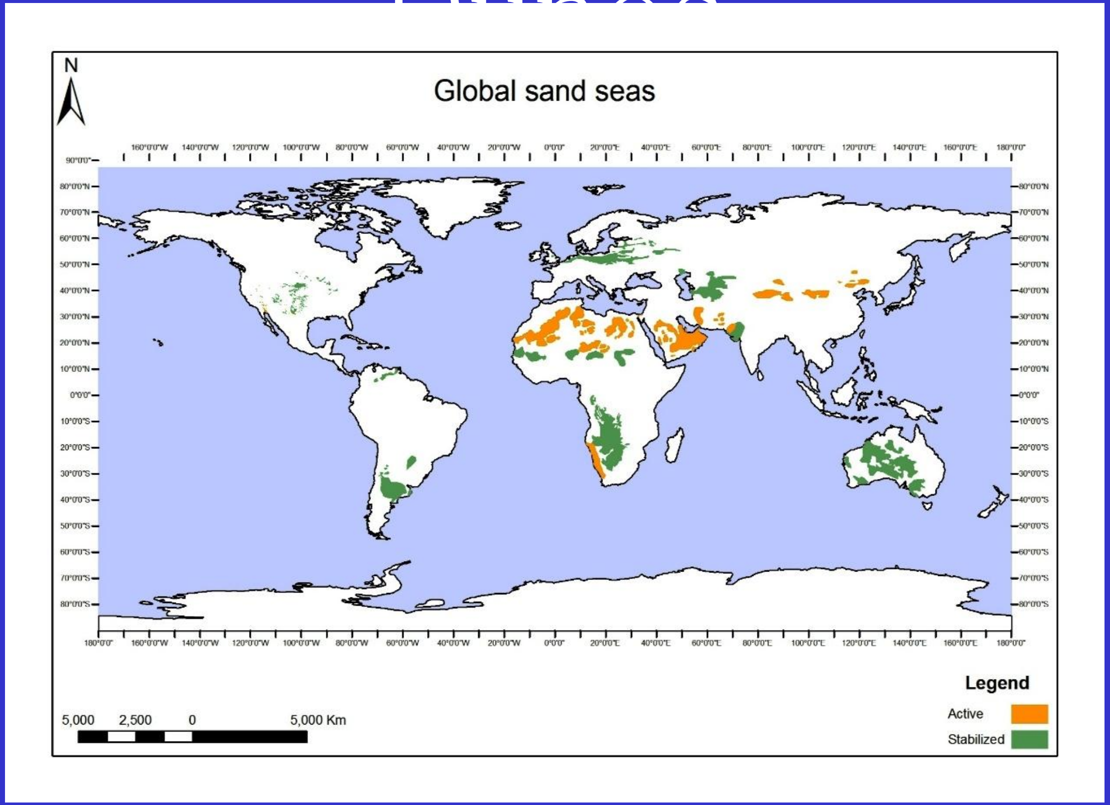
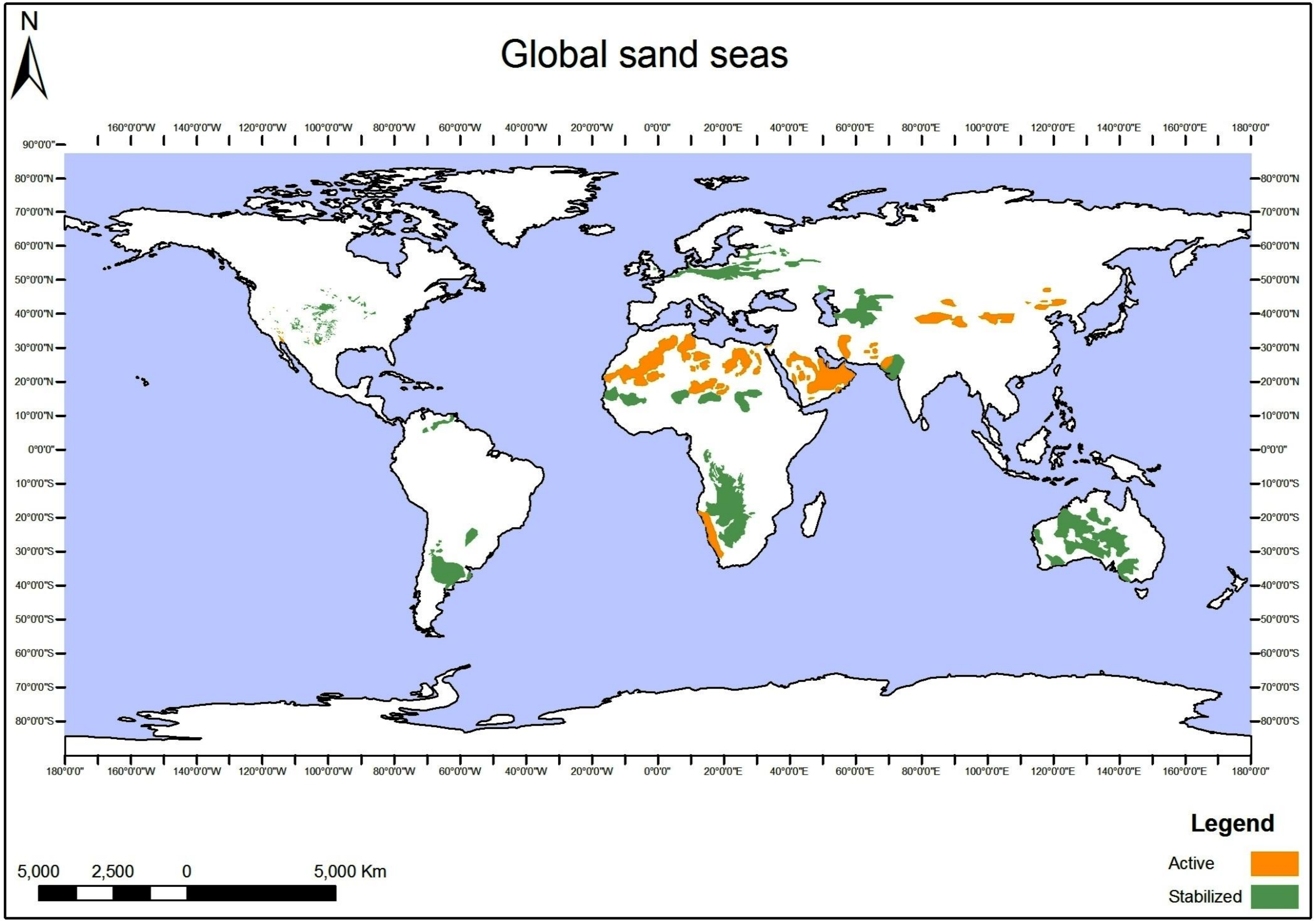
Climatic Factors Affecting Mobility and Stability of Sand Dunes

