THE EFFECT OF SURFACE MOISTURE ON DUNEFIELD SELF-ORGANISATION:
A MODELLING CASE STUDY OF WHITE SANDS, NEW MEXICO

INTRODUCTION

This study seeks to investigate the effect of surface moisture on dunefield self-organisation by modelling the development of White Sands Dune Field, New Mexico under various surface moisture conditions.

BACKGROUND

White Sands Dune Field, is situated in New Mexico, USA. A geomorphic map of the region (Figure 1) shows a central area of barchan dunes, surrounded by parabolic dunes on the northern, eastern and southern sides. An alkali flat is present on the western side, and smaller lunette and dome dunes are found in the south of the dune field.

In the terminology of McKee (1979) the dunes at White Sands are simple dunes: they consist of individual dunes which are separated spatially. Also, the dune pattern at White Sands is simple (in the terminology of Ewing et al. (2006)), suggesting that there was only one generation of dune construction at White Sands, and that the wind regime stayed relatively constant throughout the construction.

Ewing et al. (2006) showed that at White Sands parameters such as crest length and dune spacing increase with distance from east to west, and that defect density decreases in the same direction. This is expected for dunefields which originate from a point or line source (Ewing & Kocurek, In Press). A study using historical aerial photographs of White Sands has shown that over the last 60 years the overall trend of the whole dunefield was towards a higher defect density, and lower crest lengths (Rachal & Dugas, 2009): that is, towards disorganisation, as opposed to the expected trend towards organisation (as suggested by Kocurek & Ewing, 2005; Werner, 1995). However, in the period 1963-1985, this trend was reversed and the dune field became more organised. They hypothesise that this was due to higher than average precipitation during that period. This brought the water table closer to the surface, increasing surface moisture, and reducing sediment transport across the dune field, allowing the dunes to become more organised. The more general application of this hypothesis will be the focus of this study.

Rachal and Dugas (2009) suggested that a possible reason for the trend of White Sands towards disorganisation is the wind regime, which was defined by Fryberger and Dean (1979) as obtuse bimodal (RDP/DP = 0.37). In the winter and spring months, when there is the least precipitation (Fryberger, 2004), there are very strong winds from the southwest which do a lot of geomorphic work (see sand roses, Figure 1). The winds from other directions are mainly during the wetter parts of the year when the sand is more cohesive and therefore less easily moved. This is confirmed by the measurements of Ochoa, (2005), who found that 68% of the total movement for a sampled barchan dune in 2003 occurred between January and May. The winds in the winter are not able to completely realign the dunes, but they do lead to movements of the horns of barchan dunes, which stop the horns from joining together to eventually create barchanoid ridges. This leads to an increase in sinuosity and defect density, causing the trend towards disorganisation.

Rachal and Dugas (2009) do not suggest the exact mechanism through which increased moisture may lead to self-organisation. They note that the water table at White Sands is very close to the surface (McKee, 1979), and that precipitation can raise the water table even higher. Capillary action can then bring water to the surface sediments, which both decreases the likelihood of erosion of these sediments, and increases the likelihood of deposition of sediment already in transport.

The reduction in erodibility of moist sand has been shown in a number of studies (Cornelis & Gabriels, 2003; Davidson-Arnott et al., 2008) and is an important component in mobility indices (such as Lancaster, 1988). A high enough moisture content can completely stop sediment transport. As well as reducing the erodibility of sand, moisture also increases the likelihood of deposition as saltating grains stick to the moist surface when they land, reducing the chances of reptation (Kocurek et al., 1992).

In many ways it seems common sense to assume that an increase in surface moisture will actually reduce the self-organisation achieved in a set time period, as there will be less movement of sand, less dune movement, and therefore fewer collisions between dunes. As it is the merging of dunes which causes self-organisation (Ewing et al., 2006), it seems logical that an increase in surface moisture will reduce self-organisation. However, Rachal and Dugas (2009) suggest that at White Sands the opposite is true, and this deserves further investigation.

HYPOTHESES

Number	Hypothesis	Rationale
1	A sudden increase of moisture in the White Sands model will lead to increased organisation of the dunefield.	Suggested by Rachal and Dugas (2009; Figure 6)
2	Dunefields which develop in areas with high moisture content will be more organised than those which develop in areas of low moisture.	A generalisation of the work of Rachal and Dugas (2009).
3	Nearest Neighbour analysis is a robust and accurate method for measuring dunefield self-organisation from model outputs.	This method was used in a simple fashion by Wilkins and Ford (2007), but has not been yet been applied to modelled landscapes.

TABLE 1 - HYPOTHESES AND RATIONALE

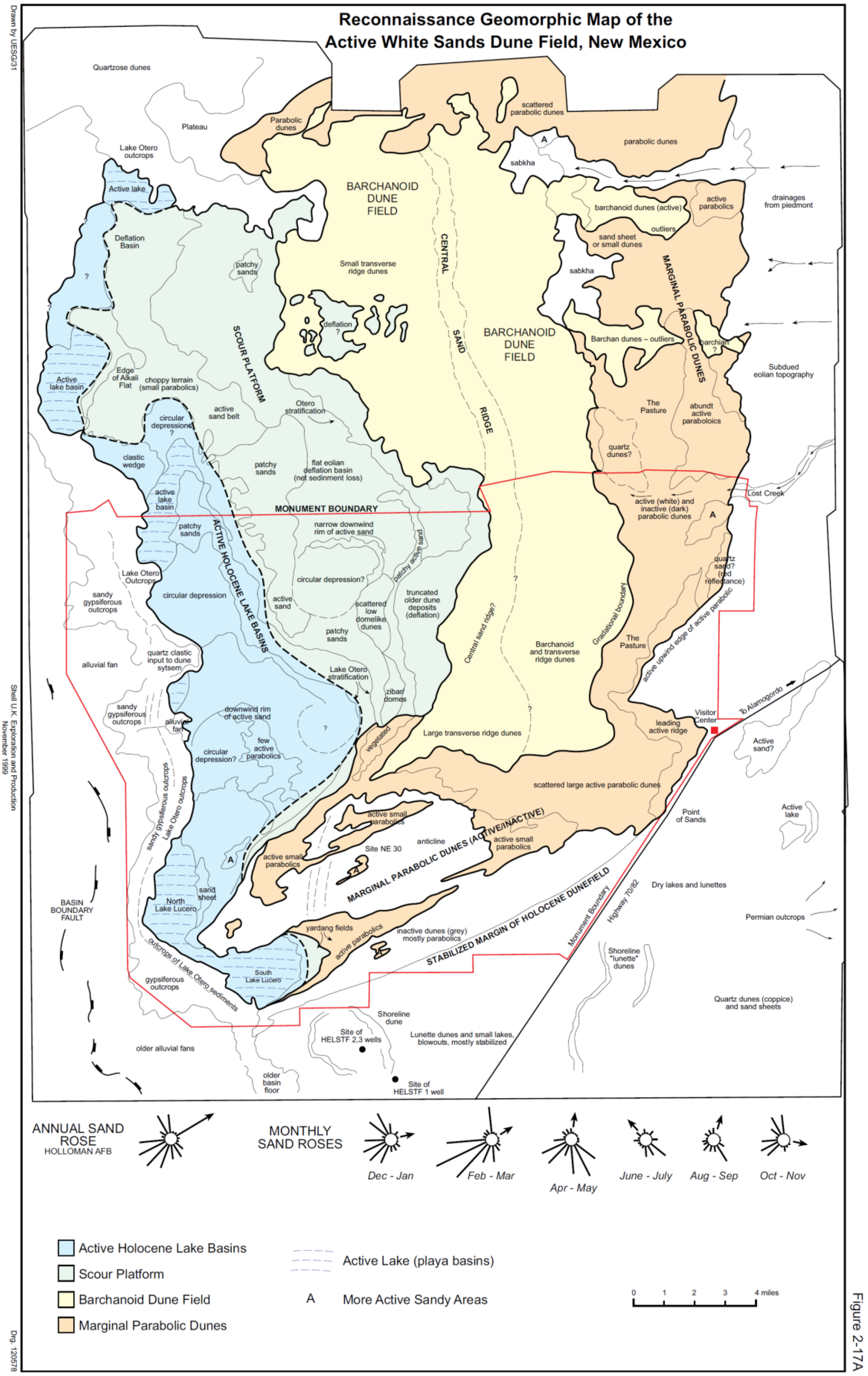

FIGURE 1 - GEOMORPHIC MAP OF WHITE SANDS DUNE FIELD AND SURROUNDING AREAS (FROM FRYBERGER (2004))

METHOD

STUDY AREA

A subset of White Sands Dune Field was chosen for use in this study (Figure 2, Table 2) to exclude areas where environmental conditions which could not be modelled were contributing to dune development.

