeland at the following co-ordinates: 51°30'12.77"N, 3°28'24.36"E. The sand nourishment here was also implemented in 2011, the same year as the mega-nourishment site chosen to be investigated. It is a magnitude of about 5 times smaller than the mega-nourishment site. The nourishment site is now no longer easily distinguishable, but GPS co-ordinates were provided to find the location of where the nourishment was deposited. The distance from the nourishment site to the dunes is only 0.13 km, whilst the distance of the nourishment along the coastline is unknown, it can be assumed to much smaller than the mega-nourishment site (by upto a magnitude of 5). The site is popular with leisure-goers and close to the town of Zoutelande, with neither of the beach nor the dunes off limits to the public.

2.1.3 Non-nourishment site

The site chosen to examine p-availability at a beach where no beach nourishment was implemented is located at just north of Castricum-aan-Zee. This site is being used as a reference site to compare the other two sites against. The site can be found at the following co-ordinates: 52°34'28.11"N, 4°36'35.31"E. The distance from the beach to the dunes on average is 0.13km in distance. The beach is again popular with leisure-goers, with the dunes not being accessible to the public.

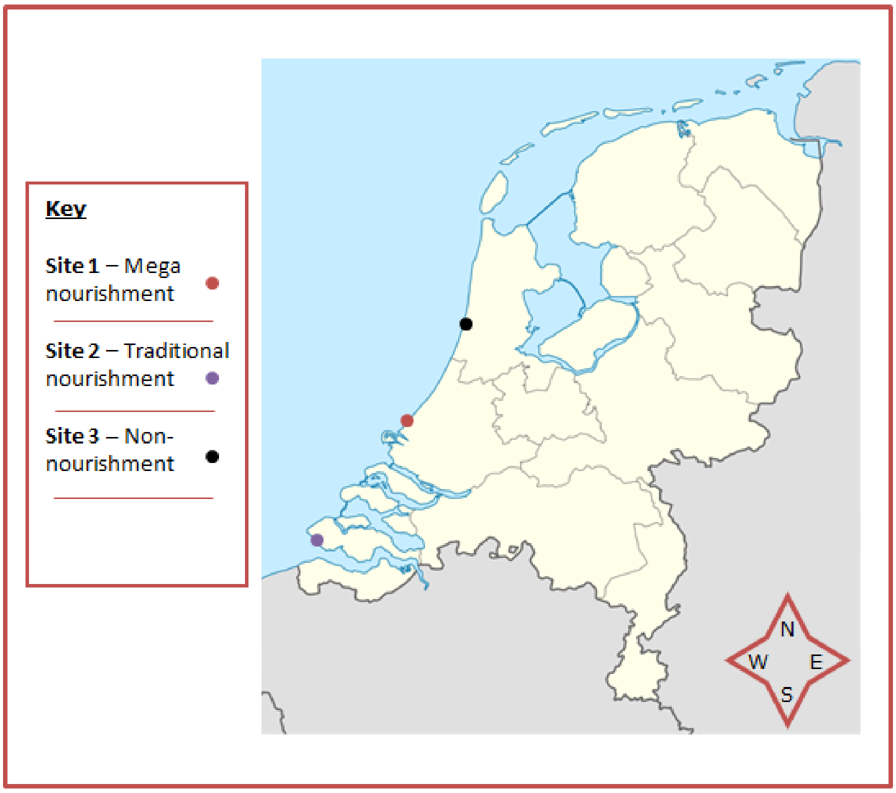


Fig.2.2 A map showing the locations of the three field sites.

Descriptive information on the transects at each site can be seen in table 2.1.

Site	Transect	Beach Transect point co-ordinates	Established dunes transect point co-ordinates
Mega-nourishment	A	52° 3'2.57"N, 4°11'1.70"E	52° 2'51.45"N, 4°11'27.59"E
	B	52° 3'5.04"N, 4°11'5.10"E	52° 2'53.93"N, 4°11'31.04"E
	C	52° 3'7.32"N, 4°11'8.62"E	52° 2'56.41"N, 4°11'34.29"E
Traditional-nourishment	D	51°30'10.97"N, 3°28'28.63"E	51°30'13.86"N, 3°28'32.15"E
	E	51°30'12.77"N, 3°28'24.36"E	51°30'15.63"N, 3°28'28.69"E
	F	51°30'14.70"N, 3°28'20.09"E	51°30'17.77"N, 3°28'24.50"E
Non-nourishment	I	52°34'25.02"N, 4°36'34.19"E	52° 33'59.5" N, 4°36'35.5" E
	J	52°34'28.11"N, 4°36'35.31"E	52°34'01.5" N, 4°36'36.45" E
	K	52°34'31.16"N, 4°36'36.66"E	52°34'29.84" N, 4°36'36.41"E

Table.2.1 – A table showing the co-ordinates of each transect for each site.

2.2 Areas of Research

The research was split into three separate areas in order to answer the four different research questions:

Firstly, it was important to determine whether the beach nourishments could be a potential new source of phosphorus to the local sand dune ecosystems. This was achieved by the chemical analysis of sediment collected from sand pits.

Secondly, it was important to determine what concentrations and forms of P were being transported to the established dunes. This was achieved by deploying sand traps to capture sediment being transported by aeolian processes.

Thirdly, to test the test the relationship with P-fractions grain size analysis was conducted on samples collected from both the sandpits and sand traps.

2.2.1Collection of sand pit sediment

The aim of this area of research was to assess whether beach nourishment could provide a potential new source of phosphorus to the local sand dune ecosystem. This was achieved by collecting data from all 3 field sites. At each site location 3 transects were laid, as shown in fig.2.3. The transects stretched from the nourishment site (were present), up the beach and into the sand dunes. Each transect will initially only had 2 sampling points along it, one at each end of the transect: the beach nourishment site (were present) and the established dunes. In the case of the non-nourishment site the beach and the established dunes were the two sampling points along the transect.

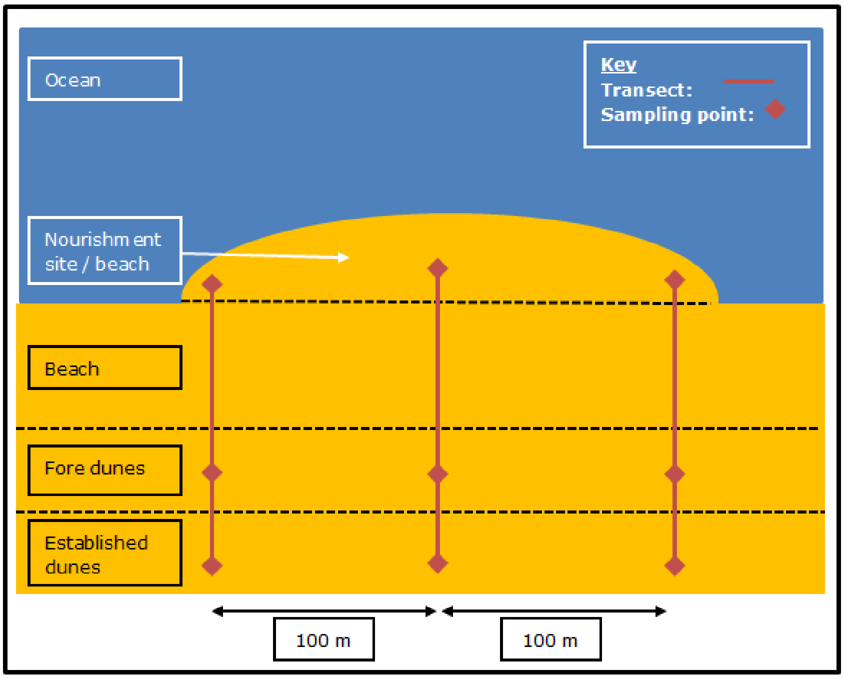


Fig.2.3: A diagram showing the transect plan for each site

At each site location, the transects were laid 100m apart, in order to collect samples from a large area of the nourishment site. At each sampling point 5 small sand pits were dug shown. Each sandpit was 5cm deep, and the sediment collected form the 5 sandpits was stored together in one geological bag and mixed together at the sample location. At each field site a total of 6 samples were collected, 3 samples from the beach / beach nourishment and 3 samples from the established dunes, meaning a total of 18 samples were collected for this stage of the analysis.

2.2.2 Collection of sand trap sediment

The aim of this area of the research was to assess what concentrations of Tot-P and individual forms of P-fractions were being transported to the established dunes. Data was again collected from the same field sites and along the same transects as the previous area of research. An extra sampling point was added to each transect at the fore dunes (as shown in fig.2.3). At each sampling point on the transect sand traps were deployed to capture sand that was being deposited by aeolian transport. Photographs showing a deployed sand trap can be seen in fig 2.5.

Fig.2.5: Two photographs showing sand traps in use in the field. On the left a detailed image showing sand being depositing on the marble covered lattice. On the right, a sand trap dug into the fore dunes at the mega-nourishment site. Source: Pit (2015).

Sand traps have been extensively used for capturing sand moved via aeolian transport, especially in the studies of movement of sand dunes (Khedr *et al*., 2014; Rotnicka, 2012; Nordstrom *et al.,* 2011; Peterson *et al*., 2011; Wang *et al*., 2011). Much research has been conducted into the use and effectiveness of sand traps, and generally the results have been favorable, obviously assuming that they are deployed correctly and are not misused (Mendez *et al*., 2011; Sherman *et al*., 2011; Li & Ni, 2003; Goossens, *et al*., 2000; Goossens & Offer, 2000). The sand traps used in this research were built by Wageningen University.

2.2.3 Chemical and grain size analysis of sediment

Once the samples were collected they were freeze-dried within 7 days. Once the freeze-drying process was complete the sediment was analysed using a sequential extraction method (SEDEX). The methodology used was written by Kraal *et al.,* (2012) and was based on the work of Ruttenberg (1992). The SEDEX method allows the analysis of Exchangeable-P (Ex-P), Fe-P, Ca-P, Detrital-P (Det-P) and Org-P. An overview of the steps of the method can be seen in fig.3.4, with a full copy of the SEDEX method used in the lab analysis found in appendix 1.

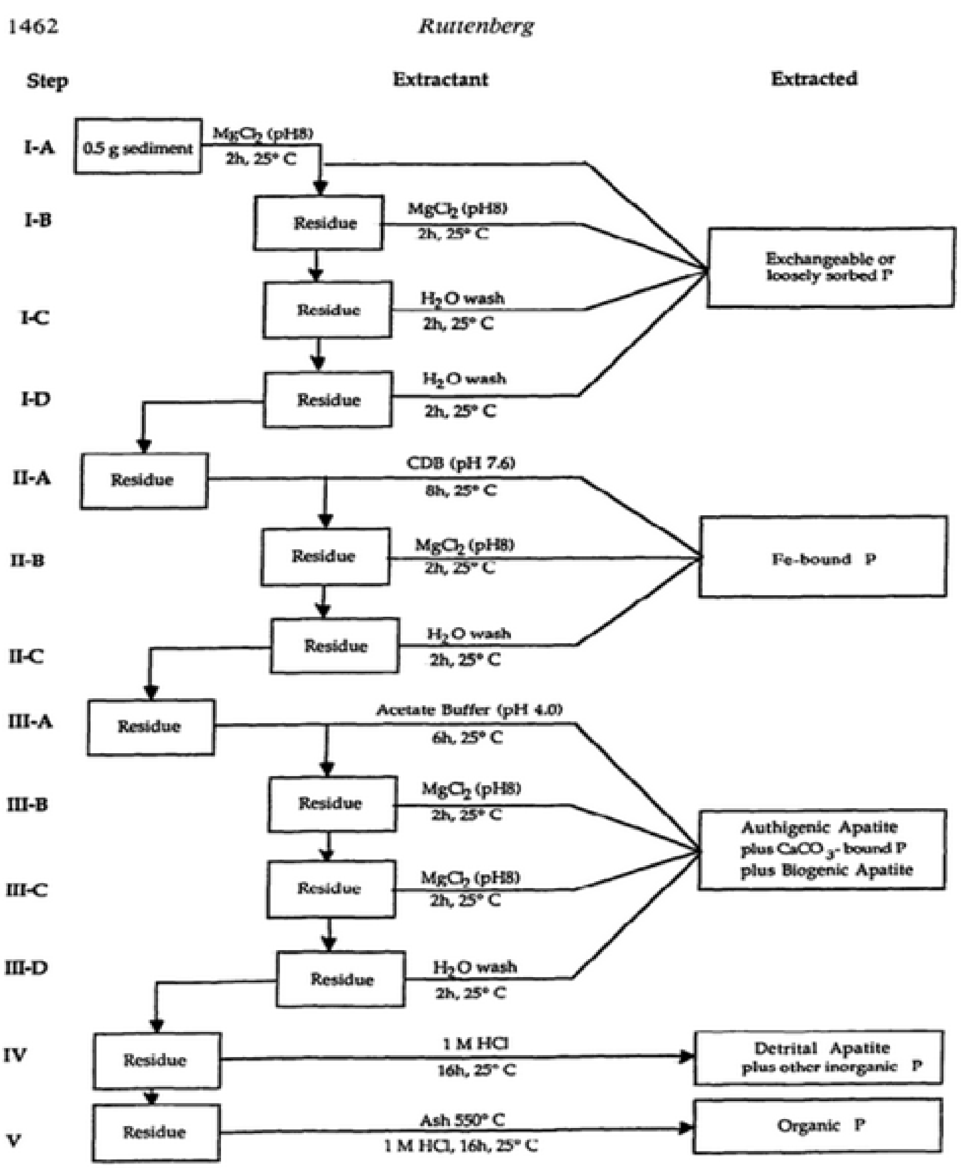


Fig.2.4: A flow-diagram showing the sequential extraction method for different forms of P found in marine sediments. (Image source: Ruttenberg, 1992, p 1462).

Samples from the central transects of each site were selected for grain size analysis (transect B, D and J from table 2.1). A limited number of samples were selected due to a combination of time constraints and physical constraints of the samples being able to analyse using the SEDEX procedure in one run. This grain size analysis composed of two parts. The first part split the samples into grain sizes: fine grain sediments (<150μm) and coarse grain sediments (>150 μm). Due to small samples sizes of the sediment collected with the sand traps, only sediment from the sand pits was used for the first part of the analysis. Objects larger than 2mm in diameter were removed from the sample (this could include plant material and large shell and rock fragments). Using a sieve and sieve automated sieve shaker the material was sieved for 12 minutes. These samples were then analysed using the SEDEX procedure to assess their Tot-P concentrations and composition of P-fractions. The second part was to assess the grain size distribution of each sample in order to identify what proportion of grain sizes were found in the samples. This part of the analysis used samples from both the sand traps and sand pits. This sample also had objects larger than 2mm in diameter removed from the sample. This part of the analysis was conducted by Iris Pit using a Malvern instrument to measure particle size below 2mm in size.

pH analysis was conducted for selected samples to give a broad overview of the sediment pH conditions at all 3 sites. The method detailed in Loch (2001) was used; weigh 5g of sediment and dilute to 15ml with UHQ, followed by mixing for 1 hour. The pH reader was than calibrated and the samples H^+ ions concentrations were measured.

2.3 Statistical Analysis

IBM SPSS Statistics (version 22) was used to statistically analyse the data. A multitude of statistical tests were identified for statistical analysis. All individual P-fractions and Tot-P of each transect point were statistically analysed to assess differences between the transect points of each site. The test to analyse the data for RQ1 and RQ2 was the one-way ANOVA (Heiberger & Neuwirth, 2009) if all assumptions were valid. Data was stringently tested for the following assumptions: normality was tested using the Shapiro-Wilk test and variance of the data was tested using Levene's test of homogeneity of variance. If the data could not fulfil these assumptions less powerful statistical tests, though which require fewer assumptions were used. In order of preference these tests were: Welch-ANOVA < Kruskall-Wallis < Mann-Whitney U test. Outliers were assessed by the use of a histogram and SPSS's built in outlier detection.