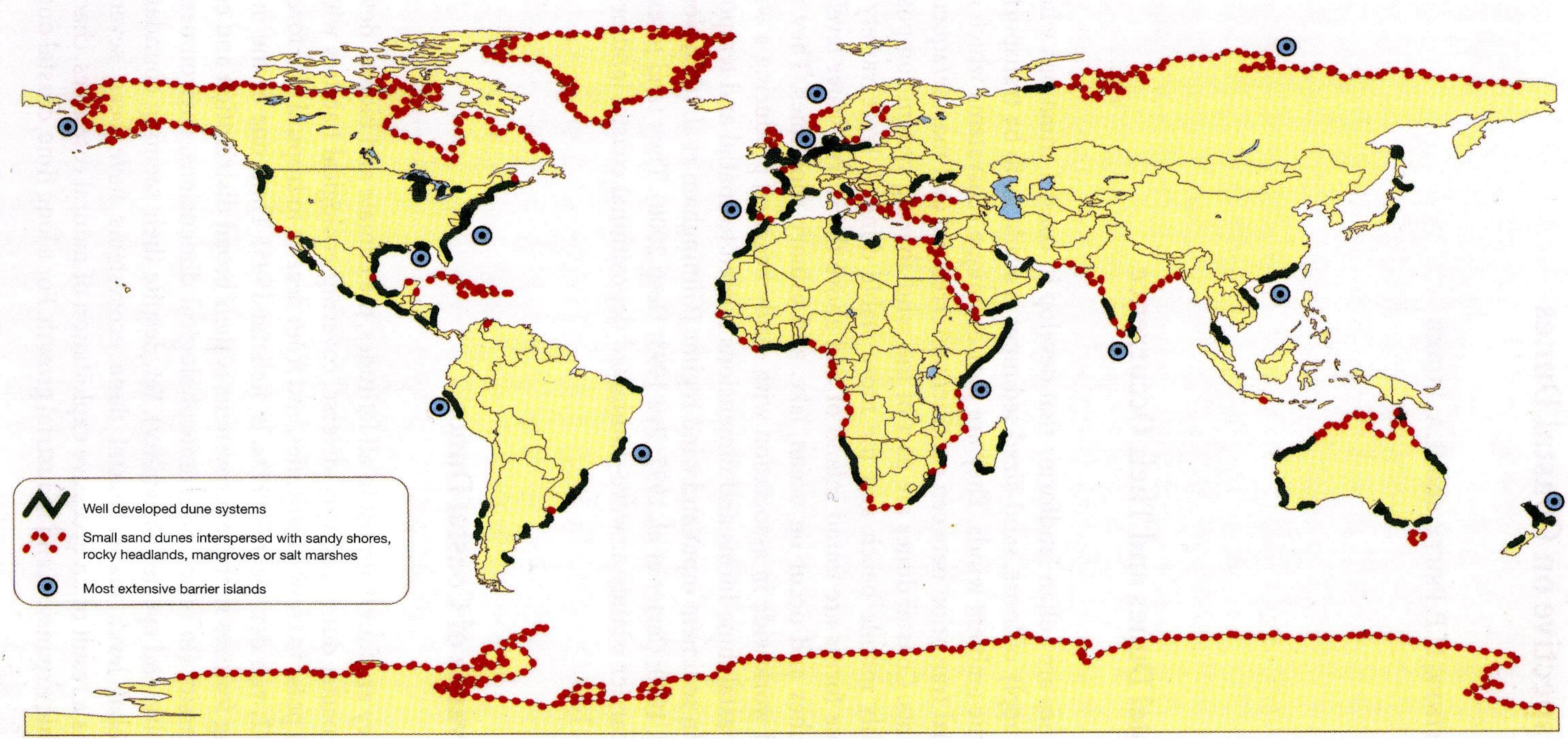


Haim Tsoar
Department of Geography and Environmental Development
Ben-Gurion University of the Negev, Beer Sheva, Israel
tsoar@bgu.ac.il