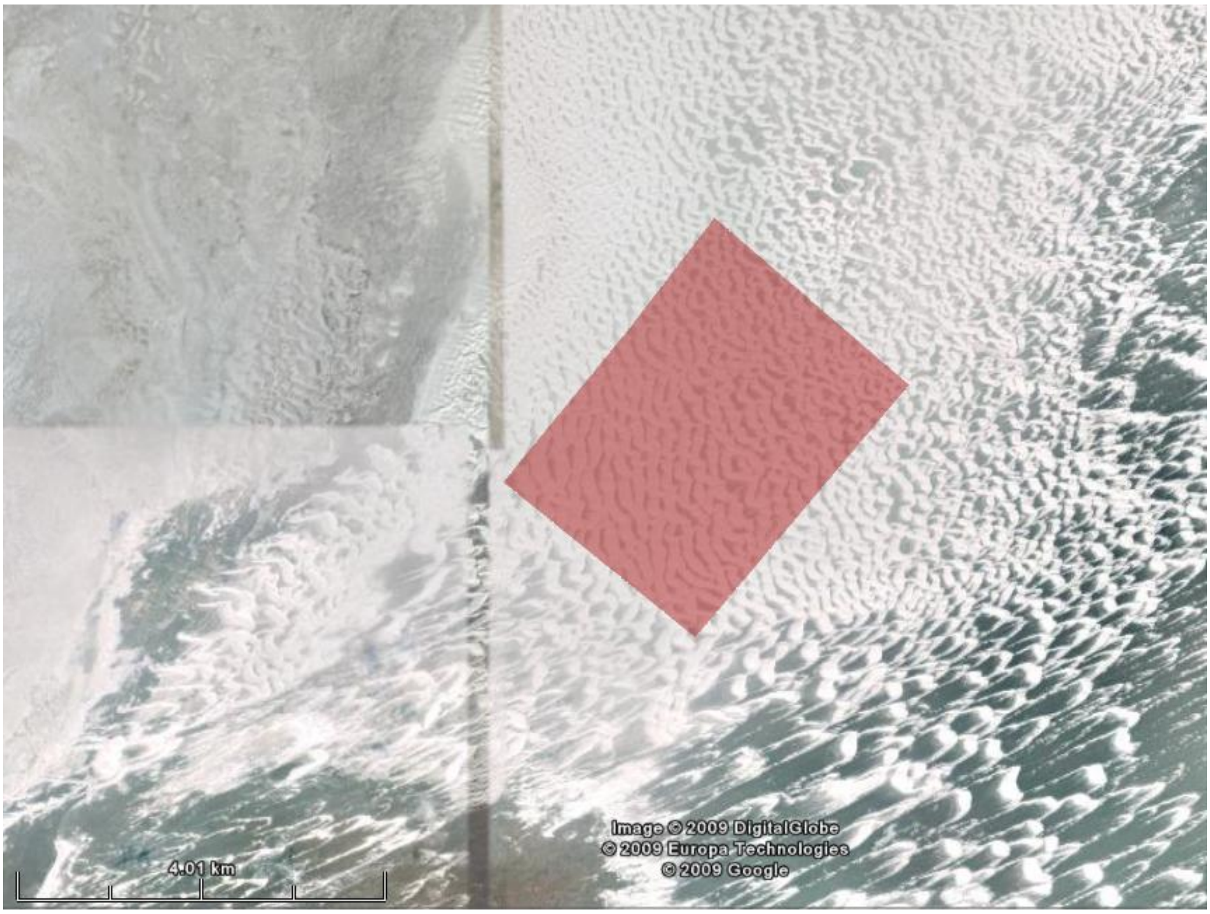

FIGURE 2 - AERIAL PHOTOGRAPH OF THE SOUTHERN PART OF WHITE SANDS DUNE FIELD, SHOWING THE MODELLING STUDY AREA (GOOGLE EARTH, 2009).

Metric	Value
Location of centre	32° 47' 19.85'' N, 106° 16' 43.60'' W
Width	2.68km
Downwind length	3.56km
Area	9.54km^2

TABLE 2 - METRICS OF THE STUDY AREA

DECAL MODEL

The *Discrete ECogeomorphic Aeolian Landscape Model* (DECAL; Baas & Nield, 2007; Nield & Baas, 2008a; Nield & Baas, 2008b) model is a modified version of the Werner (1995) model. This is a cellular automaton model, which models the movement of slabs of sediment across a surface using the process shown in Figure 3.

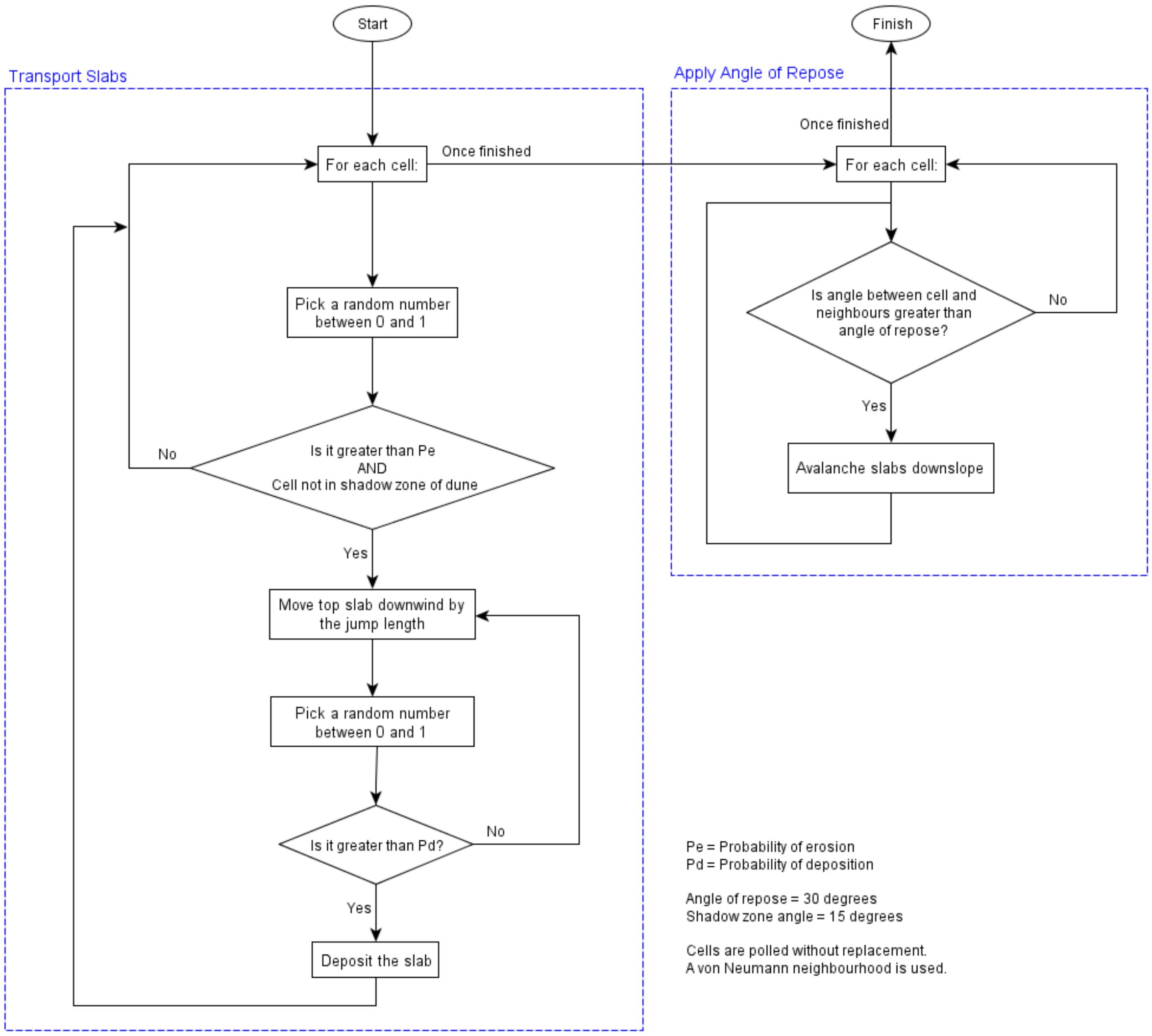

FIGURE 3 - FLOWCHART SHOWING THE STEPS INVOLVED IN THE DECAL MODEL

This model was designed as an exploratory model (Murray, 2003) intended to show general trends in dunefield development, rather than to predict the exact development of a certain dunefield. In this study the model has been parameterised to the conditions at White Sands, but it is not expected that the model will produce landscapes exactly mirroring real-world landscapes.