RQ3 was assessed using Principal component analysis (PCA) (Jolliffe, 2014). All individual P-fractions from the sediment collected from the sand traps was required to be statistically analysed to assess the variance found in the aeolian transported sediment. Data was again tested for assumptions. The observations:variable ratio was measured, the Kaiser-Meyer-Olkin test was used to test sampling adequacy, anti-correlation values of all variables were analysed, Barlett's Test of sphericity was used to test the distribution and co-variances of the data and the communalities of the variables were assessed. After the PCA was complete, Cronbach´s Alpha test was used to assess the reliability of the results of the PCA.

RQ4 was tested by the use of t-tests (Heiberger & Neuwirth, 2009). This statistically analysed the all the individual P-fractions and Tot-P by comparing the concentrations of each found in the different grain sizes. Data was tested for outliers, approximate normal distribution and homogeneity of variances.

3 Results

3.1 Sandpit tot-P and P-fraction concentration data

The results from the sediment collected by digging sand pits at the beach and established dunes transect points are presented below. The results are listed by Tot-P concentration, followed by the individual P-fractions, ordered by their overall contribution to the Tot-P. Figures showing the values of the Tot-P and individual P-fractions and how they change over the transect are shown for each site: mega-nourishment (fig.3.1), traditional-nourishment (fig.3.2) and non-nourishment (fig.3.3). Table 3.1 shows the results of statistically analysing the differences between the transect points at each site.

Tot-P

At the **mega-nourishment** site large differences in the Tot-P were found between the beach and established dunes. As shown in fig.3.1 the average concentration of Tot-P found at the beach was 15.16 µmol/g P, whilst at the established dunes it was only 5.79 µmol/g P. This is a difference of 9.37 µmol/g P between the two transect points. At the **traditional-nourishment** site, as shown in fig.3.2, smaller differences were found between the beach and established dunes. At the beach, an average concentration of 9.96 µmol/g P of Tot-P was found, whilst at the established dunes it was 2.53 µmol/g P lower, with an average Tot-P concentration of 7.15 µmol/g P.Fig3.3 highlights the minimal differences found between the beach and the established dunes at the **non-nourishment** site. There was only a difference of 0.07 µmol/g P between the two transect points, with the average Tot-P concentration at the beach being 13.48 µmol/g P and at the established dunes 13.42 µmol/g P.

None of the differences in Tot-P between the beach and established dunes at any of the sites were deemed statistically significant.

Fe-P

At the **mega-nourishment** site (fig.3.1), again large differences in the average Fe-P found at the beach (Fe-P = 10.41 µmol/g P) and the established dunes (Fe-P = 3.72 µmol/g P). There is a difference of 6.68 µmol/g P of Fe-P between the two transect points. At the **traditional-nourishment** site (fig.3.2), again smaller differences are found between the beach (Fe-P = 5.61 µmol/g P) and the established dunes (Fe-P = 3.39 µmol/g P), a difference of only 2.22 µmol/g P Fe-P between the two transect points. At the **non-nourishment** site (fig.3.3), there are again minimal differences between the two transect points. At the beach the average concentration was 12.25 µmol/g P, whilst at the established dunes it was only 0.2 µmol/g P lower, at a value of 12.04 µmol/g P.

None of the differences in Fe-P between the beach and established dunes at any of the sites were deemed statistically significant.

Det-P, Ca-P. Ex-P and Org-P

At the **mega-nourishment** site (fig.3.1) the average Det-P concentration at the beach (Det-P = 3.73 µmol/g P) was only 2.21 µmol/g P higher than at the established dunes (Det-P = 1.52 µmol/g P). While the difference between the two transect points was low, the difference was calculated to be statistically significant ($p = 0.015$). The differences between the beach and established dunes at both the **traditional** and **non-nourishment** sites were minimal and statistically insignificant.

The difference in the average concentration of Ca-P between the beach (Ca-P = 0.70 µmol/g P) and the established dunes (Ca-P = 0.07 µmol/g P) at the **mega-nourishment** site (fig.3.1) was only 0.63 µmol/g P. However, statistical analysis revealed this to be a statistically significant difference ($p = 0.006$). The differences between the beach and the established dunes at both the **traditional** and **non-nourishment** sites were both minimal and statistically insignificant.

The differences in Ex-P and Org-P between the beach and the established dunes at all 3 sites were minimal (<0.17 µmol/g P) and calculated to be statistically insignificant.

Fig.3.1: Mega-nourishment

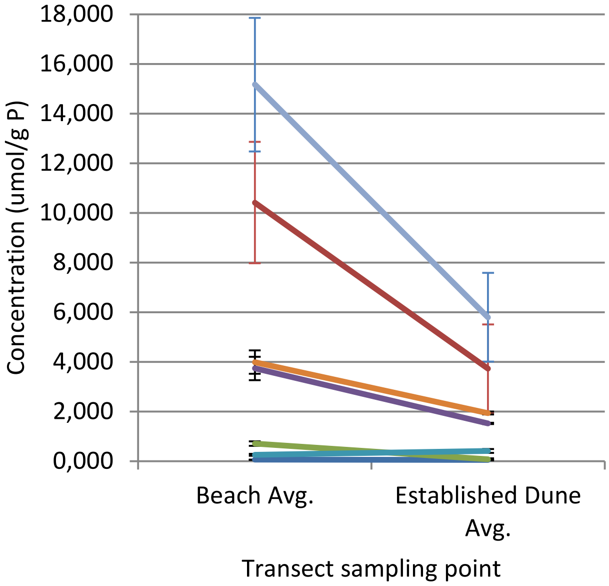


Fig.3.2: Traditional-nourishment

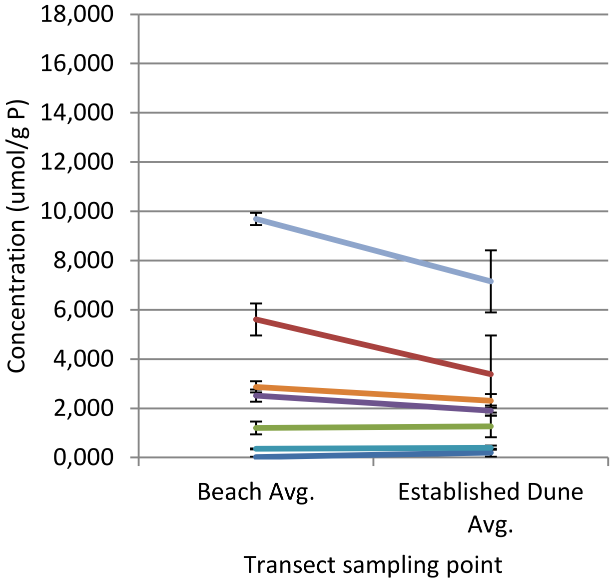
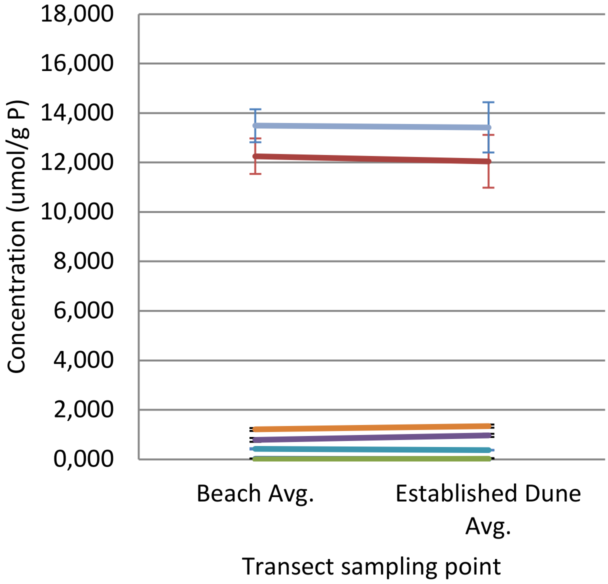


Fig.3.3: Non-nourishment



Line graphs showing the average change in P concentrations from the beach to the established dunes in sediment collected by sand pits. Mega-nourishment site (**Fig.3.1**), traditional-nourishment (**Fig.3.2**) and non-nourishment (**Fig.3.3**). Standard deviation bars shown. **Key:**

- Ex-P
- Fe-P
- Ca-P
- Det-P
- Org-P
- totorgP
- Tot-P

Site	**Ex-P**	**Fe-P**	**Ca-P**	**Det-P**	**Org-P**	**totorgP**	**Tot-P**
Mega-nourishment	0.939	0.128	**0.006**	**0.015**	0.4	0.61	0.066
Traditional-nourishment	0.7	0.897	0.917	0.175	1	0.248	0.163
Non-nourishment	0.7	0.275	0.7	0.2	0.167	0.252	0.965

Table.3.1 – A table showing the p-values of the statistical tests used to analyse the differences between the beach and established dunes at each site.

3.2 Aeolian deposited tot-P and P-fraction data

The results from the sediment collected by digging sand pits at the beach and established dunes transect points are presented below and are structured in a similar fashion as the previous section.

Tot-P

At all 3 sites, the sand captured by the sand traps in the established dunes contained higher concentrations of Tot-P than the sediment collected in the sandpits at either of the beach or the established dunes. The largest difference was found at the traditional-nourishment site, the second largest at the mega-nourishment and the smallest difference was found at the non-nourishment site. At all sites the trends of the data collected by the sand trap oppose those of the data collected by the sand pits. However, the non-nourishment site was unique as the Tot-P concentration peaked at the fore dunes, before decreasing at the established dunes (though the overall trend was still an upwards line).

At the **mega-nourishment** site (fig.3.4) the average concentration of the Tot-P at the beach was 4.93 µmol/g P, increasing to 13.03 µmol/g P at the fore dunes and then 34.06 µmol/g P in the established dunes. Compared to the data collected via the sandpits, the average concentration of the beach Tot-P was 10.23 µmol/g P lower than the beach sand pit data, whilst the average concentration of the established dunes Tot-P was 28.27 µmol/g P higher than the sandpit data. At the **traditional-nourishment** site (fig.3.5), the average concentrations of the Tot-P at the beach was 30.703 µmol/g P, slightly increasing to 31.2803 µmol/g P at the fore dunes and then considerably increasing to 91.0603 µmol/g P at the established dunes. When compared to the data collected via the sand pits, the average beach Tot-P was 20.74 µmol/g P higher than the beach sand pit data and the average established dunes Tot-P was a sizeable 83.90 µmol/g P higher than the sand pit data. At the **non-nourishment** site (fig.3.6), the average concentration of the Tot-P at the beach was 20.1903 µmol/g P, increasing to 31.1603 µmol/g P at the fore dunes, before decreasing to 24.4803 µmol/g P at the established dunes. When compared to the sandpit data, the average Tot-P beach concentration was only 6.6203 µmol/g P higher than the sandpit beach data, whilst the average Tot-P was only 11.0603 µmol/g P higher than the established dunes sand pit data.

Statistical analysis was used to test two relationships. The first analysis was to test the difference between the sand caught at all 3 transect points against the sand collected by the sand traps at the beach transect point of each site. The second analysis was to test the sand caught by sand traps at the established dunes with the sand collected by sand traps at the established dunes. The first test did not reveal any statistically significant differences. However, the second test did reveal statistically significant differences at the mega-nourishment and non-nourishment sites between the sand trap and sandpit sediment collected at the established (mega-nou $p = 0.033$ and non-nou $p = 0.035$). These p-values can be seen in table 3.2.

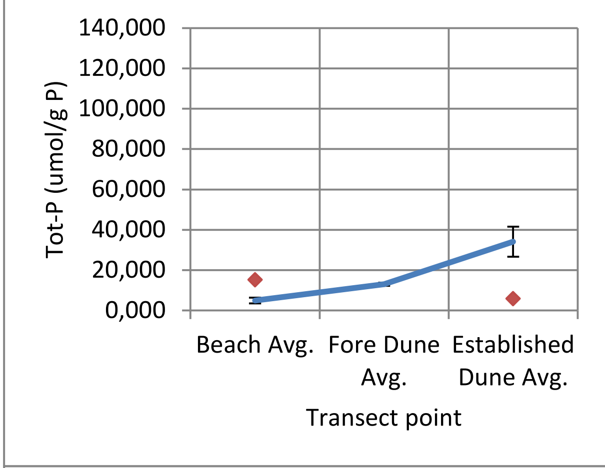


Fig.3.4: Mega-nourishment

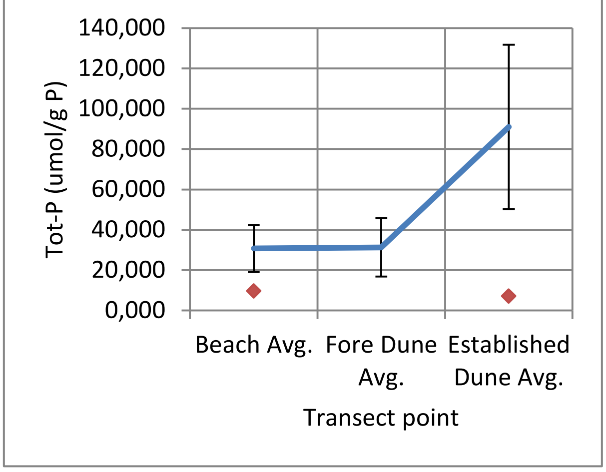


Fig: 3.5: Traditional-nourishment

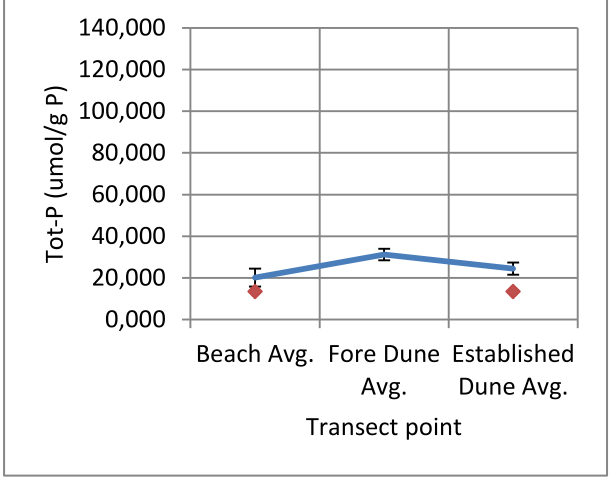


Fig3.6: Non-nourishment

Line graphs showing the average change in Tot-P concentration from the beach to the established dunes in sediment collected by sand traps (**blue lines**) with sand pit data for comparison (**red dots**). Mega-nourishment site (**Fig.3.4**), traditional-nourishment (**Fig.3.5**) and non-nourishment (**Fig.3.6**). Standard deviation bars shown.

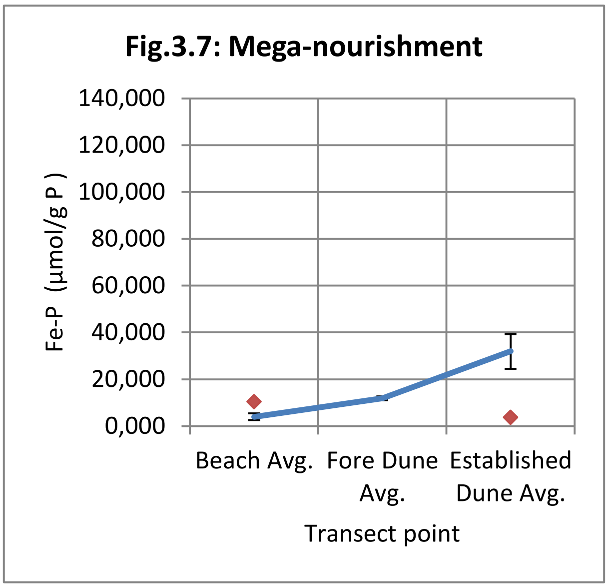
Fe-P

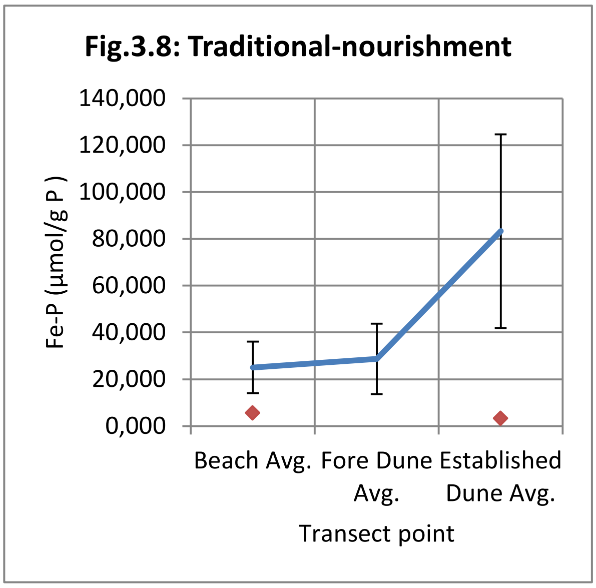
At all 3 sites the average concentrations and trends of Fe-P closely mirror the average concentrations of Tot-P. Again the Fe-P trends of the data collected at the sand traps go in the oppose the trend of the data collected in the sand pits.