Parameterisation

The parameters listed in Table 3 were used for all simulations.

Parameter	Value	Rationale
Downwind Extent	412 cells	The largest possible model space with the same aspect ratio as the study area.
Lateral Extent	300 cells	
Slab Height Ratio	0.1	Shown to produce barchan dunes (Nield, 2009)
Probability of deposition (with slabs)	0.6	
Probability of deposition (without slabs)	0.4	

Jump length	1	Jump length values above 1 have been shown to create unrealistic landforms (Nield & Baas, 2008b).
Boundary	Periodic	A non-periodic boundary would model a dune field supplied by a point or a line source, which is the case for White Sands. However, as self-organisation varies across the dune field for dunes formed from a point or line source, this would confuse the global analysis of self-organisation which will be performed below. Therefore it was decided to use a periodic boundary.
Starting morphology	Random	The actual starting morphology for White Sands is unknown, therefore a random starting morphology is used.
Upper Limit for random slab placement	4	Produced barchan dunes of manageable height and width.
Lower limit for random slab placement	0	

TABLE 3 - PARAMETERS KEPT CONSTANT FOR EACH RUN OF THE MODEL

Ewing and Kocurek (In Press) provide a list of external environmental controls which are the boundary conditions on dunefield formation, as a framework for dune field analysis. These are considered in Table 4.

Environmental Control	**Value**	**Parameterisation**
Wind regime	RDP/DP of 0.37 (Fryberger & Dean, 1979)	DECAL only models unidirectional winds. Therefore the resultant drift direction is used as the wind direction, ignoring the seasonal distribution of winds.
Source area geometry	Line source	See Table 3.
Areal limits	Constrained by size and shape of dunefield	The modelled subset is constrained by the prevalence of vegetation to the east. The aspect ratio is taken into account in Table 3.
Antecedent conditions	Changes in groundwater salinity over the dunefield, allowing vegetation growth only in certain areas (Fryberger, 2004; Langford et al., 2009)	Not present in the modelled subset.
Climate	Changes in precipitation over time affecting surface moisture and therefore sand transport (Rachal & Dugas, 2009).	The focus of this study.

TABLE 4 – ENVIRONMENTAL CONTROLS AT WHITE SANDS AND THEIR PARAMETERISATION IN THE MODEL

Scenarios

Two groups of scenarios were run: one to simulate the whole sixty year period studied by Rachal and Dugas (2009), and one to simulate dunefields created under different surface moisture conditions. Varying the value of P_e was used to model the effect of surface moisture , with low values representing higher surface moisture values. In this study, no change was made to the probability of deposition, but this could be investigated in future work.

Whole Period Scenarios

In these scenarios P_e was set to the default value of 1.0 for the first and last twenty years of the sixty-year simulation, but was reduced to the value specified in the table below for the middle twenty years. The number of iterations per year was calculated such that the theoretical amount sediment transported through the model space in one year's worth of iterations is equivalent to the estimated annual sediment flux at White Sands (see Appendix 1).

Scenario	Iterations	Analysis interval	Reduced P_e
Scenario WP1	4248	10 years	1.0 (no reduction)
Scenario WP2	4248	10 years	0.8
Scenario WP3	4248	10 years	0.5

TABLE 5 - WHOLE PERIOD SCENARIOS PARAMETER LISTING

Surface Moisture Scenarios

These scenarios were run with values of P_e ranging from 1.0 to 0.1 for the whole simulation.

Scenario	Iterations	Total run time	P_e
Scenario SM1	3540	50 years	1.0
Scenario SM2	3540	50 years	0.9
Scenario SM3	3540	50 years	0.8
Scenario SM4	3540	50 years	0.7
Scenario SM5	3540	50 years	0.6
Scenario SM6	3540	50 years	0.5
Scenario SM7	3540	50 years	0.4
Scenario SM8	3540	50 years	0.3
Scenario SM9	3540	50 years	0.2
Scenario SM10	3540	50 years	0.1

TABLE 6 - SURFACE MOISTURE SCENARIOS PARAMETER LISTING

Measuring Organisation

Wilkins and Ford (2007) suggested the use of nearest neighbour analysis as a method for quantifying dunefield organisation. Nearest neighbour analysis results in a R-value which records how clustered or dispersed the input pattern of points is (Wheeler et al., 2004). The index varies from 0 (perfectly clustered) to a theoretical maximum of 2.15 (perfectly dispersed), with 1 representing a random pattern. Wilkins and Ford (2007) suggest that as increased dunefield self-organisation leads to a more regular spacing of dunes, a highly organised dunefield will result in a high R-value. This method was also used by Bishop (2007), who found the same relationship.

However, nearest neighbour analysis works with point data, and dunes are not naturally represented as points. Wilkins and Ford (2007) suggested two methods of reducing barchan dunes to points: either by placing one point at the centre of the dune crest; or by placing one point at the centre of the dune crest, and one point at the end of each of the horns. They noted that the three-point method seemed more conservative and therefore they chose to use this for their study. Bishop (2007) chose a one-point method, placing a point at the place of maximum curvature of the dune crest.

Three methods of placing the points for nearest neighbour analysis were used in this study. The first two methods involved manually placing the points as described by Wilkins and Ford (2007). The third method was a semi-automatic method where points were automatically placed at the centre of the dune crest line (see below).

As well as the relatively new method of using nearest neighbour analysis, a traditional method of measuring dunefield organisation was used: crest length measurements. The crests of the modelled dunes were digitised using ArcGIS 9.2, and the lengths summed (using Hawth's Tools for ArcGIS; Beyer, 2004). The 'Feature to Point' function was then used to create a point layer consisting of the points at the centre of each of the crest lines, and the Average Nearest Neighbour function was used to calculate the R-value.

A repeatability analysis was performed for each of the methods, involving running the method multiple times on the same modelled dunefield to determine the variation in values returned due to differences in the manual placing of points and crest lines.

RESULTS

PRELIMINARY COMPARISON OF STATISTICAL METHODS

A preliminary study was performed to determine which of the point placement methods was most suited to this study. It was found that the three point method was very sensitive to the size of the dunes, as this method would produce lots of clusters with small dunes. This was not a problem for Wilkins and Ford (2007) as all of the dunes they were examining were roughly similar sizes, but in this study there were significant variations in dune size across the scenarios. Therefore, only the one-point methods were considered for use in this study. Figure 4 shows examples of all these methods.

The dunes created by the DECAL model appeared in ArcGIS to have no easily identifiable crest-line (see Figure 4). Therefore, for ease and repeatability of digitising, the down-wind edge of the dune was digitised. This should not affect the results as this line will have a very similar length to the crest line, and all of the dunes in this study were measured in this way.

REPEATABILITY ANALYSIS

It can be seen in Table 7 that the automatic method has a lower range and standard deviation between the repeated measurements, and so this was chosen for the rest of the analysis.

	Manual 1 point	**Automatic 1 point**
Range	0.10	0.06
Standard Deviation	0.05	0.02

TABLE 7 - REPEATABILITY OF BOTH 1-POINT METHODS

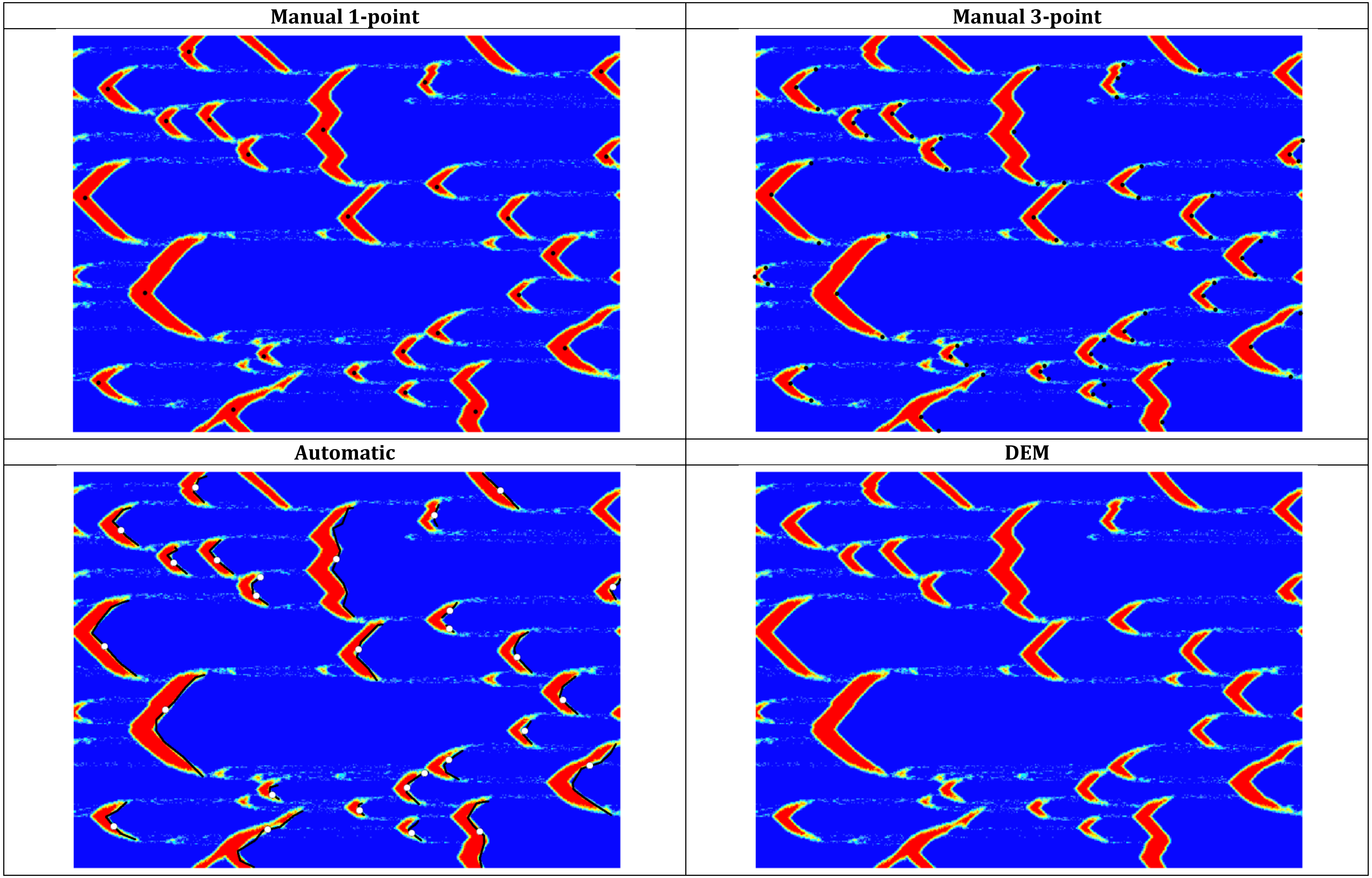

FIGURE 4 - EXAMPLE OF POINT PLACEMENT FOR ALL THREE METHODS, WITH THE BARE DEM FOR REFERENCE

Whole Period Scenarios

Year	Automatic Nearest Neighbour (no units)	Mean Crest Length (cell widths)
10	1.41	29.15
20	1.53	43.15
30	1.54	49.35
40	1.54	53.90
50	1.82	67.85
60	1.57	67.80

TABLE 8 - SCENARIO WP1 RESULTS

Year	Automatic Nearest Neighbour (no units)	Mean Crest Length (cell widths)
10	1.41	29.15
20	1.53	43.15
30	1.58	51.65
40	1.63	61.86
50	1.65	62.70
60	1.64	67.51

TABLE 9- SCENARIO WP2 RESULTS. SHADED ROWS SHOW WHERE P_E WAS REDUCED

Year	Automatic Nearest Neighbour (no units)	Mean Crest Length (cell widths)
10	1.41	29.15
20	1.53	43.15
30	1.58	45.54
40	1.50	50.81
50	1.50	50.28
60	1.92	71.76

TABLE 10 – SCENARIO WP3 RESULTS. SHADED ROWS SHOW WHERE P_E WAS REDUCED

Surface Moisture Scenarios

Scenario	P_e	Automatic Nearest Neighbour (no units)	Mean Crest Length (cell widths)
SM1	1.0	1.48	58.83
SM2	0.9	1.52	55.11
SM3	0.8	1.43	40.26
SM4	0.7	1.55	43.36
SM5	0.6	1.53	44.13
SM6	0.5	1.67	48.96
SM7	0.4	1.46	44.33
SM8	0.3	1.56	36.11
SM9	0.2	1.58	33.08
SM10	0.1	1.48	58.83