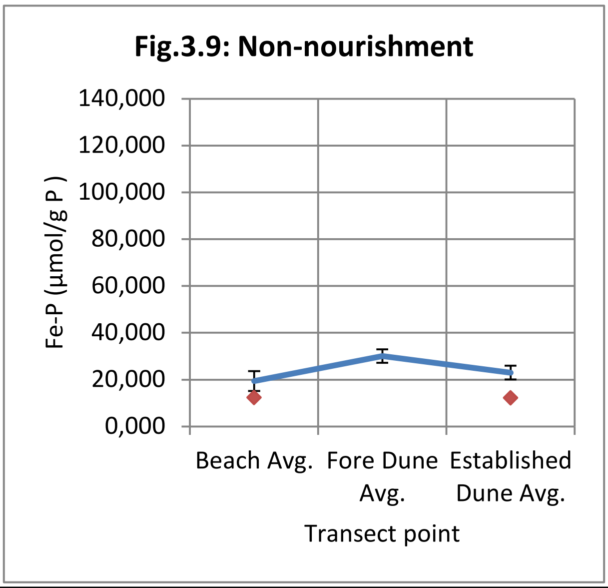
At all 3 sites the average concentrations of Fe-P closely mirror the average concentrations of Tot-P. At the **mega-nourishment** site (fig.3.7) the average Fe-P concentration at the beach is 3.98 µmol/g , increasing to 11.85 µmol/g P at the fore dunes and then to 31.98 µmol/g P in the established dunes. Compared to the data from the sediment collected by the sandpits, the beach Fe-P is 6.43 µmol/g P lower than the sand pit data, whilst the sediment captured by sandtraps in the established dunes is 28.25 µmol/g P higher than the data collected by the sand pits at the same site. At the **traditional-nourishment** site (fig.3.8) the average Fe-P concentration at the beach is 25.07 µmol/g P, increasing slightly to 28.68 µmol/g P at the fore dunes, before massively increasing to

83.24 µmol/g P in the established dunes. When comparing to this the sediment collected in the sandpits, the beach sand trap data is 19.47 µmol/g P higher and at the established dunes is substantial 79.85 µmol/g P higher. At the **non-nourishment** site (fig.3.9) the Fe-P average concentration at the beach is 19.41 µmol/g P, increasing to 30.11 µmol/g P at the fore dunes, before decreasing to 23.00 µmol/g P in the established dunes. When compared to the sediment collected in the sandpits, the Fe-P beach sand trap sediment is 7.16 µmol/g P higher, whilst at the established dunes it is 10.96 µmol/g P higher.

The use of statistical analysis revealed 4 statistically significant differences in the Fe-P. Firstly, the difference in sediment caught by sand traps in the fore dunes against the sand collected by the sand pit at the beach at the non-nourishment site was calculated to be statistically significant ($p = 0.025$). Secondly, at all 3 sites, the difference in the Fe-P between the sediment caught by the sand traps and the sediment collected by sand pits at the established dunes was calculated to be statically significant (mega-nou $p = 0.031$, trad-nou $p = 0.05$, non-nou $p = 0.039$).







Line graphs showing the average change in Fe-P concentration from the beach to the established dunes in sediment collected by sand traps (**blue lines**) with sand pit data for comparison (**red dots**). Mega-nourishment site (**Fig.3.7**), traditional-nourishment (**Fig.3.8**) and non-nourishment (**Fig.3.9**). Standard deviation bars shown.

Beach	Ex-P	Fe-P	Ca-P	Det-P	Org-P	totorgP	Tot-P
Mega-nourishment	0.507	**0.031**	0.487	0.639	0.429	0.864	**0.033**
Traditional-nourishment	0.507	**0.05**	0.827	0.827	0.275	0.827	0.149
Non-nourishment	0.1	**0.039**	0.796	0.513	0.127	0.513	**0.035**

Table.3.2 – A table showing the p-values of the statistical tests used to analyse the differences between sediment caught in the sandpits and sand traps at the established dunes.

Fig.3.10: Mega-nourishment

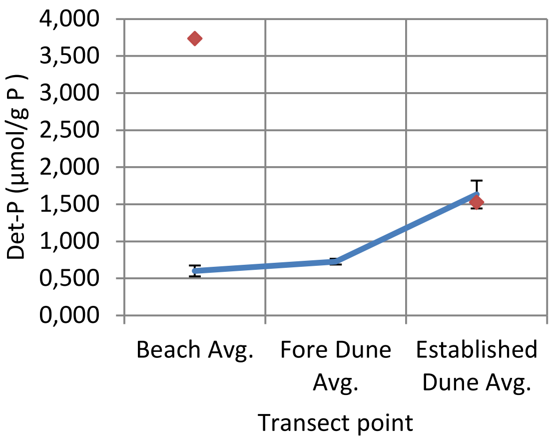
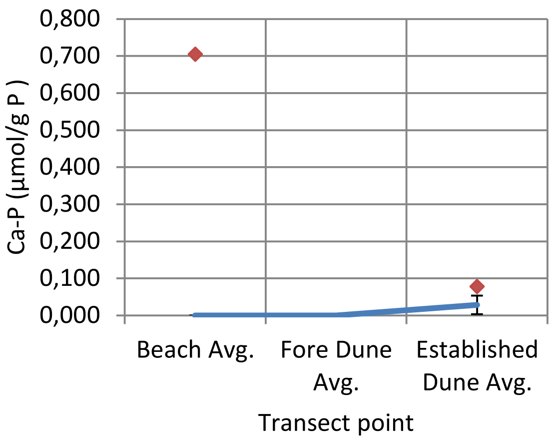


Fig.3.11: Mega-nourishment



Line graphs showing the average change in Det-P (Fig.3.10) and Ca-P (Fig.3.11) concentration from the beach to the established dunes in sediment collected by sand traps (**blue lines**) with sand pit data for comparison (**red dots**) at the mega-nourishment site. Standard deviation bars shown.

Det-P, Ca-P, Ex-P, and Org-P

Aside from the average Det-P concentration at the traditional-nourishment site, all changes of Det-P, Ca-P, Ex-P and Org-P all only changed by a difference of less than 1.00µmol/g P over the length of the transect. These changes are not substantially different from the data collected by sand pits at the beach and the established dunes.

The average concentration of Det-P at the **mega-nourishment** site (fig.3.10) only changed minimally over the length of the transect. At the beach the average Det-P concentration was 0.60µmol/g P, slightly increasing to 0.73µmol/g P at the fore dunes and then increasing again to 1.63µmol/g P at the established dunes. Compared to the average Det-P concentrations found in the sediment collected by sand traps, the beach Det-P was a little lower than the sandpit Det-P with a difference of -3.13µmol/g P recorded, whilst the established dunes sand trap Det-P was quite similar with the concentration only being 0.11µmol/g P higher than the sandpit data. At the **traditional-nourishment** site there was a larger increase in Det-P over the length of the transect. At the beach the average Det-P concentration was 3.09µmol/g P, decreasing slightly to 1.47µmol/g P at the fore dunes, before increasing to 5.31µmol/g P at the established dunes. These concentrations are quite different from the data collected by the sand pits, with the sand trap Det-P being on average 0.58µmol/g P higher than the sand pit data at the beach and 3.41µmol/g P higher than the sand pit data at the established dunes. The **non-nourishment** site showed minimal change in Det-P over the length of the transect (<0.6µmol/g P).

The average concentration of Ca-P at the **mega-nourishment** site (fig.3.11) only showed minimal change over the course of the transect <0.03µmol/g P, with the **traditional-nourishment** site only showing a change of 0.9µmol/g P over the transect and the **non-nourishment** site a change of only 0.05 µmol/g P.

At the **mega-nourishment** site the average concentration of Ex-P only changes by 0.133µmol/g P over the length of the transect, whilst at the **traditional-nourishment** site it only changes by 0.17µmol/g P. At the **non-nourishment** site it changes by 0.04µmol/g P over the length of the transect.

At the **mega-nourishment** site the average concentration of Org-P only changed by 0.12µmol/g P over the length of the transect, whilst at the **traditional-nourishment** site the Org-P changed by 0.49µmol/g P and at the **non-nourishment** site the Org-P only changed by 0.07µmol/g P.

Statistical analysis of the Det-P, Ca-P, Ex-P and Org-P showed no statistically significant differences against either the data collected at the sand pits at either the beach or established dunes.

3.3 Variance and PCA of aeolian deposited P-fraction data

At all 3 sites, Fe-P accounted for the greatest variance in the data, ranging from 0.81 to 45.1 µmol/g P at the mega-nourishment site; 0.04 to 175.54 µmol/g P at the traditional-nourishment site and 13.04 to 35.09 µmol/g P at the non-nourishment site. All the other P-fractions at all of the sites had much smaller variance.

The contributions of P-fractions to the average Tot-P concentration can be seen in Table 3.3. The rankings of largest average contributions to Tot-P of the Mega-nourishment and non-nourishment site were the same: Fe-P > Det-P > Org-P > Ex-P > Ca-P. At the traditional nourishment site, Fe-P on average was the largest single contributor to the Tot-P with the 2nd largest being Det-P again. However, Ca-P and the Org-P positions were inverted: Fe-P > Det-P > Ca-P > Org-P > Ex-P.

Beach	Transect point	Ex-P	Fe-P	Ca-P	Det-P	Org-P	totorgP	Tot-P
Mega-nourishment	Beach avg.	2,61	80,66	0,00	12,18	4,55	16,73	100,00
	Fore dunes avg.	1,66	90,93	0,00	5,59	1,82	7,41	100,00
	Est. dunes avg.	0,24	93,87	0,08	4,79	1,01	5,80	100,00
	Average	1,50	88,49	0,03	7,52	2,46	9,98	100,00
Traditional-nourishment	Beach avg.	0,00	81,66	5,64	10,07	2,63	12,70	100,00
	Fore dunes avg.	0,54	91,68	2,07	4,70	1,01	5,70	100,00
	Est. dunes avg.	0,19	91,42	1,73	5,83	0,84	6,67	100,00
	Average	0,24	88,25	3,15	6,86	1,49	8,36	100,00
Non-nourishment	Beach avg.	0,41	96,35	0,24	1,68	1,31	3,00	100,00
	Fore dunes avg.	0,27	96,62	0,05	2,00	1,07	3,06	100,00
	Est. dunes avg.	0,51	93,95	0,28	4,08	1,18	5,26	100,00
	Average	0,40	95,64	0,19	2,59	1,19	3,77	100,00

Table 3.3: A table showing the breakdown of the Tot-P into each P-fraction by percent.

PCA of the mega-nourishment site suggested that Fe-P was the dominant variable, followed by Det-P, Ca-P and then Org-P as can be seen in table3.4. Ex-P was discounted from the analysis as its anti-correlation value was below 0.5, failing a required assumption of the data. The reliability of the test was very poor, with a Cronbach's alpha value of 0.097. However, the PCA does generally agree with the percentage contribution rankings detailed in the previous paragraph. PCA of the traditional-nourishment site suggested that Ca-P and Org-P were the most important components of Tot-P. The test had a Cronbach's alpha value of 0.66, deeming it relatively "*reliable*". However, Fe-P, Det-P and Ex-P had to be removed from the analysis as their anti-correlation and Kaiser-Meyer-Olkin values were not sufficient to pass the PCA data assumptions. PCA of the non-nourishment data was not possible as none of the individual P-fractions had sufficient anti-correlation or Kaiser-Meyer-Olkin values.

Component Matrix[a]

	Component
	1
Fe-P	,959
Ca-P	,821
Det-P	,961
Org-P	,799

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3,155	78,878	78,878	3,155	78,878	78,878
2	,538	13,441	92,319			
3	,269	6,718	99,037			
4	,039	,963	100,000			

Extraction Method: Principal Component Analysis.

Table.3.4: A table showing the PCA results for a component matrix and total variance explained results of the mega-nourishment site.

Component Matrix[a]

	Component
	1
Ca-P	,934
Org-P	,934

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1,745	87,248	87,248	1,745	87,248	87,248
2	,255	12,752	100,000			

Extraction Method: Principal Component Analysis.

Table.3.5: A table showing the PCA results for a component matrix and total variance explained results of the traditional-nourishment site.

Grain size and its relationship with P-fractions

Fig3.12 shows that the mega-nourishment site it was found that there was a substantially higher Tot-P in finer grain sizes (87.43 µmol/g P) than in the larger grain size (16.81 µmol/g P). This difference in Tot-P is predominantly explained by the large difference in Fe-P found in the grain sizes, with 76.55 µmol/g P found in finer grain sizes and only 14.83 µmol/g P found in larger grain sizes. There are also notable differences in the Det-P and Org-P found between the grain sizes with considerably more being found in the finer grain sizes (Fig.3.7).

The differences in Tot-P ($p = 0.039$) and TotOrg-P ($p = 0.003$) between the two grain sizes were deemed to be statistically significant. Interestingly, Fe-P nor Det-P and Org-P (the components of TotOrg-P) were not found to be significant, nor were Ex-P or Ca-P.

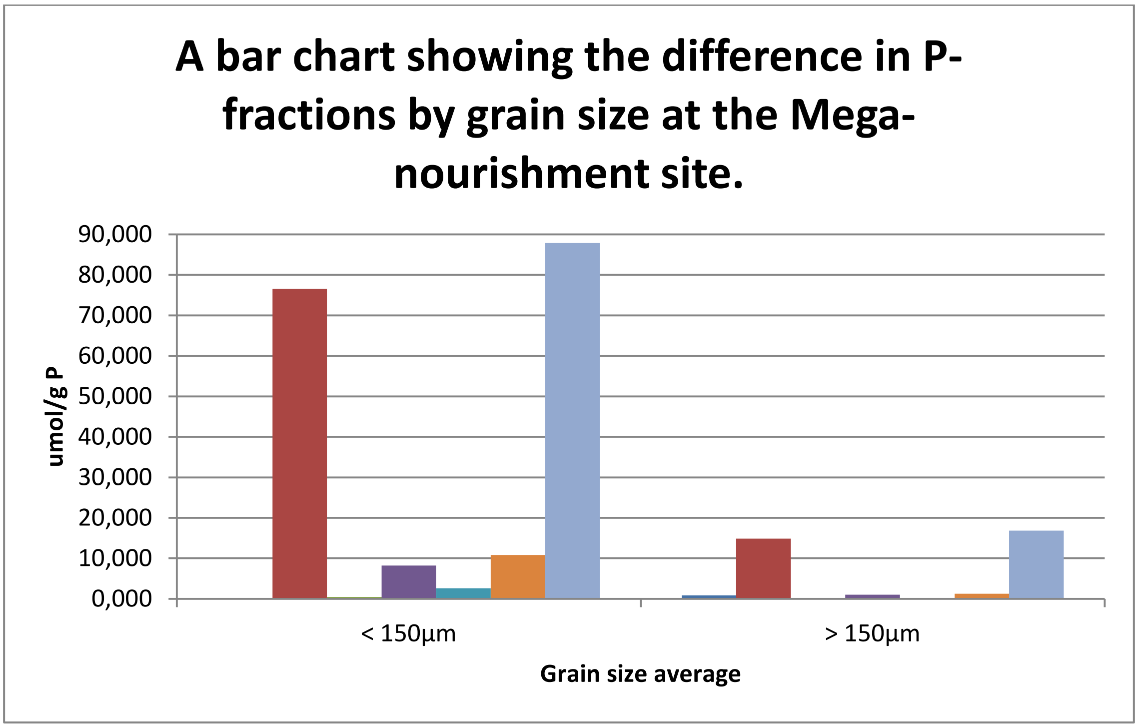


Fig.3.12. A bar plot showing the average P concentrations of individual P-fractions and Tot-P between finer grain size (< 150µm) and larger grain sizes (>150µm) at the mega-nourishment site.