TABLE 11 - RESULTS FOR THE SCENARIOS LISTED IN TABLE 6

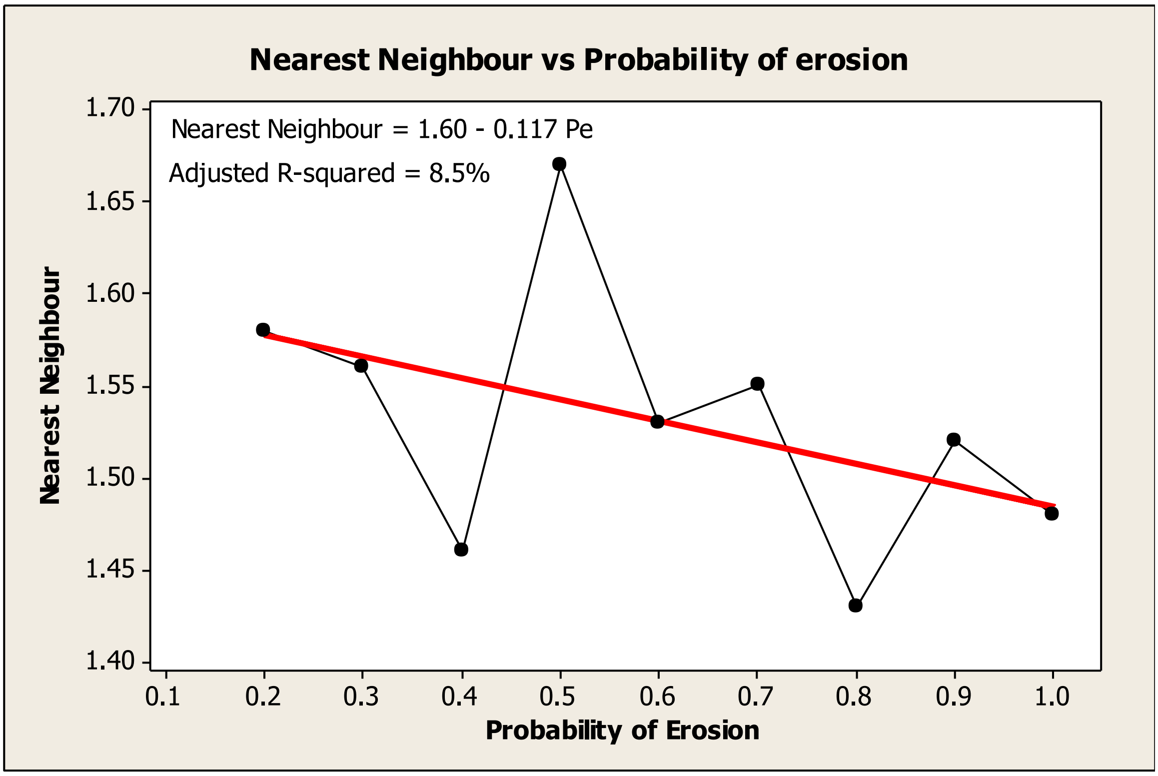

FIGURE 5 - NEAREST NEIGHBOUR VALUES FOR SCENARIOS SM1 TO SM10, WITH DIFFERENT P_E VALUES

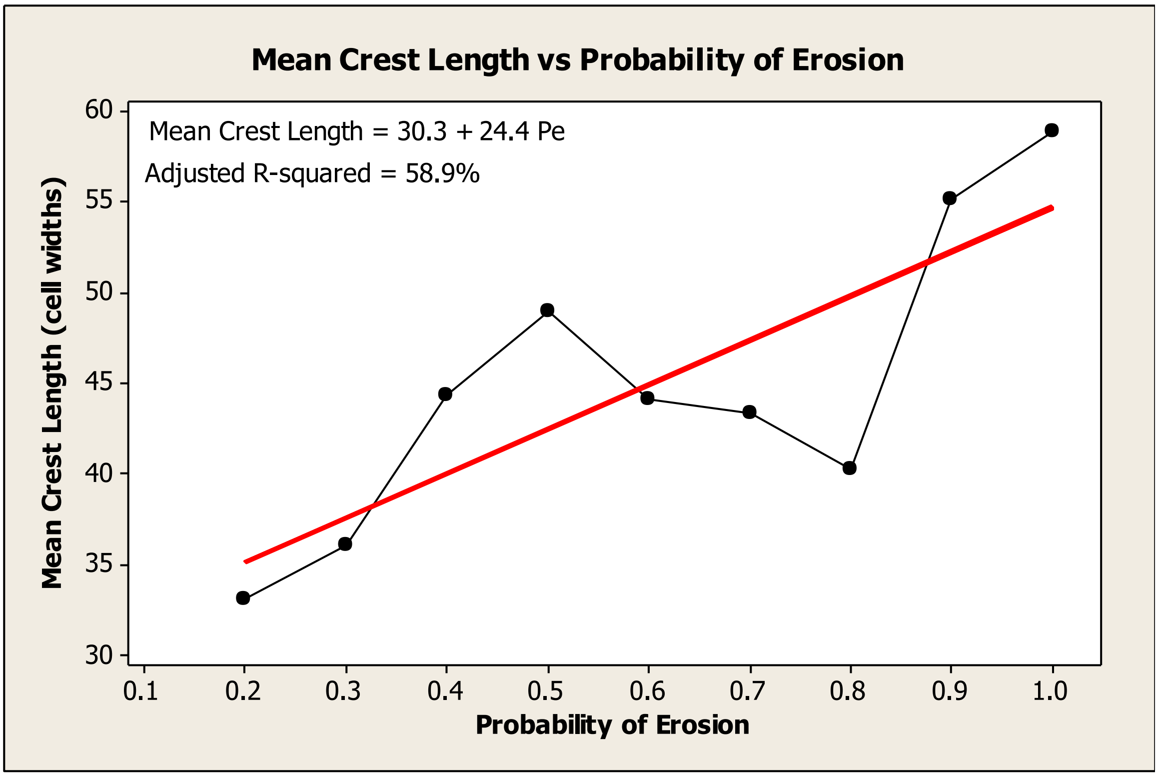

FIGURE 6 - MEAN CREST LENGTH VALUES FOR SCENARIOS SM1 TO SM10, WITH DIFFERENT P_E VALUES

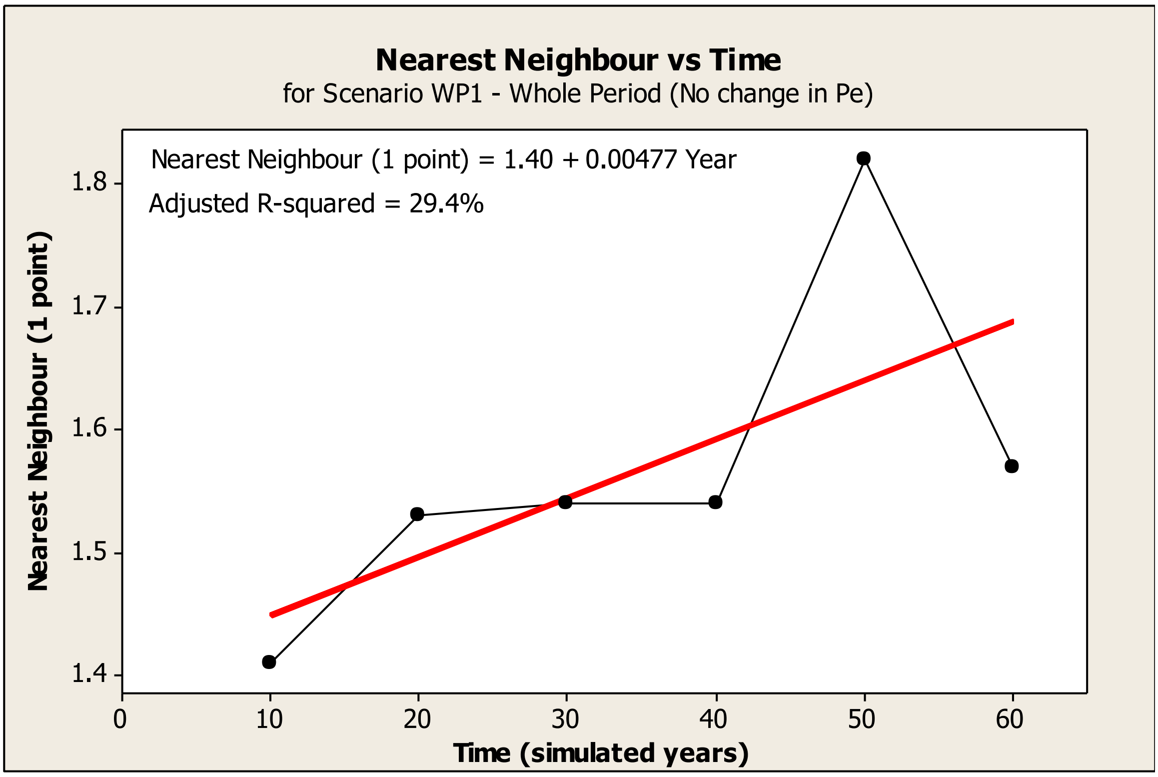

FIGURE 7 - NEAREST NEIGHBOUR RESULTS FOR SCENARIO WP1 REPRESNTING A PERIOD OF 60 YEARS WITH NO CHANGE IN P_E

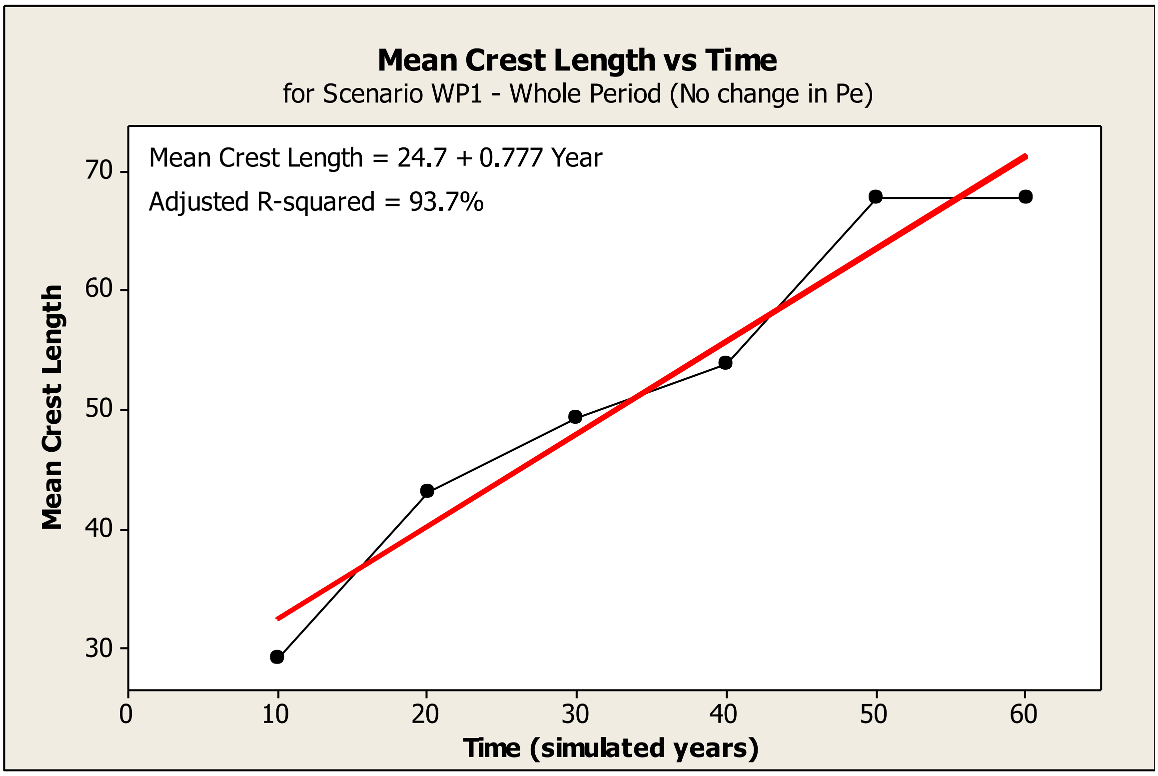

FIGURE 8 – MEAN CREST LENGTH RESULTS FOR SCENARIO WP1 REPRESNTING A PERIOD OF 60 YEARS WITH NO CHANGE IN P_E

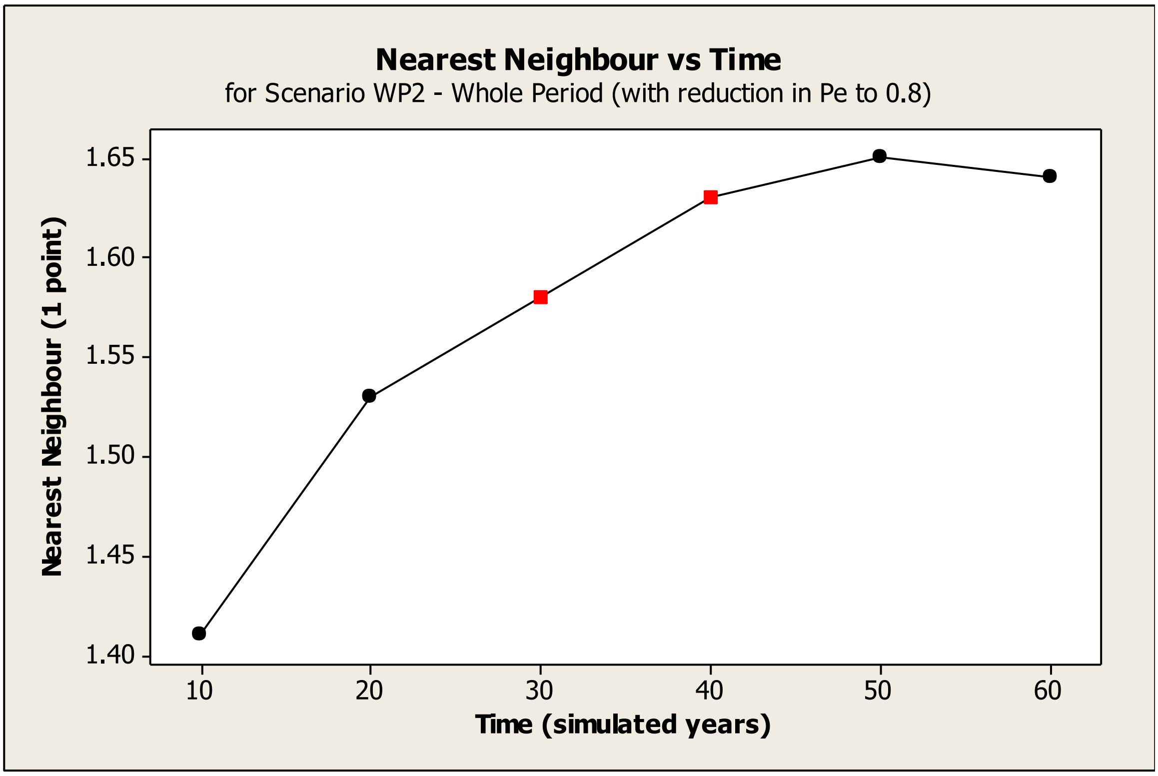

FIGURE 9 - NEAREST NEIGHBOUR RESULTS FOR SCENARIO WP2 REPRESNTING A PERIOD OF 60 YEARS WITH A REDUCTION IN P_E TO 0.8 FOR THE MIDDLE 20 YEARS

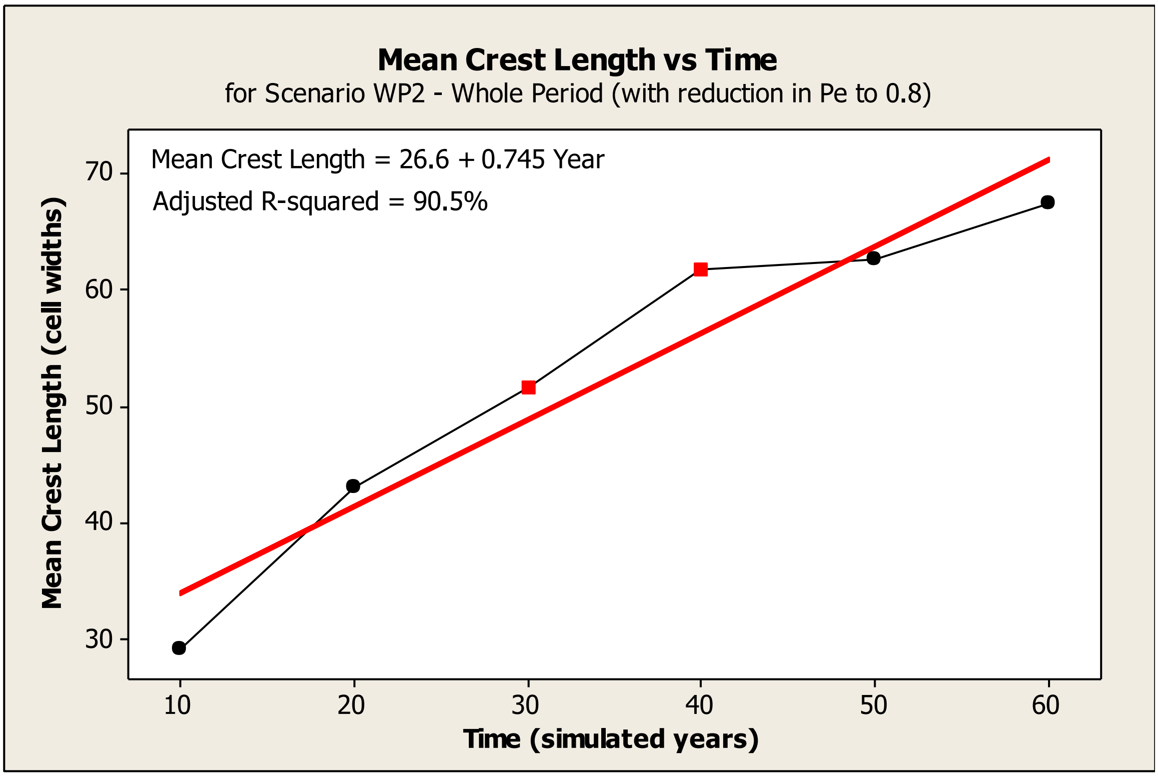

FIGURE 10 – MEAN CREST LENGTH RESULTS FOR SCENARIO WP2 REPRESNTING A PERIOD OF 60 YEARS WITH A REDUCTION IN P_R TO 0.8 FOR THE MIDDLE 20 YEARS

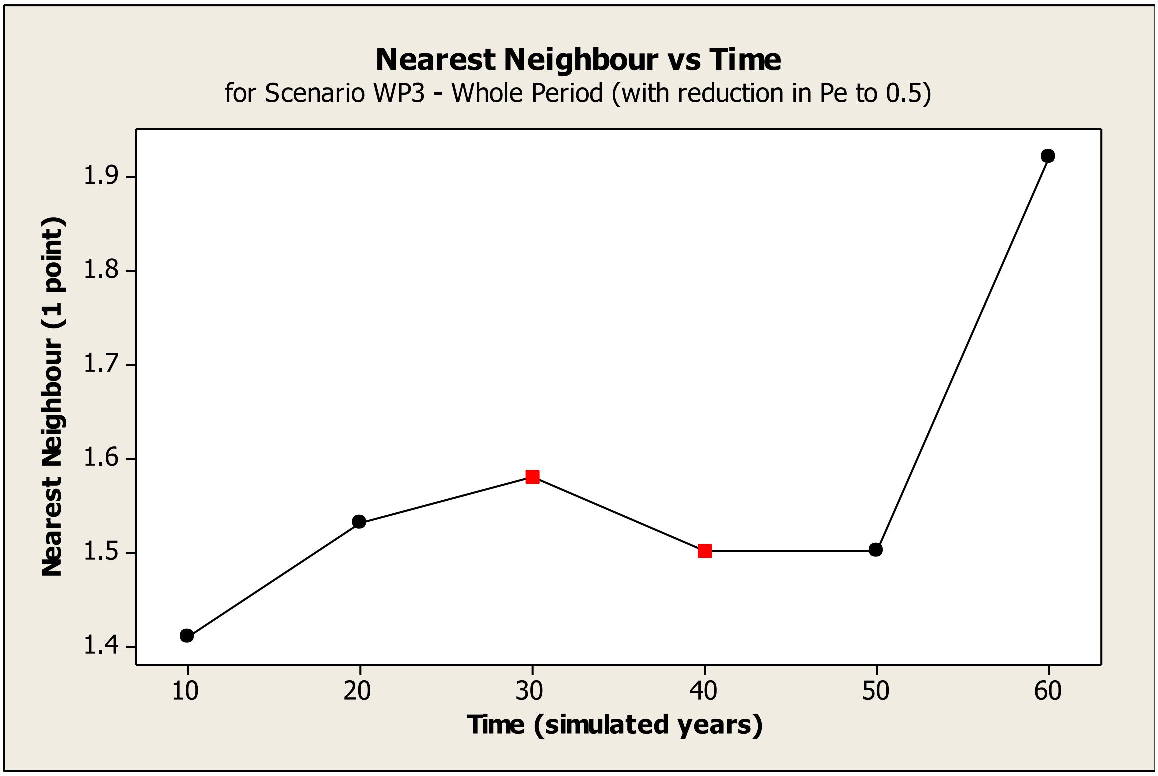

FIGURE 11 - NEAREST NEIGHBOUR RESULTS FOR SCENARIO WP3 REPRESNTING A PERIOD OF 60 YEARS WITH A REDUCTION IN P_E TO 0.5 FOR THE MIDDLE 20 YEARS