The traditional-nourishment (Fig.3.13) site exhibits similar characteristics as the Mega-nourishment sediment, though the differences are on a slightly smaller scale. Again there is substantially higher Tot-P observed in the finer grain sizes (70.48 µmol/g P) than the larger grain sizes (40.41 µmol/g P). Again, this large difference in Tot-P is mainly caused by differences found in the Fe-P in the two grain sizes, with there being 57.39 µmol/g P of Fe-P in the finer grain size, but only 26.65 µmol/g P in the larger grain size. Det-P is also quite a bit higher in the fine grain size

(10.74 µmol/g P) than in the larger grain size (3.14 µmol/g P), however ,opposite to the Mega-nourishment observations, Org-P is found in higher concentrations in the larger grain sizes (7.15 µmol/g P) than in the finer grain size (0.78 µmol/g P). None of the differences in Tot-P or individual P-fractions between the two grain sizes were found to be statistically significant.

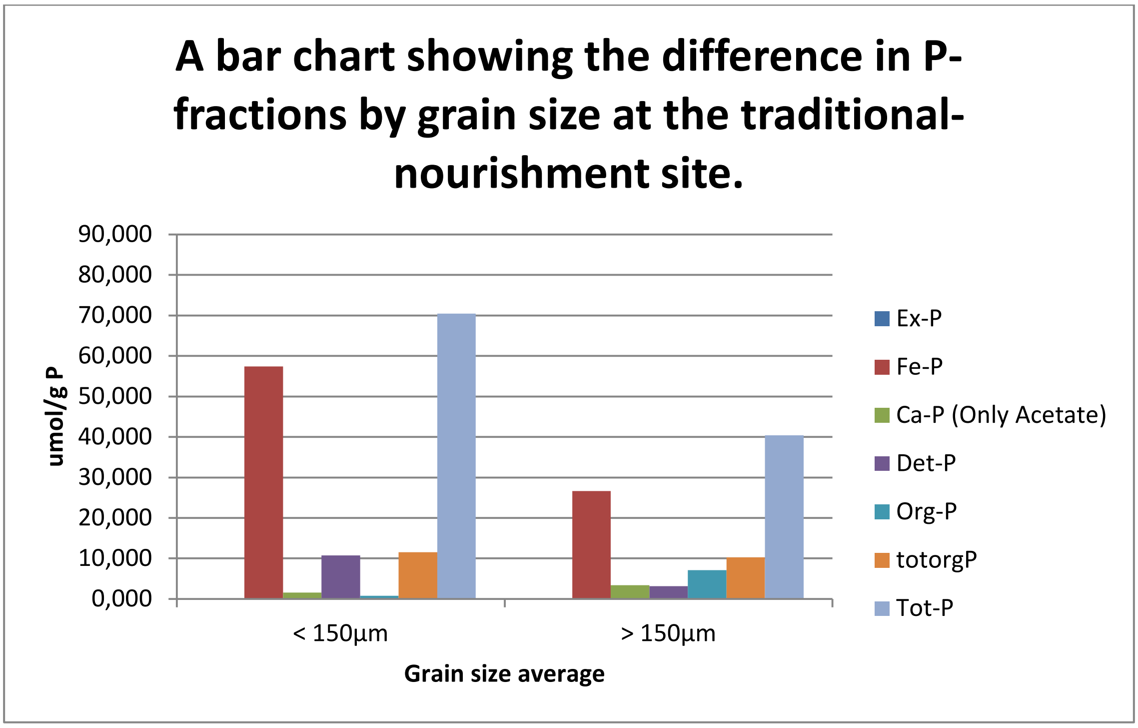


Fig.3.13. A bar plot showing the average P concentrations of individual P-fractions and Tot-P between finer grain size (< 150µm) and larger grain sizes (>150µm) at the traditional-nourishment site.

Beach	Transect point	Ex-P	Fe-P	Ca-P	Det-P	Org-P	totorgP	Tot-P
Mega-nourishment	<150µm beach	0,000	62,106	0,637	10,137	0,595	10,733	73,475
	<150µm est. Dunes	0,000	90,987	0,265	6,356	4,595	10,951	102,202
	<150µm beach	1,373	12,507	0,000	0,688	0,048	0,736	14,616
	>150µm est. Dunes	0,124	17,147	0,000	1,420	0,309	1,729	19,000
	<150µm Avg	0,000	**76,546**	**0,451**	**8,247**	**2,595**	**10,842**	**87,838**
	>150µm Avg	**0,749**	14,827	0,000	1,054	0,178	1,233	16,808
	Avg	0,374	45,687	0,225	4,650	1,387	6,037	52,323
Traditional-nourishment	<150µm beach	0,000	76,135	1,683	9,876	0,666	10,542	88,360
	<150µm est. Dunes	0,000	38,650	1,448	11,609	0,898	12,507	52,606
	<150µm beach	0,000	18,107	6,480	4,727	14,118	18,845	43,431
	>150µm est. Dunes	0,124	35,191	0,345	1,553	0,183	1,736	37,396
	<150µm Avg	0,000	**57,393**	1,566	**10,742**	0,782	**11,524**	**70,483**
	>150µm Avg	**0,062**	26,649	**3,412**	3,140	**7,151**	10,290	40,414
	Avg	0,031	42,021	2,489	6,941	3,966	10,907	55,448
Non-nourishment	<150µm beach	0,124	33,596	0,617	4,274	0,248	4,522	38,859
	<150µm est. Dunes	0,124	42,029	0,669	0,988	0,701	1,689	44,512
	<150µm beach	0,000	32,681	0,000	10,995	0,165	11,160	43,841
	>150µm est. Dunes	0,262	24,212	0,000	0,744	0,148	0,892	25,366
	<150µm Avg	0,124	**37,812**	**0,643**	2,631	**0,474**	3,106	**41,686**
	>150µm Avg	**0,131**	28,447	0,000	**5,870**	0,156	**6,026**	34,604
	Avg	0,128	33,130	0,322	4,250	0,315	4,566	38,145

Table. 3.6: A table showing the relationship between grain size, Tot-P concentration and individual P-fractions. Yellow cells denote the highest average value.

At the non-nourishment site (Fig.3.14), the differences between the Tot-P are much lower than at the other two sites. Whilst there is still slightly more Tot-P in the finer grain size (41.69 µmol/g P) than in the larger grain size (34.6 µmol/g P), the difference between the two grain sizes is much lower than at the mega- and traditional-nourishment sites. Again, this difference is predominantly explained by Fe-P with there being 37.81 µmol/g P in the finer grain size and 28.45 µmol/g P in the larger grain size. Curiously, the difference in Ca-P between the two grain sizes at the non-nourishment site was statistically significant (p = 0.002). None of the other individual p-fractions or Tot-P had statistically significant differences between the two grain sizes.

When cross-comparing the sites is becomes immediately apparent that on average there is substantially higher P concentrations found in finer grain sizes at the mega-nourishment site (Tot-P = 87.84 µmol/g P) and traditional-nourishment site (Tot-P = 70.48 µmol/g P) than at the non-nourishment site (Tot-P=41.69 µmol/g P).

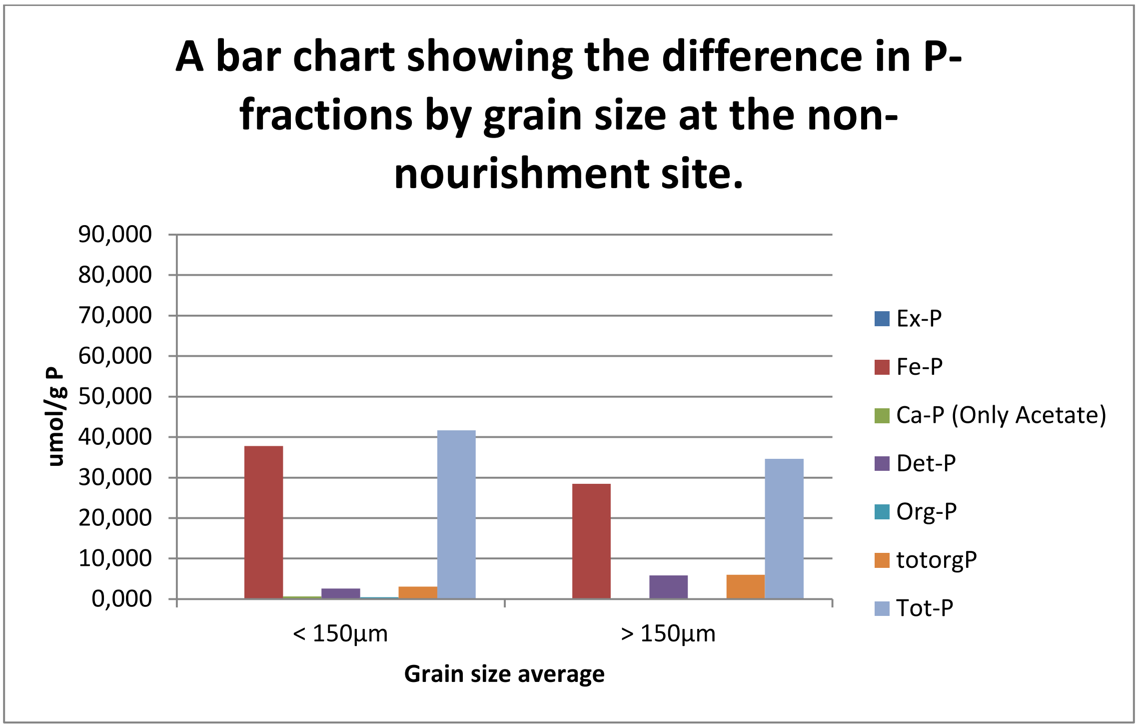


Fig.3.14. A bar plot showing the average P concentrations of individual P-fractions and Tot-P between finer grain size (< 150µm) and larger grain sizes (>150µm) at the non-nourishment site.

The results from the grain size distribution can be seen in fig.3.15 – fig.3.19. Please note that there is no grain size distribution for the sandpit data in the fore dunes, as no sandpit was dug there. At all transect points the mega-nourishment sites had the largest proportion of finest material. 7.72% of the sediment collected from the sand pit was made up of sediment with a grain size < 150µm, whilst 1.82% of the sediment from the sand traps consisted of grains smaller than 150µm. The smallest grain recorded at the mega-nourishment site was as small as 16µm.The traditional-nourishment site had the next largest proportion of fine material, with 0.38% of the sediment from the sand pits containing grains <150µm. 0.36% of the sediment caught in the sand traps consisted of grains <150µm. The smallest grain size recorded at the traditional-nourishment site was 88µm. The non-nourishment in contrast to the other two sites contained no fine grained sediment (<150µm), with the smallest grain size being recorded there being 177µm.

Fig.3.15: Beach sandpit grainsize

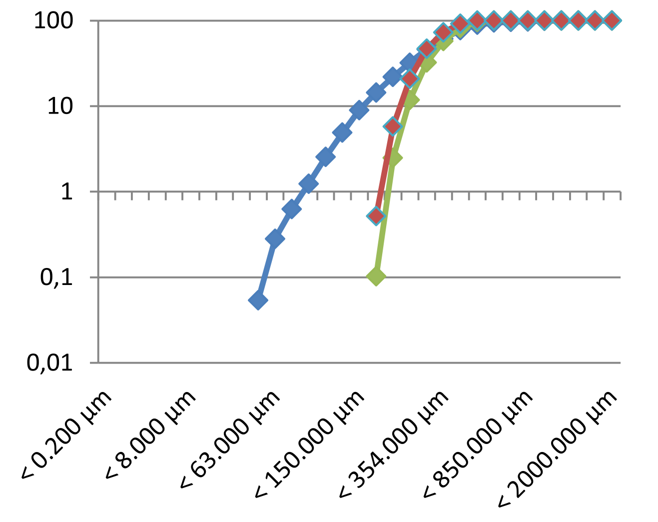
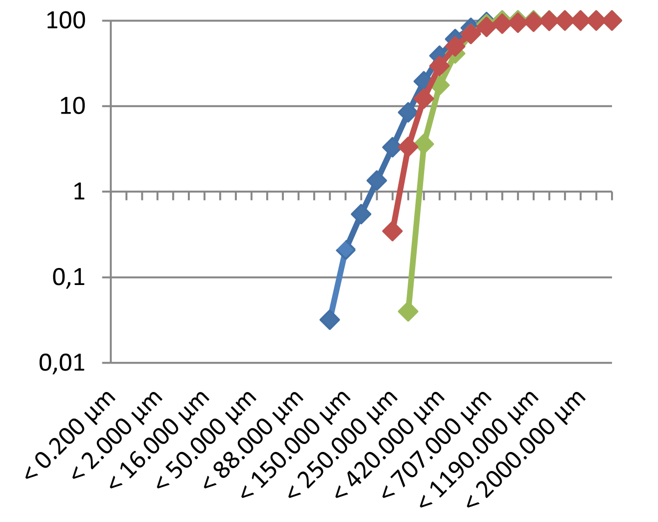


Fig.3.16: Beach sandtrap grainsize



Logarithimic line graphs comparing the grain size distribution at each transect point: Beach TP – sandpit (fig.3.15), beach – sandtrap (fig.3.16), fore dunes sand trap (fig.3.17), established dunes – sandpit (fig.3.18), established dunes – sandtrap (fig.3.19). Key:

- Mega-nourishment
- Traditional-nourishment
- Non-nourishment

Fig.3.17: Fore dunes sandtrap grainsize

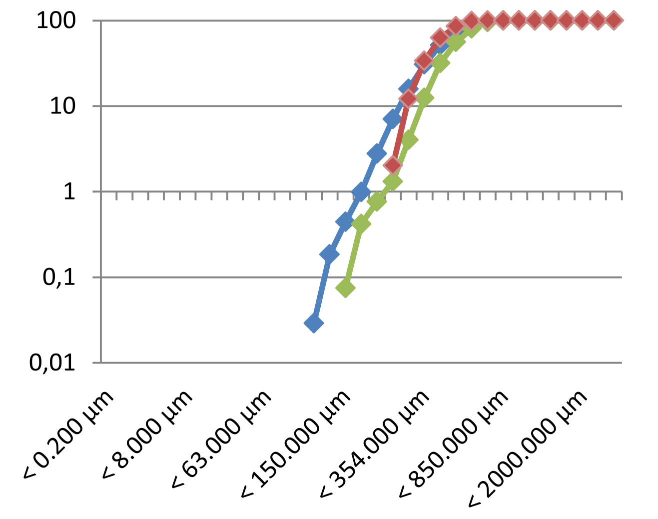


Fig. 3.18: Est. dunes sandpit grainsize

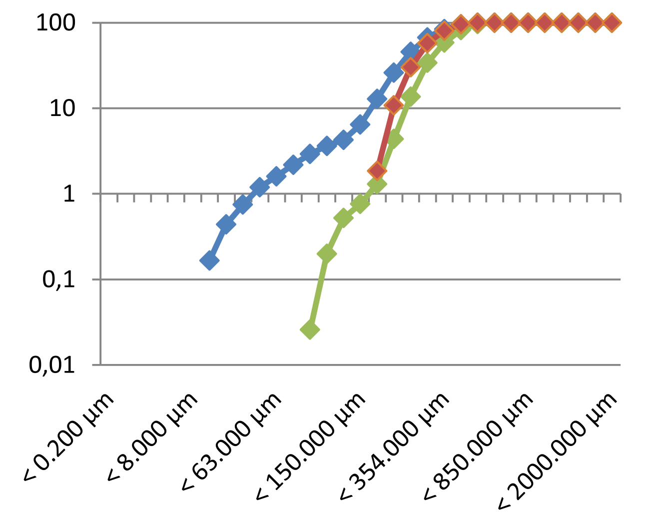
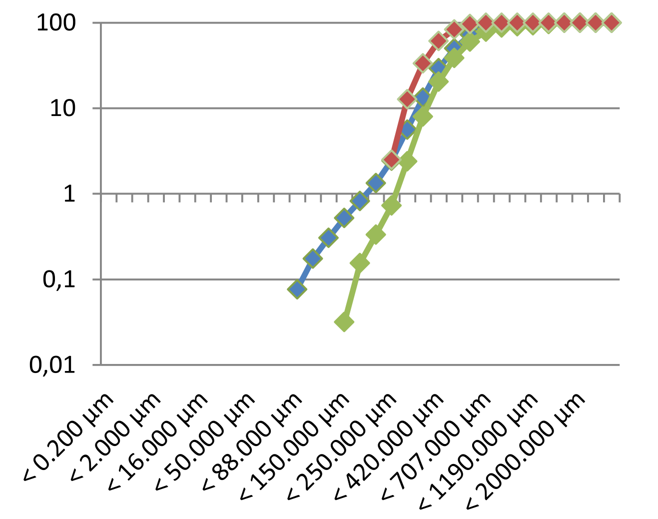


Fig.3.19: Est. dunes santrap grainsize



4 Discussion

Sandpit tot-P and P-fraction concentration data

A qualitative trend analysis of the sediment at the mega-nourishment site certainly suggests that mega-nourishment could provide a potential major source of phosphorus for the local sand dune ecosystem. On average the Tot-P concentration at the beach transect points were 9.37 µmol/g P higher than the average found at the established dunes. In contrast, at the traditional-nourishment site the beach only contained 2.54 µmol/g more P than at the established dunes. At the non-nourishment site this difference between the beach and the established dunes was as low as 0.07µmol/g P. The differences in these figures are huge, with the difference between the mega-nourishment and non-nourishment being 13,285% and the difference between the traditional-nourishment and non-nourishment site being 240%. Fig.3.2 and fig. 3.3 shows that the main sources of this change in Tot-P is Fe-P, with Fe-P at the beach transect point accounting for 68.67% (10.41 µmol/g P at mega-nourishment) and 57.83% (5.6 µmol/g P at traditional-nourishment) of Tot-P, whilst at the established dunes Fe-P accounts for 64.29% (3.72 µmol/g P at mega-nourishment) and 47.36% (3.99 µmol/g P at traditional-nourishment) of Tot-P. For comparison purposes the Fe-P found at the non-nourishment accounted for a larger proportion of the Tot-P than at either of the beach-nourishment sites, but there was very little difference between the actual concentrations of Fe-P between the beach (12.25 µmol/g P and 90.85%) and established dunes (12.08µmol/g P and 89.77%). The values of Tot-P found at the mega-nourishment beach transect point (15.16 µmol/g P) were also higher than at the traditional nourishment beach transect point (9.69 µmol/g P). However, these differences may also be due to differences in the original local composition of the sand and is not an accurate gauge of the effects of the nourishment techniques. To highlight this point, the Tot-P found at the non-nourishment beach transect point was 13.49 µmol/g P, which is higher than the traditional-nourishment beach transect point. Therefore, it is more reliable to examine the differences between the beach and established dunes transect points at each site.

This qualitative trend analysis would suggest that at both of the beach-nourishment sites, there is either an additional input of P at the beach or an additional removal of P at the established dunes. It is, however, feasible to reasonably remove the possibility that there is an additional removal of P in the established dunes at the beach-nourishment sites that is not present at the non-nourishment site. Firstly, all three sites share relatively similar vegetation that could not account for these large differences in Tot-P found in the established dunes when compared with the beach transect points. Whilst there are some differences in pH between the established dunes of the beach-nourishment sites and non-nourishment site, this shouldn't result in the overall removal P from a system, just a change into another P-fraction. Moreover, the leaching of P from the soils is also usually very minor and there are no reasons to expect this to be significantly different across the sites (Schoumans & Groenendijk *et al.* 1998), nor should the levels of erosion and runoff be substantially different (Van der Meulen *et al*., 2012). Therefore, it is reasonable to suggest that this difference in the Tot-P between the beach and established dunes at the beach-nourishment sites may be due to the beach-nourishment itself. This statement is further augmented by the fact that a large component of Tot-P found at the beach transect point consists of Fe-P. Though a thorough literature search was conducted, it was not possible to find any other work that analysed P concentrations in beach-nourishments and the local sand dune ecosystem. However, it is possible to draw on other studies to strengthen the findings found in this research. Firstly, Slomp *et al*., (1996) suggests that coastal marine sediments can act as both a temporary and permanent sink of P and it is these sediments that are being dredged up for beach-nourishment projects. Building on this research, Bramha *et al*., (2014) and Andrieuw-Loyer & Aminot (2001) found that Fe-P concentrations in sediments was positively correlated to the quantity of fine sediment found in the sample, with both Greene (2002) and Hamm *et al*., (2002) stating that beach-nourishments are usually composed of a high proportion of fine grain sediment. It is therefore quite logical to suggest that the high quantities of Fe-P being found at the beach transect points of the beach-nourishment sites is due to the beach-nourishment consisting of fine sediment sourced from the rich iron-oxide fine grain sediments, as described by Slomp *et al*., (1996) and Andrieux-Loyer & Aminot (2001), which then is deposited onto the beaches as described by Greene (2002) and Hamm *et al*., (2002).

Interestingly, when this data was statistically analysed, using a combination of one-way ANOVA, Welch one-way ANOVA, Kruksall-Wallis and Mann-Whitney U tests (depending on the assumptions the data fitted) neither the differences in the Tot-P or Fe-P between the beach and established dunes transect points at any of the sites, including non-nourishment, were deemed statistically significant. This, in my opinion is due to the dataset having a low sample size, but a very high standard deviation and is a potential example of type II statistical error. This is reinforced by the fact that the identified Fe-P trends is what was expected based on previous literature, as described in the last paragraph. Curiously, at the mega-nourishment site, the differences found in Ca-P ($p = 0.006$) and Det-P ($p = 0.015$) between the beach and established dunes were statistically significant. In contrast to the dataset used in the statistical analysis of Fe-P and Tot-P the Ca-P and Det-P datasets have much smaller standard deviations, whilst still having the same sample size. No other statistically significant differences were found at any of the sites. The statistically significant difference in Ca-P between the beach and established dunes is supported by the work of Greene (2002), who also stated that beach-nourishment sediment would contain high quantities of shell fragments, which Andrieux-Loyer & Aminot (2001) state to be a source of Ca-P in coastal areas.

The qualitative trend analysis suggests that both form of beach-nourishment are indeed providing a potential new source of phosphorus to the sand dune ecosystem with their being substantially higher Tot-P concentrations found at the beach transect points than in the established dunes. Another key identified trend is that the difference in the Tot-P being made available by the two beach-nourishment techniques. Mega-nourishment seems to provide more P to the beach than traditional-nourishment, with greater differences also recorded between the beach and established dunes transect points also recorded at the mega-nourishment site than at the traditional-nourishment site. Opposing this, at the non-nourishment site there was very little difference in the Tot-P concentration found at the beach and established sand dunes. Whilst these findings are not further strengthened by statistical analysis, due to a form of Type II error, it did identify statistically significant differences in Ca-P and Det-P at the mega-nourishment site.

Aeolian deposited tot-P and P-fraction data

The most significant form of P being transported to the established dunes at all 3 sites is the Fe-P. At the mega-nourishment site the Fe-P average concentration of the sand being deposited there by aeolian transport was 28.25 µmol/g P higher than the Fe-P average concentration of the sediment collected from the sand pits at the established dunes. At the traditional-nourishment site, this difference is even larger, with the Fe-P concentration of the sediment being deposited having an average concentration 79.85 µmol/g P higher than the average concentration of the sediment collected in the sand pits at the established dunes. For use as comparison the sediment being deposited by aeolian transport at the established dunes at the non-nourishment site is only 10.96 µmol/g P higher than the sediment collected by sand pits at the established dunes there. As a result, the aeolian transported sand that is being deposited at the established dunes contains 487% more P/g than the sediment collected in the sand pits, whilst the traditional-nourishment site contains a substantial 1115% more. Comparably, the sediment being deposited at the non-nourishment site only contains 81% more P/g than the sediment collected in the sand pits. These findings are to be expected, due to the high concentration of the Fe-P found in the sand pits at the beach of the beach-nourishment sites. I believe that the Fe-P is being transported from the beach, where the nourishment was deposited, by aeolian transport to the established dunes. This theory is reinforced by the findings of Van der Meulen *et al*., (2014), who found that in 4 years a substantial quantity of sand was transported from the beach to the fore and established dunes. Moreover, these findings are further reinforced by other findings from this research. It was found that Fe-P is more commonly found in finer grain sizes (<150µm) than larger grain sizes at the beach-nourishment sites, and it is these finer grains that are more easily transported by aeolian transport (Kok *et al.,* 2012; Anderson & Bunas, 1993).

Fig.3.7 and fig.3.8 show that at the beach-nourishment sites sand that is deposited further inland has higher Fe-P concentrations than transect points closer to the tidal area. This is most likely caused by the Fe-P being found in finer grains, that are easier to transport and therefore more likely to travel further inland from the beach-nourishment deposition (Kok *et al.,* 2012; Anderson & Bunas, 1993). Conflicting this, the non-nourishment site (fig.3.9) does not show this trend, with instead the highest concentration of Fe-P being found at the fore dunes, at the middle of the transect. This could be due to grasses in the fore dunes at the non-nourishment site trapping more sand than the beach-nourishment sites, as Van der Meulen *et al*., (2014) found that in the fore dunes where vegetation was present sand could accumulate by upto 200cm a year. Alternatively it could be due to the wind patterns and particular wind vortices forming on the day of collection when using the sand traps (Van der Meulen *et al.,* 2014; Kok *et al*., 2012).

The statistical analysis of the sand from the mega-nourishment site collected in the sand pits identified Ca-P and Det-P as potential sources of phosphorus for the sand dune ecosystem. Analysis of the sand captured in sand traps at the mega-nourishment site revealed that both the Det-P and Ca-P not to be easily transported with sand by aeolian transport. This is probably due to the Ca-P identified in the sand pits being sourced from marine shell fragments which are comparably quite heavy to individual sand grains, making them harder to transport by aeolian processes. These findings match those of Greene (2002) and Hamm *et al*, (2002) who both stated that marine shell fragments are not easily transported away from the deposition site of the nourishment. A similar reason may be found for why no significant concentration of Det-P was found in the aeolian transported sand at the established dunes at the mega- and non-nourishment sites. Det-P mostly consists of fluorapatite derived from igneous or metamorphic rocks, which are generally quite heavy minerals (Meng *et al*., 2015; Ruttenburg, 1992). Therefore, this would also result in Det-P being quite difficult to transport by aeolian processes. However, countering this is the fact that the average Det-

P concentrations transported to the established dunes by aeolian processes at the traditional nourishment site, being 3.41 µmol/g P higher than the sediment collected by the sand pits. However, this can be explained by the fact that the distance between the beach and the established dunes was much shorter at the traditional nourishment site (122m) than the mega-nourishment site (603m), meaning, that on an exceptionally windy day, as it was, it may be possible to move the Det-P grains to this comparably closer transect point. This is a theory is given further credit by the research of Petersen *et al*., (2011), and Arens (1996) who found that whilst sand could be transported upto distances of 100m inland over the fore dunes crest in seasonal high wind events, generally the further the dunes were from the beach the more difficult it was for the sand to be transported further inland.

At all 3 sites, Ex-P and Org-P were not found in substantial concentrations in the aeolian transported sand at any point along the transect. This is caused by neither the beach-nourishment sites, nor the non-nourishment sites contacting high concentrations of these P-fractions in sediment collected from the beach sand pits, meaning that these P-fractions simply are not available to be transported by aeolian processes. Although an extensive literature review was implemented, it was exceptionally difficult to find any other comparable studies to measure these results of these specific P-fractions against. Whilst research has examined the geochemical effects of beach-nourishment in the Netherlands (Stuyfzand *et al*., 2012; Stuyfzand, *et al*., 2010) neither of the papers analyse the individual P-fractions, nor do other papers from outside the Netherlands (Abu Hilal *et al*., 2009; Rasheed *et al*., 2009).

A comparison of the sandtrap and sandpit data

A comparison of the general trends of the sandpit and sandtrap data reveal an interesting phenomenon at the beach-nourishment sites. At the beach-nourishment sites sandpit data the Tot-P concentration decreases as the transect moves inland, however the sand trap data reveals the opposite trend as Tot-P concentrations increase as the transect moves inland. This is all part of the same process: the movement of sand from the nourishment point via aeolian transport to the established dunes. The sand that was deposited by the beach-nourishment can most likely be identified as the sediment collected in the sand pits at the beach transect points. Particular P-fractions of this sand is transported by aeolian processes to the established dunes, predominantly Fe-P, which is generally found in finer grains that are more easily transported. Statistical analysis adds further rigidity to these findings, with the sand being collected by the sand-traps not being statistically different from the sand collected in the sandpits at the beach transect points. However, at all three sites, it was significantly different from the sediment collected in the sandpits in the established dunes. This is also explained by the finer grain sizes of the Fe-P being easier to transport by aeolian processes (Kok *et al.,* 2012; Anderson & Bunas, 1993). Similar trends were also found for Tot-P at the mega- and non-nourishment site, which can be explained by Tot-P predominantly consisting of Fe-P. Interestingly, this is not the case at the traditional-nourishment site were a huge average difference in Tot-P was found between the data collected in the sand pit and sandtraps in the established dunes. This lack of a statistically significant difference can be explained by the severely limited data, combined with the high standard deviation (as shown in fig.3.8) making the statistical test less accurate. These findings contrast those of Abu Hilal *et al,* (2009) and Rasheed *et al*., (2009), who examined the environmental impacts of beach-nourishment along the Jordanian coast. Both found that beach-nourishments were generally within the pollution levels of the deposition areas, however neither examined the role of P in beach-nourishments, therefore the findings from this research build upon those of Abu Hilal *et al*., (2009) and Rasheed *et al*., (2009) by adding an extra dimension of studying environmental impacts of beach-nourishments in the future.

Ca-P, Det-P, Ex-P, and Org-P concentrations of the sandtrap data were not found to be statistically different from the sandpit data. This is due to two reasons. Firstly; Ca-P, which is predominantly found in marine shell-fragments; and Det-P, which is found in metamorphic and igneous rocks are generally too heavy to be transported by wind, hence not being found in sediment captured by the sand traps. Ex-P and Org-P were found in relatively low concentrations in the sandpit data to begin with, so there is no source of these P-fractions to be moved by aeolian transport.