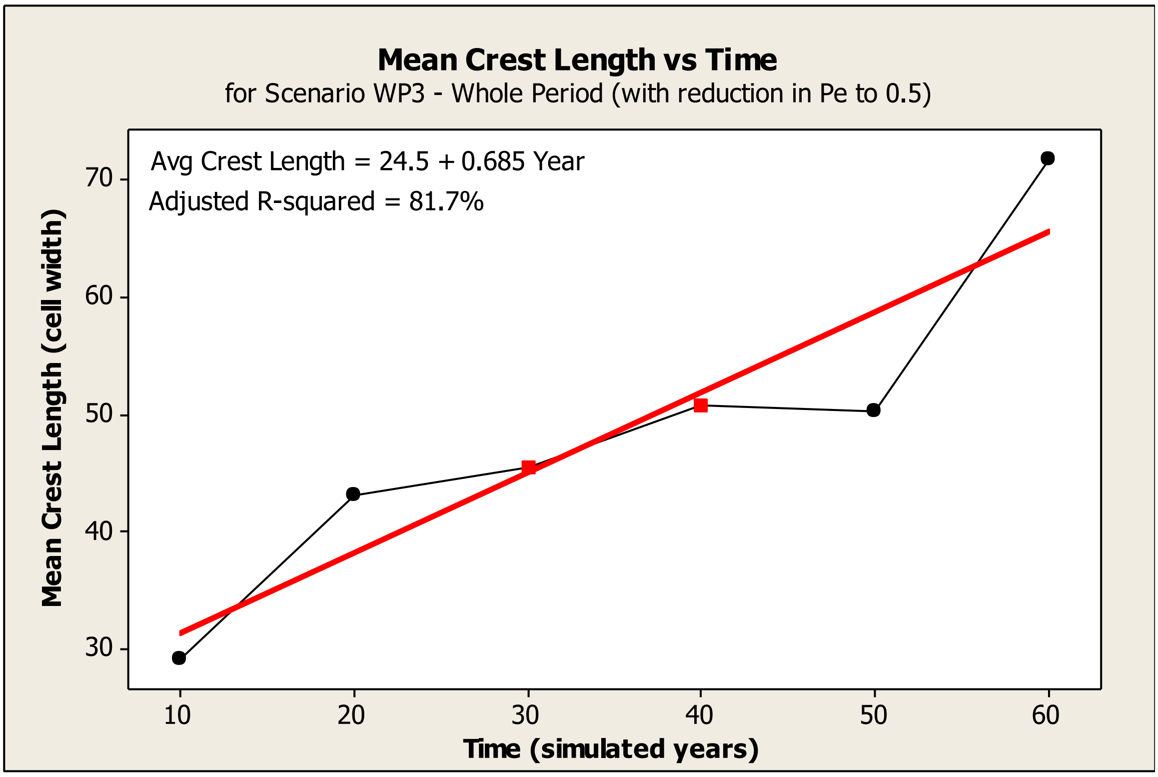

FIGURE 12 – MEAN CREST LENGTH RESULTS FOR SCENARIO WP3 REPRESNTING A PERIOD OF 60 YEARS WITH A REDUCTION IN P_E TO 0.5 FOR THE MIDDLE 20 YEARS

DISCUSSION

ASSESSMENT OF MODEL SKILL

To assess the skill of the DECAL model in representing White Sands, the data was analysed to check that the trends of the outputs were in the direction that was expected from the literature. Scenario WP1 (Figure 8 and Figure 9) shows that there is a general trend towards organisation in a dunefield with no P_e perturbations, when quantified with both mean crest length and nearest neighbour. This is the opposite of what was found at White Sands (Rachal & Dugas, 2009), suggesting that the model has a low skill. However, a trend towards organisation is suggested for many other dunefields (Kocurek & Ewing, 2005; Werner, 1995) so it seems likely that the reason for the trend towards disorganisation at White Sands is because the model does not represent a key part of the dunefield system at White Sands (for example, the seasonally varying winds).

WHOLE PERIOD SCENARIOS

The Whole Period set of scenarios show general positive trends, showing that the modelled dunefields become more organised over time as expected. However, there does not seem to be any recognisable pattern in the changes in organisation which occur when P_e is reduced for twenty years. It was expected that the graphs produced may look similar to Rachal and Dugas (2009; Figure 6), but this was not the case. It could be that increased moisture levels (as represented by lowered P_e values) do not have an effect on dunefield self-organisation, or it could be that there is an effect but it is not noticeable within twenty model years.

SURFACE MOISTURE SCENARIOS

The results from the Surface Moisture scenarios show a trend towards disorganisation with increasing moisture (decreasing P_e) when assessed by mean crest length (R^2 = 58.9%), and an insignificant trend towards organisation when assessed by the Nearest Neighbour analysis (R^2 = 8.5%). It is widely shown in the literature that the trend of mean crest length can be used as an assessment of self-organisation, and therefore it is assumed that the mean crest length is a more accurate measure of self-organisation than nearest neighbour analysis. Using mean crest length shows that an increase in surface moisture leads to a decrease in self-organisation, and this suggests that hypothesis 2 is incorrect and that the common sense answer described above may be correct. It should be noted that statistical outputs from the model show that in these scenarios the dunefield may not have reached a steady state, which could lead to an inaccurate assessment of self-organisation (see Appendix 2).

SUITABILITY OF NEAREST NEIGHBOUR ANALYSIS FOR ASSESSING DUNEFIELD SELF-ORGANISATION

Nearest Neighbour analysis is a relatively new technique for the assessment of dunefield self-organisation, and has not been used with model outputs before. The measurements of nearest neighbour seemed to give the expected trend (for example, Scenario WP1, Figure 9), but the statistic seemed to be very sensitive (see, for example, the sudden peaks in Figure 5), and varied considerably for small changes in P_e. Further work should be carried out to assess the suitability of nearest neighbour analysis for dunefield self-organisation quantification.

CONCLUSIONS

The results obtained from this study do not seem to support the findings of Rachal and Dugas (2009). No significant changes were found when scenarios were run attempting to replicate the increase in surface moisture seen at White Sands between 1963-1985 (Hypothesis 1). The second set of simulations appeared to show that dunefields which develop in areas of high surface moisture are actually less self-organised than dunefields which develop under lower surface moisture conditions, which directly contradicts the general application of Rachal and Dugas' theory (Hypothesis 2).

However, it should be realised that there are various uncertainties present in this modelling study, and that the trends observed in the simulations may not be the same as those which will be experienced in the real world. Certain key parts of the dune system at White Sands are not incorporated into the model (such as seasonal variations in both wind directions and surface moisture), and it is suggested that it is for this reason that the results found by Rachal and Dugas are not replicated in this study. This shows an important outcome of this type of exploratory modelling: that by only modelling what are thought to be the most essential parts of the dunefield system it can show when other unmodelled aspects are key to creating certain behaviours.

In this limited study it was impossible to fully assess the usefulness of nearest neighbour analysis for quantifying dunefield self-organisation (Hypothesis 3). Further work is needed to assess this. A useful output of this study is showing that what was thought by Wilkins and Ford (2007) to be the best method of representing barchan dunes as points is very sensitive to differing sizes of dunes.

REFERENCES

Baas, A. C. W. & Nield, J. M., 2007, 'Modelling vegetated dune landscapes', *Geophysical Research Letters*, 34 (L06405).

Beyer, H. L., 2004, *Hawth's Analysis Tools for ArcGIS*, http://www.spatialecology.com/htools [Accessed 30/11/2009].

Bishop, M. A., 2007, 'Point pattern analysis of north polar crescentic dunes, Mars: A geography of dune self-organisation', *Icarus*, 191, pp. 151-7.

Cornelis, W. M. & Gabriels, D., 2003, 'The effect of surface moisture on the entrainment of dune sand by wind: an evaluation of selected models', *Sedimentology*, 50, pp. 771-90.

Davidson-Arnott, R. G. D., Yang, Y., Ollerhead, J., Hesp, P. A. & Walker, I. J., 2008, 'The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach', *Earth Surface Processes and Landforms*, 33, pp. 55-74.

Ewing, R. C. & Kocurek, G., In Press, 'Aeolian dune-field pattern boundary conditions', *Geomorphology*, In Press, Corrected Proof.

Ewing, R. C., Kocurek, G. & Lake, L. W., 2006, 'Pattern analysis of dune-field parameters', *Earth Surface Processes and Landforms*, 31, pp. 1176-91.

Fryberger, S., 2004, *Geological Overview of White Sands National Monument*, http://www.nps.gov/archive/whsa/Geology%20of%20White%20Sands/GeoHome.html [Accessed 20/10/2009].