A comparison of aeolian deposited data of the 3 sites

The most significant difference between the three sites is the concentration of Fe-P found in the aeolian transported sediment at the established dunes when compared to the sediment being transported along the beach. At the beach-nourishment sites, the concentration of Fe-P found in aeolian transported sand increases substantially over the transect. At the mega-nourishment site the Fe-P concentration of the aeolian transported sand increases from 3.98 µmol/g P at the beach to 31.98 µmol/g P at the established dunes, an increase of 28 µmol/g P. At the traditional-nourishment site, this increase in Fe-P concentration is even larger, increasing from 25.07 µmol/g P at the beach to 83.24 µmol/g P at the established dunes. A significant increase of 58.17 µmol/g P. At the non-nourishment site, it is a different story, with only a small increase of 3.59 µmol/g P between the beach and the established dunes. It is possible that the large difference in aeolian transported Fe-P sediment found at the sites is due to the origin of the sand being transported. In the established dunes this is quite likely to be sand that has been transported from the beach. At the beach-nourishment sites this beach area will be composed of deposited nourishment sand, whilst at the non-nourishment site, this will consist of similar sand to the sand found in the sand dunes. The sand that is being transported to the beach at all 3 sites will be sand that has moved along the coastline via longshore transportation (Van Rijn, 1997; Vincent, 1979). At the non-nourishment site this sand should in theory be similar to the sand that is also being transported to the established dunes, hence the little difference between the recorded values at the transect points. However at the beach-nourishment sites, the sand that is being transported to the beach will be different, as the sand being transported to the beach will have come from further down the coastline, not from the beach-nourishment, like the sand being transported to the established dunes. While this is just a theory to explain the results I have found, it is similar to what Van der Wal (2004) found when her research analysed the movement of sand from nourishment sites to fore dunes in the Netherlands over a 5 year period.

Det-P at the traditional-nourishment site is slightly higher at the fore dunes than at the other 2 sites, which is quite unusual. However, this could be explained by abnormal wind force, direction and vortices (Van der Meulen *et al.,* 2014; Kok *et al*., 2012).

Ca-P, Ex-P and Org-P do not exhibit any major differences between the aeolian transported sediment of the three sites.

The relationship between P-fraction and grain size

Sediment that was collected in the sand pits from all 3 sites was sieved into two samples, fine grain (<150µm) and coarse grain (>150µm) per sand trap. Sediment from the sand traps were not sieved for this analysis as not enough was collected for the sieving process.

In both fine and coarse grain sizes at all site Tot-P was found to predominantly consist of the Fe-P fraction. To explain why the Tot-P differentiates so much between the grain sizes it is necessary to explain why the Fe-p variates.

The SEDEX analysis of the fine and coarse grain revealed that fine grain sediment at the beach transect points beach-nourishment sites contained noticeably more Fe-P than the coarse grain. In table 3.6 it can be seen that the fine grain sediment contains 49.6 µmol/g P than the coarse grain. At the traditional-nourishment site a similar difference is observed, with the fine grain containing 52.03µmol/g P more than the coarse grain. I believe this can be explained by the fact that the beach-nourishment sediment is marine sediment dredged up from the North Sea, which is rich in iron-oxide fine grain sediments (Slomp *et al*., 1996). Andrieux-Loyer & Aminot's (2001) research of P-fractions and their relationship with sediment grain size in French coastal areas found the same trends. Contrasting these differences observed at the beach-nourishment sites, the differences in Fe-P concentration between the fine and coarse grain at beach transect point at the non-nourishment site is much lower. The fine grain only containing 0.92µmol/g P more Fe-P than the coarse grain. This further reinforces the theory that the fine grain sediment at the beach-nourishment sites contains high concentrations of Fe-P due to its marine sediment origin. Further inland, at the established dunes the mega-nourishment shows an even larger difference (73.15µmol/g P) in Fe-P contained by the fine grain sediment when compared to the coarse grain sediment. However at the traditional-nourishment site the difference between the two grain sizes was much smaller at only 3.46µmol/g P, whilst the difference substantially increased at the non-nourishment site to 17.817µmol/g P. It is difficult to interpret what exactly causes these big changes in the Fe-P concentration at the traditional and non-nourishment site, but it is possible to speculate that it may be related to N-mineralisation, grass encroachment and microbial activity in the soil (Kooijman *et al*., 2009).

Ex-P, Ca-P, Det-P and Org-P generally do not show major differences in their concentrations between the two grain sizes.

Statistical analysis was used to assess the relationship between grain size, Tot-P and P-fractions. Although large differences were found in Fe-P between the grain sizes at the mega- and traditional-nourishment sites they were not calculated to be statistically significant. This can be explained by a severely limited data set (only 2 records per grain size per site) combined with comparably quite a high standard deviation in the samples. At the mega-nourishment site a statistically significant relationship was found in Tot-P between the two grain sizes ($p = 0.039$). This is interesting, as Tot-P is predominantly determined by the Fe-P concentration of the sample, however the Tot-P in this case has a slightly lower standard deviation, meaning that in this case it the difference was statistically significant. No other differences in the P-fraction concentrations of the two grain sizes at the mega- or traditional-nourishment site were calculated to be statistically significant. Intriguingly, at the non-nourishment site the statistical analysis did reveal a statistically significant difference in the Ca-P concentration between the fine and coarse grain sediment. This is due to the larger grain size not containing any Ca-P at all. This I believe is a case of perhaps the limited sampling not being representative of reality, as usually Ca-P is found in marine shell fragments which are quite large fragments (Andrieux-Loyer & Aminot, 2001). In the preparation process for the grain size analysis any objects larger than 2mm were removed from the sample and this will have included marine shell fragments larger than 2mm in diameter.

Grain size distribution

The results from the grain size distribution of a selection of sediment from sand pit and sand trap data revealed that the mega-nourishment site contained the largest average proportion of fine grain sediment (7.72%), whilst the traditional-nourishment site only contained an average proportion of 0.38% of fine grain. Comparatively, the non-nourishment site contained not a single fine grain, with 0% of its proportion consisting of fine grain sediment. This suggests that beach-nourishments contain more fine grain sediment than the sediment found at non-nourishment sites. This finding matches the work of Greene (2002) and Hamm *et al,.* (2002), who stated that beach-nourishments introduce a higher proportion of fine grain sediment to a beach. Interestingly, this is the opposite of the findings of Van der Wal (1998), who found that beach-nourishment sediment was less likely to be transported via aeolian processes than non-nourishment sand as the beach-nourishment sediment contained large quantities of shell fragments. This difference between the findings of this research and that of Van der Wal (1998) can probably be explained by the fact that shell fragments larger than 2mm were removed from the sample before grain size analysis, whereas in Van der Wal's (1998) research they were not. Why the large difference in proportion of fine grain sediment between the two beach-nourishment sites is another matter. This may be due to the depth the sediment was sourced from. Van Duin *et al*., (2012) state that in normal situations, a traditional-nourishment will only dredge up sediment from the Holocene epoch, which varies between 2m to over 10m in thickness. However, in cases of larger nourishments, such as a mega-nourishment sand will be dredged up from deeper depths as more sand is required. When this occurs sand can be dredged up from the Pleistocene epoch, containing sediment from Weichselian (last ice age), Eemian (interglacial) and Saalian (2nd from last ice age). Personal communication with Pit (2015), confirmed that the dredging of sediment for the mega-nourishment site did in this case dredge sediment from the Pleistocene epoch. During glacial periods dust deposition is 2-20 times higher than it is during an interglacial (Mahowald *et al*., 1999), like the Holocene period, so it is therefore quite possible that the higher proportion of fine grain sediment in the mega-nourishment site may be sourced from this period of increased dust deposition.

Summary of findings

The approach taken by this research provides an overview of how differing scales of beach-nourishments cause differences in P-availability in sand dune ecosystems. Firstly, it was found that mega- and traditional-nourishments can indeed provide potential major source of phosphorus to a sand dune ecosystem. At both of the beaches were the nourishments were deposited substantially higher values (mega = 9.37 µmol g more/ P; trad = 2.54 µmol g/ P more) of Tot-P were recorded at the beach than in the established dunes. At the non-nourishment site this difference (only 0.07 µmol g/ P more) between the sand collected from the beach and the established dunes was not present. The increased Tot-P found at the beach-nourishment sites is due to the large proportion of Fe-P found in the sand at the beaches at the beach-nourishment sites, which has most likely originated from the rich iron-oxide marine sediments described by Andrieux-Loyer & Aminot (2001) and Slomp *et al*. (1996).

Secondly it was found that higher concentrations of Fe-P were being transported by aeolian processes to the established dunes than what had been recorded in the sand pits at all 3 sites. This is due to the fine grain size that Fe-P is associated with, making it easier to transport by aeolian processes (Kok *et al*., 2012; Anderson & Bunas, 1993). At the mega-nourishment site the sand being caught in the sand traps was 28.25 µmol g/ P more than the sand collected in the sand pits there, whilst at the traditional-nourishment site it was considerable 79.85 µmol g/ P increase was recorded. Comparably, at the non-nourishment site the sediment caught in the sand traps at the established dunes only recorded a 10.96 µmol g/ P increase on the sediment collected in the sand traps there. The large quantities of Fe-P being transported to the established dunes at the beach-nourishment sources is likely coming from the deposited nourishment on the beach, though this cannot be proven beyond doubt as there is no way to trace the sand. However, this explanation is complimented by the findings of Van der Meulen *et al*., (2014) and Van der Wal (2004), who also found that sand was aeolian transported from the beach to the established dunes. Additionally, it was also found that in most situations that Ca-P and Det-P are often too heavy to be moved by aeolian transportation, matching the works of Greene (2002) and Hamm *et al*., (2002), meaning that not all of the P that is made available by a nourishment on the beach can be transported to the established dunes. More research needs to be done here to ascertain fully the origin of the sand being transported to the established dunes.

Thirdly, at the beach-nourishment sites a comparison of the sediment caught in with the sand traps with the sediment collected in the sand pits revealed opposing trends in Tot-P and Fe-P over distance. The sand trap data showed an increase in Tot-P and Fe-P concentrations as sediment was deposited inland, whilst the sandpit data showed a decrease in the soil Tot-P and Fe-P concentrations as the transect went further inland. This suggests that aeolian transport could be responsible for a movement of Tot-P and Fe-P from the beaches to the established dunes at beach-nourishment sites. This again would be supported by the findings of Van der Meulen *et al*. (2014) and Van der Wal (2004). At the non-nourishment sites this relationship is not observed.

Fourthly, it was found that grain size plays an important role in the transportation of Fe-P with significantly more Fe-P found in fine grain sizes than in the coarse grain sediment at the beach-nourishment sites. At the non-nourishment site only 0.92 µmol g/ P more Fe-P was found in the fine grain than in the coarse grain. These findings suggest that the fine-grained Fe-P are complimented by those of Andrieux-Loyer & Aminot (2001) and Slomp *et al*. (1996) who found similar properties in North Sea sediments. It was also found that the mega-nourishment nourishment site contained far more fine grain material than either the traditional or non-nourishment site, theoretically making it easier for Fe-P to be transported to the established dunes.

Limitations

Whilst this paper has made progression into analysing the role of beach-nourishment in effecting P-availability it still has its limitations and space for further research. Firstly, much of the analysis was compounded by issues with the reliability of statistical tests, with many type II errors detected. This was due to the small sample numbers collected and the natural high standard deviation of the data. In order to address this issue, further work should collect more samples in order to have a larger dataset to perform statistical analysis on, thus reducing the effect of the large standard deviation in statistical tests.

Furthermore, this paper has not taken into account the role of the individual coastal dynamics at each site. There is a large variability in the sand volume that can be moved over time and this varies from geographical location to location. As the sand trap samples were collected on different days from each site and only for a maximum of 5 days at each site, it really is only a small snapshot of what sand is being deposited in the sand traps over the life of a beach-nourishment project. Further work should address this by examining the wind direction and force to see whether these factors may affect the p-availability in sand dune ecosystems.

In the SEDEX analysis of the sand trap sediment there a contamination occurred when the $MgCl_3$ was extracted. This resulted in the Ca-P values of the sand trap data only consisting of data from the acetate extraction of the SEDEX and not the full acetate + $MgCl_3$ sum as it should be. Luckily, from the first SEDEX of the sandpit data the $MgCl_3$ did not extract a significant amount P, so this contamination only would have had a limited effect in altering the Ca-P value of the sandtrap data. This contamination was not carried over to any later steps in the extraction, as the blanks of the later steps had the correct values for a blank.

Furthermore this paper did not take into account the role of saltation, the process where sand hops along the surface. This process of saltation can mobilise a variety of particles that normally would not be transported by aeolian processes, thus potentially causing some contamination of the results from the sand traps (Kok *et al*., 2012). Finally, this paper could have included a more in-depth analysis of the role of pH on effect P-availability in the sand dune ecosystems, as more acidic pH can increase the solubility of Fe-P, thus making it easier for plants to absorb the P (Kooijman *et al*., 2008).

Taking all of the above limitations, especially, the statistical limitations of this paper, the findings of this paper can be better classified as explaining general trends found at beach-nourishment sites than an accurate measurement of significant differences between nourishment sites.

5 Conclusions

In summary it seems that beach-nourishments can affect the P-availability of sand dune ecosystems over time. Beach-nourishment does provide a potential new source of phosphorus as the work of Andreix-Loyer & Aminot (2001) and Slomp *et al* (1996) suggest. Furthermore aeolian transport can move substantial concentrations of the Tot-P in the form of the fine-grained Fe-P to the established dunes, building on the findings of Van der Meulen *et al*. (2014), Kok *et al*., (2012) and Van der Wal (2004). This is important to consider, because as beach-nourishments and particularly mega-nourishments become more common it would be wise to know what further effects they can have on P-availability in the sand dune ecosystems. This paper only provides a tiny snapshot in the lives of a mega and traditional-nourishments, but the trends it shows are of concern. If these trends continue it could be possible that the overall concentration of Tot-P will increase, potentially causing a change in the ecosystem found at the sand dunes. What this change could result in this paper cannot answer, so more research is required to assess what effects of increased Tot-P and, particularly Fe-P, could have on sand dune ecosystems.

It has also been found that grain size of the beach-nourishment is an important consideration, as increased proportions of fine grain equates to an increase of Fe-P in sites where beach-nourishments have occurred. This research is a logical progression of the findings of Andrieux-Loyer & Aminot (2001) and Slomp *et al.* (1996). It could be wise to further research the relationship between the proportion of fine-grained sediment and Fe-P from more potential borrowing sites in the North Sea, before using it in a beach-nourishment. Better knowledge and avoidance of using marine sediments that contain high proportions of fine grain sediment as borrowed material for beach-nourishments would reduce Tot-P and Fe-P then being transported from the beach-nourishment site to the established sand dunes.

Whilst this paper does have its limitations, with the lack of statistical reliability being a prominent issue, the trends that constantly reoccur in the variety of the data analysed in the paper are enough to suggest that beach-nourishments could cause substantial changes in P-availability in sand dune ecosystems when compared to non-nourished sites.

6 Reference List

Abu Hilal, A. H., Rasheed, M. Y., Al Hihi, E. A. and S. A. Al Rousan. 2009. Characteristics and potentrial environmental impacts of sand material from sand dunes and uplifted marine terraces as potential borrow sites for beach nourishment along the Jordanian coast of the Gulf of Aqaba. *Journal of Coastal Conversation*. **13** (4). pp 247-261.

Airoldi, L., Abbiati, M., Beck, M. W., Hawkins, S. J., Jonsson, P. R., Martin, D., Moschella, P. S., Sundelof, A., Thompson, R. C. and P. Aberg. 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. *Coastal Engineering*. **52** (10-11). pp 1073-1087.

Anderson, R. S. and K. L. Bunas. 1993. Grain-size segregation and stratigraphy in Aeolian ripples modelled with a cellular-automation. *Nature*. **365** (6448). pp 740-743.

Andersson, A. J., Mackenzie, F. T. and J. P. Gattuso. 2011. Effects of ocean acidification on benthic processes, organisms and ecosystems. In: Gattuso, J. P. and L. Hansson. eds. *Ocean Acidification*. Oxford: Oxford University Press. pp 122-53.