Fryberger, S. & Dean, G., 1979, 'Dune forms and wind regime', *A study of global sand seas*, 1052, pp. 137–69.

Google Earth, 2009, *Image centred on 32° 47' 19.85'' N 106° 16' 43.60'' W*, http://earth.google.com [Accessed 30/11/2009].

Kocurek, G. & Ewing, R. C., 2005, 'Aeolian dune field self-organization - implications for the formation of simple versus complex dune-field patterns', *Geomorphology*, 72 (1-4), pp. 94-105.

Kocurek, G., Townsley, M., Yeh, E., Havholm, K. & Sweet, M. L., 1992, 'Dune and dune-field development on Padre Island, Texas with implications for interdune deposition and water-table-controlled accumulation', *Journal of Sedimentary Petrology*, 62 (4), pp. 622-35.

Lancaster, N., 1988, 'Development of linear dunes in the southwestern Kalahari, southern Africa', *Journal of Arid Environments*, 14, pp. 233-44.

Langford, R. P., Rose, J. M. & White, D. E., 2009, 'Groundwater salinity as a control on development of eolian landscape: An example from the White Sands of New Mexico', *Geomorphology*, 105, pp. 39-49.

McKee, E., 1979, 'A study of global sand seas', USGS Professional Paper 1052.

Murray, A. B., 2003, 'Contrasting the Goals, Strategies and Predictions associated with Simplified Numerical Models and Detailed Simulations', in P. R. Wilcock & R. M. Iverson (eds), *Prediction in Geomorphology*, AGU Books Board, Washington DC.

Nield, J. M., 2009, *Abridged User Manual for GEOG3048 Version of DECAL*, School of Geography, University of Southampton.

Nield, J. M. & Baas, A. C. W., 2008a, 'The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response', *Global and Planetary Change*, 64 (1-2), pp. 76-92.

Nield, J. M. & Baas, A. C. W., 2008b, 'Investigating parabolic and nebkha dune formation using a cellular automaton modelling approach', *Earth Surface Processes and Landforms*, 33 (5), pp. 724-40.

Ochoa, R. D., 2005, 'Repeated high-precision topographic surveys of a barchan sand dune at White Sands, New Mexico using ground-based LIDAR', MSc thesis, Texas Tech University.

Rachal, D. M. & Dugas, D. P., 2009, 'Historical dune pattern dynamics: White Sands Dune Field, New Mexico', *Physical Geography*, 30 (1), pp. 64-78.

Simons, D. B., Richardson, E. V. & Nordin, C. F., 1965, *Bedload equation for ripples and dunes*, USGS Professional Paper 642-H.

Werner, B. T., 1995, 'Eolian dunes: Computer simulations and attractor interpretation', *Geology*, 23 (12), pp. 1107-10.

Wheeler, D., Shaw, G. & Barr, S., 2004, *Statistical Techniques in Geographical Analysis*, 3rd edition, David Fulton Publishers Ltd, London.

Wilkins, D. E. & Ford, R. L., 2007, 'Nearest neighbour methods applied to dune field organisation: The Coral Pink Sand Dunes, Kane County, Utah, USA', *Geomorphology*, 83, pp. 48-57.

APPENDIX 1

The average dune height of barchan dunes at White Sands was taken to be 15m (from Fryberger, 2004), and the average barchan migration speed was calculated to be 2.6m yr^{-1} (also from Fryberger, 2004).

The dune migration equation (from Simons et al., 1965) states that:

$$V_d = \frac{q_b}{kH\rho_{pb}}$$

Where V_d is the migration velocity, q_b is the sediment flux at the slipface, k is 0.5 for simplified barchan dunes, H is the dune height, and ρ_{pb} is the bulk density of the material the dunes are formed from.

Re-arranging this formula and using the values calculated above with a bulk density of 1600kg m^{-3} for gypsum gives a sediment flux of 31200 m^3 yr^{-1}, which is equivalent to 11.8 m^3 m^{-1} yr^{-1} for this study area (with a study area lateral width of 2.64km).

The formula for theoretical sediment transport in the DECAL model (Nield & Baas, 2008b) is:

$$q = \frac{h_s L P_e}{P_d I}$$

Where Q is the theoretical sediment flux, h_s is the slab height ratio, L is the jump length, P_e is the probability of erosion, P_d is the probability of deposition and I is the number of iterations. Calculating the resultant flux for the values given in Table 3 with a P_e of 1.0 gives a theoretical sediment transport rate of 0.17m^3 m^{-1} $iteration^{-1}$. This can then be converted to the number of iterations representing the sediment flux of White Sands in one year as below:

$$I = \frac{0.17}{q} = \frac{0.17}{11.8} = 0.014 \text{ years iterations}^{-1}$$

Inverting this gives an answer of 70 iterations $year^{-1}$.

APPENDIX 2

A graph showing the number of avalanche events per cell throughout a model scenario can be produced from the DECAL model (Figure 13). It is generally expected that, unless there is some perturbation part way through the scenario, the avalanche frequency will grow to a peak, and then flatten out as the dunefield reaches a steady state without many dunes merging together or shedding new dunes (Nield, J., personal communication). However, in the Surface Moisture scenario series, this does not seem to occur. Instead, there seems to be a downward trend in avalanche events.

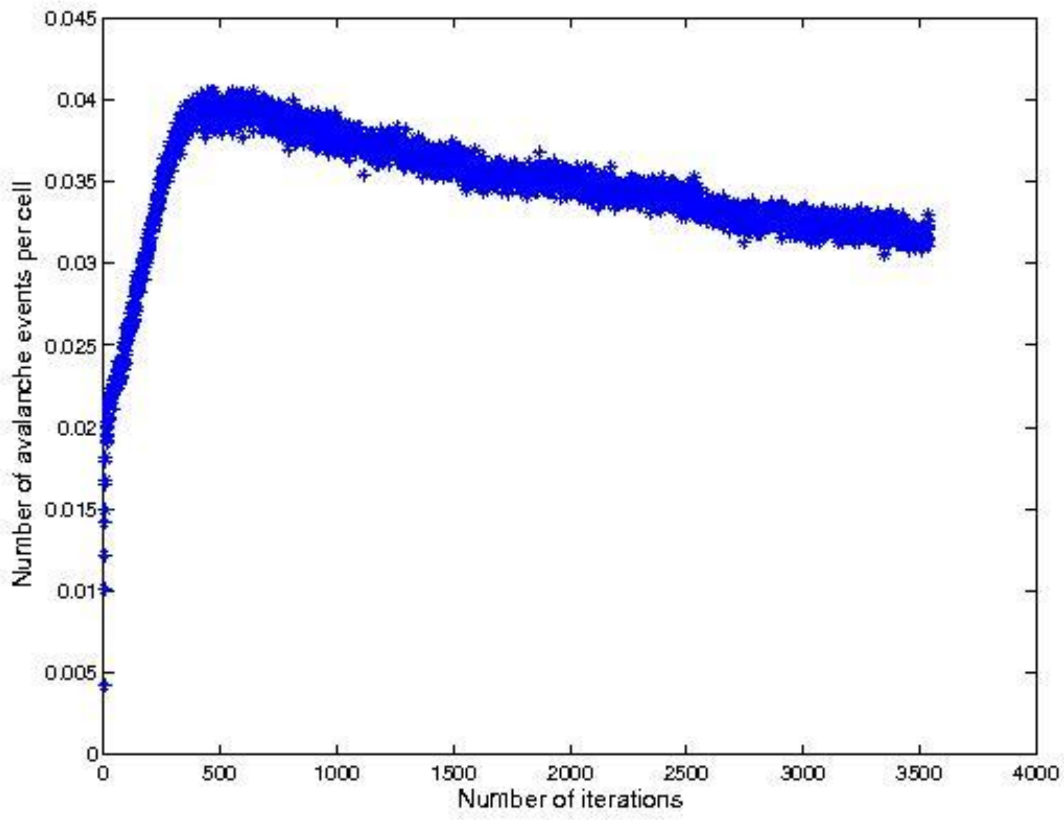

FIGURE 13 - AVALANCHE FREQUENCY FROM SCENARIO SM3, WITH P_E SET TO 0.8.

The model author suggested that this could be due to the fact that with a lower P_e not all of the sediment will be transported in the large dunes which have formed, and this sediment will create smaller dunes which decrease the avalanching frequency (Nield, J., personal communication). This is likely to be the case here, as a number of small dunes were spotted in all model scenarios (see Figure 4).

These smaller dunes which have formed will influence the measures of dunefield organization themselves, and the merging of them with larger dunes will mean that the dunefield is not in a steady-state condition. This could give another reason as to why the model does not accurately reflect the conditions at White Sands, as White Sands is assumed to be in a relatively steady-state condition.