Andrieux-Loyer, F. and A. Aminot. 2001. Phosphorus forms related to sediment grain size and geochemical characteristics in French coastal areas. *Estuarine, Coastal and Shelf Science*. **52** (5). pp 617-629.

Anthony, K. R. N., Kline, D. I., Diaz-Oulido, G., Dove, S. and O. Hoegh-Guldberg. 2008. Ocean acidification causes bleaching and productivity loss in coral reef builders. *Processings of the National Academy of Sciences of the United States of America.* **105** (45). pp 17442-17446.

Arens, S. M. 1996. Patterns of sand transport on vegetated foredunes. *Geomorphology*. **17** (4). pp 339-250.

Arens, S.M., Mulder, J. P. M., Slings, Q. L., Geelen, L. H. W. T. and P. Damsma. 2013. Dynamic dune management, integrating objectives of nature development and coastal safety: Examples from the Netherlands. *Geomorphology*. **199** (Si). pp 205-213.

Bakker, C., Rodenburg, J. and P. M. van Bodegom. 2005. Effects of Ca- and Fe-rich seepage on P availability and plant performance in calcareous dune soils. *Plant and Soil*. **275** (1-2). pp 111-122.

Beusekom, J. E. E. van. and Jonge, V. N. de. 1998. Retention of phosphorous and nitrogen in the Ems estuary. *Estuaries*. **21** (4). pp 527-539.

Bramha, S. N., Mohanty, A. K., Padhi, R. K., Panigrahi, S. N. and K. K. Satpathy. 2014. Phosphorous speciation in the marine sediment of Kalpakkam coast, southeast coast of India. *Environmental Monitoring and Assessment*. **186** (10). pp 6003-6015.

Brion, N., Baeyans, W., de Galan, S., Elskens. M. and R. W. P. M. Laane. 2004. The North Sea: source or sink for nitrogen and phosphorus to the Atlantic Ocean? *Biogeochemistry*. **68** (3). pp 277-296.

Caraco, N., Cole, J. and G. E. Likens. 1990. A comparison of phosphorus immobilization in sediments of freshwater and coastal marine systems. *Biogeochemistry*. **9** (3). pp 277-290.

Davison, A. T., Nicholls, R. J., and S. P. Leatherman. 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. *Journal of Coastal Research*. **8** (4). pp 984-1022.

Duin, C. F. van., Vrij Peerdeman, M., Jaspers, C. J., Bucholc, A. M. and S. C. Wessels. 2012. *MER winning suppletiezand Noordzee 2013 t/m 2017*. Houten: Grontmij Nederland B. V.. pp 81-83.

Dutch Water Sector. 2011. *Projects: The Sand Motor – Building with Nature*. [Online]. [Accessed on 04 August 2015]. Available from: http://www.dutchwatersector.com/solutions/projects/186-the-sand-motor.html.

Ecomare. 2015. *Ecomare Encyclopedia: Dune Areas*. [Online]. [Accessed on 11 May 2015]. Available from: http://www.ecomare.nl/en/encyclopedia/regions/landforms/dunes/.

Eisma, D. 1968. Composition, origin and distribution of Dutch coastal sands between Hoek van Holland and the island of Vlieland. *Netherlands Journal of Sea Research*. **4** (2). pp 123-267.

Eisma, D. and K. Kalf. 1979. Distribution and particle size of suspended matter in the southern bight of the North Sea and the Eastern Channel. *Netherlands Journal of Sea Research*. **13** (2). pp 298-324.

Gazeau, F., Quiblier, C., Jansen, J. M., Gattuso,, J. P., Middelburg, J. J. and C. H. R. Heip. 2007. Impact of elevated CO_2 on shellfish calcification. *Geophysical Research Letters*. **34** (7). pp 1-5.

Giardino, A., Mulder, J., de Ronde, J. and J. Stronhorst. 2011. Sustainable development of the Dutch Coast: Present and future. *Journal of Coastal Research*. [Special Issue] (61). pp 166-172.

Goossens, D. and Z. Y. Offer. 2000. Wind tunnel and field calibration of six aeolian dust samplers. *Atmospheric Environment*. **34** (7). pp 1043-1057.

Goossens, D., Offer, Z. and G. London. 2000. Wind tunnel and field calibration of five aeolian sand traps. *Geomorphology*. **35** (3-4). pp 233-252.

Greene, K. 2002. *Beach Nourishment: A Review of the Biological and Physical Impacts*. Washington DC, USA: ASMFC Habitat Management Series # 7.

Grizzetti, B., Bouraoui, F. and A. Aloe. 2012. Changes in nitrogen and phosphorus loads to European Seas. *Global Change Ecology*. **18** (2). pp 769-782.

Hamm, L., Capobianco, M., Dette, H. H., Lechuga, A., Spanhoff, R. and M. J. F. Stive. 2002. A summary of European experience with shore nourishment. *Coastal Engineering*. **47** (2). pp 237-264.

Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., Lechuga, A. and R. Spanhoff. 2002. Beach nourishment projects, practices, and objectives - a European overview. *Coastal Engineering*. **47** (2). pp 81-111.

Heiberger, R. M. and E. Neuwirth. 2009. *R Through Excel – A Spreadsheet Interface for Statistics, Data Analysis, and Graphics*. London: Springer. pp 165-187.

Jickells, T. 2005. External inputs as a contributor to eutrophication problems. *Journal of Sea Research*. **54** (1). pp 58-69.

Jokiel, P. L., Rodgers, K. S., Kuffner, I. B., Andersson, A. J., Cox, E. F. and F. T. Mackenzie. 2008. Ocean acidification and calcifying reef organisms: a mesocom investigation. *Coral Reefs*. **27** (3). pp 473-483.

Jolliffe, I. 2014. *Principal Component Analysis*. [Online]. Wiley StatsRef: Statistics Reference Online. [Accessed 23 May 2015]. Available from: http://onlinelibrary.wiley.com/doi/10.1002/9781118445112.stat06472/abstract?systemMessage=Wiley+Online+Library+will+have+intermittent+access+on+8th+August+2015+from+10%3A00-16%3A00+BST+%2F+05%3A00-11%3A00+EDT+%2F+17%3A00-23%3A00+SGT+for+essential+maintenance.++Apologies+for+the+inconvenience.&userIsAuthenticated=false&deniedAccessCustomisedMessage=.

Jones, M. L. M., Wallace, H. L., Norris, D., Brittain, S. A., Haria, S., Jones, R. E., Rhind, P. M., Reynolds, B. R. and B. A. Emmett. 2004. Changes in vegetation and soil characteristics in coastal sand dunes along a gradient of atmospheric nitrogen deposition. *Plant Biology*. **6** (5). pp 598-605.

Kachi, N. and T. Hirose. 1983. Limiting nutrients for plant growth in coastal sand dune soils. *Journal of Ecology*. **71** (3). pp 937-944.

Khedr, E., Abou Elmagd, K. and M. Halfawy. 2014. Rate and budget of blown sand movement along the western bank of Lake nasser, southern Egypt. *Arabian Journal of Geosciences*. **7** (9). pp 3441-3453.

Kooijman, A. M. 2004. Environmental problems and restoration measures in coastal dunes in the Netheralnds. In: Martínez, M. L. and N. P. Psuty. Eds. *Coastal Dunes: Ecology and Conservation*. Berlin: Springer. pp 243-258.

Kooijman, A. M. and M. Besse. 2002. The higher availability of N and P in lime-poor than in lime-rich coastal dunes in the Netherlands. *Journal of Ecology*. **90** (2). pp 393-403.

Kooijman, A. M., Dopheide, J. C. R., Sevink, J., Takken, I. and J. M. Verstraten. 1998. Nutrient limitations and their implications on the effects of atmospheric deposition in coastal dunes; lime-poor and lime-rich sites in the Netherlands. *Journal of Ecology*. **86** (3). pp 511-526.

Kooijman, A. M., Lubbers, I. and M. van Til. 2009. Iron-rich grasslands: Relations between soil organic matter and sorption of Fe and P. *Environmental Pollution*. **157** (11). pp 3158-3165.

Kraal, P., Jilbert, T. and F. Sulu-Gambari. 2012. *Sequential Phosphorus Extraction*. Unpublished.

Kok, J. F., Parteli, E. J. R., Michaels, T. I. and D. B. Karam. 2012. The physics of wind-blown sand and dust. *Reports on Progress in Physics*. **75** (10). pp 1-73.

Langdon, C. and M. J. Atkinson. 2005. Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature / irradiance and nutrient enrichment. *Journal of Geophyiscal Research.* **110** (9). pp 1-16.

Li, Z. S. and J. R. Ni. 2003. Sampling efficiency of vertical array aeolian sand traps. *Geomorphology*. **52** (3-4). pp 243-252.

Loch, J. P. G. 2001. Inleiding Bodemkunde (RW-MBIB): Practicumhandleiding.

Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S. P., Prentice, I. C., Schulz, M. and H. Rodhe. 1999. Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments. *Journal of Geophysical Research-Atmospheres*. **104** (D13). pp 15895-15916.

Mendez, M. J., Funk, R. and D. E. Buschiazzo. 2011. Field wind erosion measurements with Big Spring Number Eight (BSNE) and Modified Wilson and Cook (MWAC) samplers. *Geomorphology*. **129** (1-2). pp43-48.

Meng, J., Yao, P., Bianchi, T. S., Li, D., Zhao, B., Xu, B. and Z. Yu. 2015. Detrital phosphorus as a proxy of flooding events in the Changjiang River Basin. *Science of the Total Environment*. **517** (1). pp 22-30.

Neset, T. S. S. and D. Cordell. 2011. Global phosphorus scarcity: Identifying synergies for a sustainable future. *Journal of the Science of Food and Agriculture*. **92** (1). pp 2-6.

Nordstrom, K. F., Jackson, N. L. and K. H. Korotky. 2011. Aeolian sediment transport across Beach Wrack. *Journal of Coastal Research*. **59** (Special Issue). pp 211-217.

Oliff, H., Huisman, J. and B. F. Van Tooren. 1993. Species dynamics and nutrient accumulation during early primary succession in coastal sand dunes. *Journal of Ecology*. **81** (4). pp 693-706.

Petersen, P. S., Hilton, M. J. and S. J. Wakes. 2011. Evidence of aeolian transport across an *Ammophila arenaria*-dominated foredune, Mason Bay, Stewart Island. *New Zealand Geographer*. **67** (3). pp 174-189.

Peterson, C. H. and M. J. Bishop. 2005. Assessing the environmental impacts of beach nourishment. *Bioscience*. **55** (10). pp 887-896.

Pit, I. 2015. *Email from Iris Pit*. 3 August.

Ramaekers, G. 2015. *Coastal Erosion and Protection*. Coastal Processes: The Dutch Approach, 24 February, Utrecht.

Rasheed, M., El-Hihi, E., Al-Rousan, S. and A. Abu-Hilal. 2009. Chemical evaluation of sand material sources for beach replenishment along the coast of the Gulf of Aqaba, Red Sea. *Chemistry and Ecology*. **25** (5). pp 371-384.

Rijn, L. E. van.. 1997. Sediment transport and budget of the central coastal zone of Holland. *Coastal Engineering*. **32** (1). pp 61-90.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke. C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. and J. Foley. 2009. Planetary Boundaries: Exploring the safe operating space of humanity. *Ecology and Society*. **14** (2). 32.

Roelse, P. 1996. *Evaluatie van zandsuppleties aan de Nederlands kust 1975-1994*. Report RIKZ-96.028. The Hague, Netherlands: Rijkswaterstaat.

Rotnicka, J. 2012. Aeolian vertical mass flux profiles above dry and moist sandy beach surfaces. *Geomorphology*. **187**. pp 27-37.

Ruttenberg, K. C. 1992. Development of a sequential extraction method for different forms of phosphorus in marine sediments. *Limnology and Oceanography*. **37** (7). pp 1460-1482.

Schoumans, O. F. and P. Groenendijk. 1998. Modeling soil phosphorus levels and phosphous leaching from agricultural land in the Netherlands. *American Society of Agronomy*. **29** (1). pp 111-116.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and F. Zhang. 2011. Phosphorus dynamics: From soil to plant. *Plant Physiology.* **156** (3). pp 997-1005.

Sherman, D. J., Li, B. L., Farrell, E. J., Ellis, J. T., Cox, W. D., Maia, L. P. and P. H. G. O. Sousa. 2011. Measuring aeolian saltation: a comparison of sensors. *Journal of Coastal Research*. **59** (Special Issue). pp 280-290.

Slobbe, E. van., Vriend, H. J. de., Aarninkhof, S., Lulofs, K., Vries, M. de. and P. Dircke. 2013. Building with nature: in search of resilient storm surge protection strategies. *Natural Hazards*. **66** (3). pp 1461-1480.

Slomp, C. P. and P. van Cappellen. 2007. The global marine phosphorus cycle: sensitivity to oceanic circulation. *Biogeosciences*. **4** (2). pp 155-171.

Slomp, C. P., van der Gaast, S. J. and W. van Raaphorst. 1996. Phosphorus binding by poorly crystalline iron oxides in North Sea sediments. *Marine Chemistry*. **52** (1). pp 55-73.

Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J. P., Mathys, M., Provoost, S., Sabbe, K., Stienen, E. V. M., Van Lancker, V., Vincx, M. and S. Degraer. 2006. Beach nourishment: an ecologically sound coastal defence alternative? A review. *Aquatic Conservation-Marine and Freshwater Ecosystems*. **16** (4). pp 419-435.

Stive, M. J. F., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G. J., van Gelder-Maas, C., van Thiel de Vries, J. S. M., de Vries, S., Henriquez, M., Marx. S. and R. Ranasinghe. 2013. A new alternative to saving our beaches from sea-level rise. *Journal of Coastal Research*. **29** (5). pp 1001-1008.

Stuyfzand, P. J., Arens, S. M. and A. P. Oost. 2010. *Geochemische effecten van zandsuppleties langs Hollands kust*. Den Haag: Ministerie van Economische Zaken, Landbouw en Innovatie.

Stuyfzand, P. J., Arens, S. M., Oost, A. P. and P. K. Baggelaar. 2012. *Geochemische effecten van zandsuppleties langs Hollands kust: Langs de kust van Ameland tot Walcheren*. Den Haag: Ministerie van Economische Zaken, Landbouw en Innovatie.

Veer, M. A. C. and A. M. Kooijman. 1997. Effects of grass-encroachment on vegetation and soil in Dutch dry dune grasslands. *Plant and Soil*. **192** (1). pp 119-128.

Vincent, C. E. 1979. Longshore sand transport rates – A simple model for the East Anglian Coastline. *Coastal Engineering*. **3** (2). pp 113-136.

Wal, D. van der. 1998. The impact of the grain-size distribution of nourishment sand on aeolian sand transport. *Journal of Coastal Research*. **14** (2). pp 620-631.

Wal, D. van der. 2004. Beach-dune interactions in nourishment areas along the Dutch Coast. *Journal of Coastal Research*. **20** (1). pp 317-325.

Wang, X. M., Zhang, C. X., Wang, H. T., Qian, G. Q., Luo, W. Y., Lu, J. F. and L. Wang. 2011. The significance of Gobi desert surfaces for dust emissions in China: an experimental study. *Environmental Earth Sciences*. **64** (4). pp 1039-1050.

Zee, C. van der., Roevros, N. and L. Chou. 2007. Phosphorus speciation, transformation and retention in the Scheldt estuary (Belgium/The Netherlands) from the freshwater tidal limits to the North Sea. *Marine Chemistry*. **106** (1-2). pp 76-91.

Appendixes

Appendix 1

Sequential Phosphorus Extraction ☺

Peter Kraal, Tom Jilbert, **Fatimah Sulu-Gambari**

(Based on Ruttenberg 1992, current from November 2012)

Extractions

Sample and Solution Preparation

Preparations are best carried out the week before the extractions commence. Prepare stock solutions according to Table 1 in a fume cupboard. Weigh ≈0.1 g sediment into 50 ml centrifuge tubes. Prepare two sets of 20ml syringes fitted with filters for each sample, which will be interchanged and washed in UHQ for the duration of the extraction procedure. Preparation is conducted for 60 samples (58 sediment samples and 2 blanks).

Table 1: extraction solution stock recipes

	Stock (≈60 samples)	**End vol (ml)**	**Recipe**
1	0.3 M Na-Citrate	1600	141.2 g Na-citrate in 1600 ml UHQ
2	1 M $NaHCO_3$	400	33.6 g Na- Bicarbonate in 400 ml UHQ
3	1 M $MgCl_2$	2000	406.6 g $MgCl_2$ in 2000 ml UHQ
4	1 M Na- acetate	1000	164.06 g Na-acetate in 1000 ml UHQ
5	1 M CH_3COOH	1000	60 ml acetic acid in 940 ml UHQ
6	1 M Acetate Buffer	2000	300 ml **4** and 1700 ml **5**
7	1 M HCl	2000	166.6 ml 37% HCl (or 192.6 ml 32% HCl) in 1833.4 ml UHQ

Notes:

[1] The first step should be carried out in the same week as the chemical prep, to accommodate the remaining extractions within a five-day week

[2] The first two steps of the extractions are conducted in a nitrogen-purged glove-box

[3] Centrifuge for 5-10 minutes at 2500-2800 rpm; make sure to clean the centrifuge after the CDB step

[4] i.e. 8ml Na citrate, 1ml bicarbonate and 0.2 g dithionite **per sample**

[5] This filtrate will then be thawed and diluted 10* in UHQ for analysis with ICP-OES

Day 1- Extraction of Exchangeable P [1,2]

- Add 10ml $MgCl_2$ to each sample tube
- Shake for 30 minutes, centrifuge [3] to pellet sediment, weigh tubes, filter and store filtrate at 4°C (label as **$MgCl_2$ 1**)
- **$MgCl_2$ 1 is analysed to give the Exchangeable P fraction**

Day 2- Extraction of Fe-bound P [2]

- Dissolve 12g Na dithionite in 480ml Na-citrate and 60ml Na-bicarbonate (pH ≈ 7.5) [4] and add 9ml to each sample tube
- Shake for 8 hours, weigh tubes, centrifuge, filter and store filtrate at -20°C (label as **CDB**) [5]
- Add 10ml $MgCl_2$ to each sample tube (label as **$MgCl_2$ 2**)
- Shake for 30 minutes, weigh tubes, centrifuge, filter and store filtrate at 4°C
- **CDB + $MgCl_2$ 2 results combined return the Fe-bound P fraction**

Day 3 and 4- Extraction of Authigenic P, Ca-P and Detrital P

- Add 10 ml acetate buffer (pH 4) to each sample tube
- Shake for 6 hours, weigh tubes, centrifuge, filter and store filtrate at 4°C (label as **Acetate**)
- Add 10ml $MgCl_2$ to each sample tube
- Shake for 30 minutes, weigh tubes, centrifuge, filter and store filtrate at 4°C (label as **$MgCl_2$ 3**)
- Add 10ml HCl to each sample tube
- Shake for 24 hours, weigh tubes, centrifuge, filter and store filtrate at 4°C (label as **HCl 1**)
- **Acetate and $MgCl_2$ 3 combined result in the Authigenic and Ca-P fractions**
- HCl 1 represents the Detrital P fraction

Day 4 and 5- Ashing to extract Total Organic P

- Convey sediment from sample tubes to labelled ceramic crucibles by flushing sample tubes contents 2-3 times with UHQ; air dry the emptied sample tubes

- Dry sediment at 50°C for ≈24 hours (or 90°C for ≈12 hours, or 80°C for ≈16 hours)
- And measure Acetate and MgCl2
- Ash samples for 2 hours at 550°C in a muffle oven (total oven time, including pre-heating is ≈3 hours)
- Convey ashed samples to the air-dried sample tubes (loosen the sediment using a spatula and grind them slightly in the crucible before transfer)
- Add 10 ml HCl to ashed samples
- Shake for 24 hours, weigh tubes, centrifuge, filter and store filtrate at 4°C (label as HCl 2)
- HCl 2 represents the Organic P fraction
- Measure HCL

<u>Colourimetric Phosphate Analysis</u>

Solution preparation

Notes:

* Standards (provided) used to make Stock solutions:

- Stock 1: Make a stock solution by diluting 0.95 ml (of 1000 mg/L) Merck stock to 100 ml (to make a 100 µM P solution)
- Stock 2: Dilute 10 ml Stock 1 to 100 ml (to make a 10 µM P solution)

Table 2: Calibration Series

	C_p (µM)	Standard* (µl)	Matrix (µl)[1]	Ahm[2]-asc solution (µl)	UHQ (µl)[3]
1	0	0 of Stock 2	800	800	2400
2	1	400 of Stock 2	800	800	2000
3	2	800 of Stock 2	800	800	1600
4	4	1600 of Stock 2	800	800	800
5	5	2000 of Stock 2	800	800	400
6	10	400 of Stock 1	800	800	2000
7	20	800 of Stock 1	800	800	1600
8	40	1600 of Stock 1	800	800	800
		Sample (µl)		**Ahm-asc solution (µl)**	**UHQ (µl)[3]**
		800		800	2400

[1] Where matrix comprises the extraction solvent i.e. $MgCl_2$, CDB, acetate or HCl; the volume of matrix added to each cuvette corresponds to the amount of sample also added.

[2] Ammonium heptamolybdate; the recipe for which is given in the next section

[3] Volume of water required to reach and end volume of 4ml in each cuvette; volumes in table apply for a 10* dilution of samples, thus requiring 800 µl matrices.

Measurement of Extracts

- Prepare two molybdate solutions according to the recipes in Table 3 below. Then, make a ***mixing reagent*** by dissolving 0.4225 g ascorbic acid in 200 ml of each molybdate solution.

Table 3: Molybdate solution for samples (stored in the dark at 4°C no longer than 2 months)

	Stock (≈76 cuvettes)[3]	End vol (ml)	Recipe regular samples (Ahm 1)	Recipe HCl samples (Ahm 2)
1	Ammonium heptamolybdate (Ahm)	500	2.4 g	2.4 g
2	Sulphuric acid		28 ml	13.5 ml
3	Potassium antimony oxide tartrate hemihydrate		0.0565 g	0.0565 g
4	UHQ		Dilute to 500 ml	Dilute to 500 ml

[3] 16 standards, 58 samples, 2 blanks

- To each cuvette:

    Add UHQ

    Add standard **or** sample

    Add ***mixing reagent***

- Measure the absorbance of the solution in the cuvette at 880 nm (between 10 and 100 minutes after preparation)

Appendix 2:

Sand pit data:

Transects A-C = mega-nourishment, D-F = traditional-nourishment, I – K = non-nourishment

1 = Beach, 3 = established dunes

label	Ex-P	Fe-P	Ca-P	Det-P	Org-P	totorgP	Tot-P
BLANK 1	0,00	0,00	0,00	0,00	0,00	0,00	0,00
A1	0,028	**7,009**	**0,859**	**2,662**	**0,261**	**2,923**	**10,821**
A3	**0,035**	3,018	0,168	1,565	0,238	1,803	5,023
B1	0,073	**8,216**	**0,503**	**4,353**	0,337	**4,689**	**13,482**
B3	**0,086**	0,554	0,000	1,525	**0,504**	2,030	2,670
C1	**0,069**	**16,013**	**0,749**	**4,187**	0,170	**4,357**	**21,188**
C3	0,044	7,601	0,064	1,475	**0,500**	1,975	9,685
Beach Avg.	**0,057**	**10,413**	**0,704**	**3,734**	0,256	**3,990**	**15,164**
Established Dune Avg.	0,055	3,724	0,077	1,522	**0,414**	1,936	5,793
Avg.	0,066	11,548	0,652	4,091	0,254	4,345	16,611
D1	**0,043**	4,386	1,420	**3,085**	**0,315**	**3,400**	9,249
D3	0,000	**6,243**	**1,595**	1,799	0,265	2,064	**9,903**
E1	0,000	**5,450**	**1,579**	**2,179**	**0,391**	**2,571**	**9,599**
E3	**0,580**	3,876	0,268	1,561	0,344	1,905	6,629
F1	0,006	**6,979**	0,606	2,277	0,360	2,638	**10,229**
F3	0,006	0,047	**1,940**	**2,352**	**0,590**	**2,943**	4,935
Beach Avg.	0,016	**5,605**	1,202	**2,514**	0,355	**2,869**	**9,692**
Established Dune Avg.	**0,196**	3,389	**1,268**	1,904	**0,400**	2,304	7,156
Avg.	0,106	4,497	1,235	2,209	0,378	2,587	8,424
I1	**0,054**	13,034	0,000	0,691	**0,477**	1,169	14,256
I3	0,000	**13,471**	0,000	**1,037**	0,379	**1,417**	**14,888**
J1	0,000	**13,128**	0,000	0,693	**0,426**	1,119	**14,247**
J3	**0,039**	9,604	**0,069**	**1,055**	0,349	**1,404**	11,116
K1	**0,028**	10,594	0,000	**0,962**	0,371	**1,333**	11,955
K3	0,000	**13,068**	0,000	0,810	**0,382**	1,191	**14,259**
Beach Avg.	**0,027**	**12,252**	0,000	0,782	**0,425**	1,207	**13,486**
Established Dune Avg.	0,013	12,048	**0,023**	**0,967**	0,370	**1,337**	13,421
Avg.	0,020	12,150	0,012	0,875	0,397	1,272	13,453
BLANK 2	0,000	0,000	0,000	0,000	0,000	0,000	0,000

Appendix 3:

Sand trap data:

Transects A-C = mega-nourishment, D-F = traditional-nourishment, I – K = non-nourishment

1 = Beach, 2= fore dunes, 3 = established dunes. SS= <150µm, LS = >150µm.

Beach	Transect p	Ex-P	Fe-P	Ca-P (Onl	Ca-P (Inc	Det-P	Org-P	totorgP	Tot-P
	BLANK 1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mega-nourishment (sand traps)	A1	**0,124**	0,813	0,000	0,000	0,570	0,269	0,839	1,776
	A2	**0,124**	13,024	0,000	0,000	0,672	0,278	0,950	14,099
	A3	0,000	**34,485**	0,000	**0,058**	**1,692**	**0,310**	**2,002**	**36,487**
	B1	**0,262**	4,343	0,000	0,000	0,763	0,186	0,950	5,554
	B2	**0,262**	9,963	0,000	0,000	0,694	0,218	0,912	11,137
	B3	0,124	**45,099**	**0,086**	**0,207**	**1,974**	**0,350**	**2,324**	**47,633**
	C1	0,000	6,795	0,000	0,000	0,471	0,219	0,690	7,485
	C2	**0,262**	12,556	0,000	0,000	0,817	0,217	1,034	13,852
	C3	0,124	**16,346**	0,000	0,000	**1,231**	**0,372**	**1,603**	**18,073**
	Beach Avg.	0,129	3,983	0,000	0,000	0,602	0,225	0,826	4,938
	Fore Dune Avg.	**0,216**	11,848	0,000	0,000	0,728	0,238	0,965	13,029
	Established Dune Avg.	0,083	**31,977**	**0,029**	**0,088**	**1,633**	**0,344**	**1,976**	**34,064**
	Average	0,143	15,936	0,010	0,029	0,987	0,269	1,256	17,344
Traditional-nourishment (sand traps)	D1	0,000	0,044	1,838	2,186	2,343	0,958	3,301	5,182
	D2	**0,124**	13,956	0,802	0,937	1,548	0,296	1,844	16,726
	D3	**0,124**	**58,489**	**3,925**	**4,956**	**12,920**	**1,408**	**14,328**	**76,867**
	E1	0,000	42,003	**1,464**	**2,186**	**6,253**	**1,206**	**7,459**	50,926
	E2	**0,262**	8,768	0,752	0,956	2,302	0,337	2,639	12,421
	E3	**0,262**	**175,542**	0,793	0,822	1,597	0,464	2,061	**178,658**
	F1	0,000	33,168	**1,895**	**2,065**	0,675	0,258	0,933	35,995
	F2	**0,124**	**63,305**	0,387	0,394	0,559	0,310	0,869	**64,686**
	F3	**0,124**	15,684	0,000		**1,409**	**0,424**	**1,833**	17,641
	Beach Avg.	0,000	25,071	**1,732**	**2,146**	3,090	**0,807**	3,898	30,701
	Fore Dune Avg.	**0,170**	28,676	0,647	0,762	1,469	0,314	1,784	31,277
	Established Dune Avg.	**0,170**	**83,238**	1,573	-	**5,309**	0,765	**6,074**	**91,055**
	Average	0,113	45,662	1,317	1,813	3,289	0,629	3,919	51,011
Castricum-aan-Zee (No nourishment)	I1	0,000	**28,883**	0,147	**0,136**	0,513	0,299	0,812	**29,843**
	I2	**0,124**	23,870	0,048	0,110	0,688	0,330	1,018	25,061
	I3	**0,124**	23,549	**0,203**	-	**1,670**	**0,356**	**2,026**	25,902
	J1	0,124	16,317	0,000	0,000	0,287	0,260	0,547	16,989
	J2	0,124	**31,364**	0,000	0,000	0,645	0,325	0,969	**32,458**
	J3	0,124	16,872	0,000	-	**0,784**	**0,332**	**1,117**	18,113
	K1	**0,124**	13,037	0,000	0,000	0,217	0,235	0,452	13,613
	K2	0,000	**35,089**	0,000	-	0,533	**0,343**	**0,876**	**35,965**
	K3	**0,124**	28,587	0,000	-	**0,543**	0,180	0,723	29,434
	Beach Avg.	0,083	19,412	0,049	0,045	0,339	0,265	0,604	20,148
	Fore Dune Avg.	0,083	**30,108**	0,016	-	0,622	**0,332**	0,954	**31,162**
	Established Dune Avg.	**0,124**	23,003	**0,068**	-	**0,999**	0,289	**1,288**	24,483
	Average	0,097	24,174	0,044	0,049	0,653	0,295	0,949	25,264
	DEEPSEA	0,124	142,858	0,000	0,000	0,648	0,678	1,327	144,310
	DEEPSEA	0,000	34,523	0,319		2,654	0,163	2,817	37,659
	DEEPSEA	0,000	0,000	0,000		0,570	0,198	0,768	0,768
Zandmotor	SS B1	0,000	62,106	0,637	1,463	10,137	0,595	10,733	73,475
	SS B2	0,000	90,987	0,265		6,356	4,595	10,951	102,202

	DEEPSEA	0,124	142,858	0,000	0,000	0,648	0,678	1,327	144,310
	DEEPSEA	0,000	34,523	0,319		2,654	0,163	2,817	37,659
	DEEPSEA	0,000	0,000	0,000		0,570	0,198	0,768	0,768
Zandmotor	SS B1	0,000	62,106	0,637	1,463	10,137	0,595	10,733	73,475
	SS B2	0,000	90,987	0,265		6,356	4,595	10,951	102,202
	LS B1	1,373	12,507	0,000		0,688	0,048	0,736	14,616
	LS B2	0,124	17,147	0,000		1,420	0,309	1,729	19,000
Zoutelande (Traditional Nourishm	SS E1	0,000	76,135	1,683		9,876	0,666	10,542	88,360
	SS E2	0,000	38,650	1,448		11,609	0,898	12,507	52,606
	LS E1	0,000	18,107	6,480		4,727	14,118	18,845	43,431
	LS E2	0,124	35,191	0,345		1,553	0,183	1,736	37,396
Castricum-aan-Zee (No nourishment)	SS J1	0,124	33,596	0,617		4,274	0,248	4,522	38,859
	SS J2	0,124	42,029	0,669		0,988	0,701	1,689	44,512
	LS J1	0,000	32,681	0,000		10,995	0,165	11,160	43,841
	LS J2	0,262	24,212	0,000		0,744	0,148	0,892	25,366