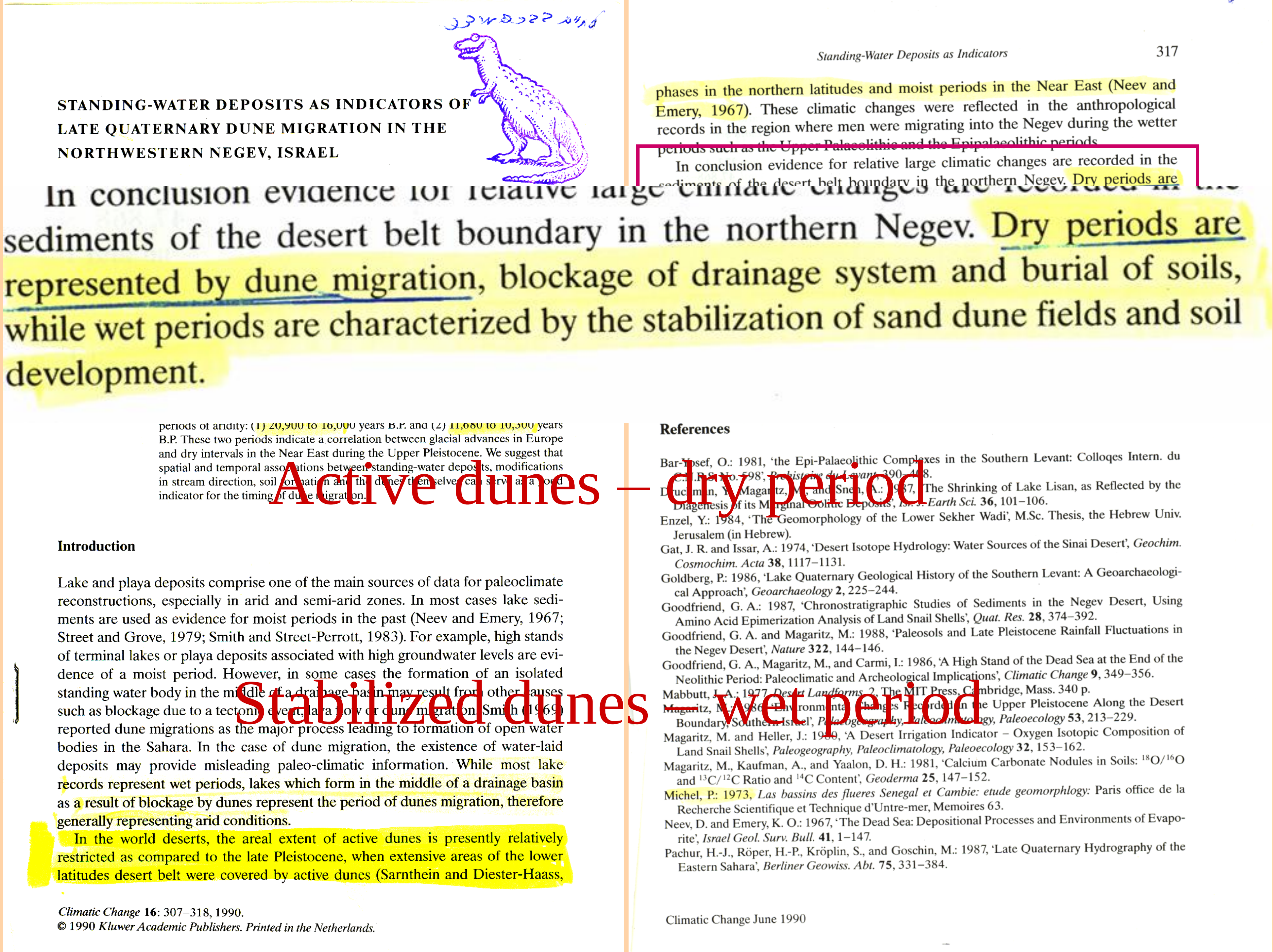


From: Tsoar, 2013. Critical environments: sand dunes and climate change. In: Shroder, J., Lancaster, N., Sherman, D.J., Baas, A.C.W. (Eds.), *Treatise on Geomorphology*. Academic Press, San Diego, CA, vol. 11, Aeolian Geomorphology, pp. 414–427.

Coastal Dunes of the World



From: Martinez, M.L. and Psuty, N.P. (Editors), 2004. Coastal Dunes Ecology and Conservation. Springer, Berlin.



Active dunes – dry period

Stabilized dunes – wet period

[illegible]

STANDING-WATER DEPOSITS AS INDICATORS OF LATE QUATERNARY DUNE MIGRATION IN THE NORTHWESTERN NEGEV, ISRAEL

periods of aridity: (1) 20,900 to 16,000 years B.P. and (2) 11,680 to 10,300 years B.P. These two periods indicate a correlation between glacial advances in Europe and dry intervals in the Near East during the Upper Pleistocene. We suggest that spatial and temporal associations between standing-water deposits, modifications in stream direction, soil formation and the dunes themselves can serve as a good indicator for the timing of dune migration.

Introduction

Lake and playa deposits comprise one of the main sources of data for paleoclimate reconstructions, especially in arid and semi-arid zones. In most cases lake sediments are used as evidence for moist periods in the past (Neev and Emery, 1967; Street and Grove, 1979; Smith and Street-Perrott, 1983). For example, high stands of terminal lakes or playa deposits associated with high groundwater levels are evidence of a moist period. However, in some cases the formation of an isolated standing water body in the middle of a drainage basin may result from other causes such as blockage due to a tectonic event, lava flow or dune migration. Smith (1969) reported dune migrations as the major process leading to formation of open water bodies in the Sahara. In the case of dune migration, the existence of water-laid deposits may provide misleading paleo-climatic information. While most lake records represent wet periods, lakes which form in the middle of a drainage basin as a result of blockage by dunes represent the period of dunes migration, therefore generally representing arid conditions.

In the world deserts, the areal extent of active dunes is presently relatively restricted as compared to the late Pleistocene, when extensive areas of the lower latitudes desert belt were covered by active dunes (Sarnthein and Diester-Haass,

Climatic Change **16**: 307–318, 1990.

phases in the northern latitudes and moist periods in the Near East (Neev and Emery, 1967). These climatic changes were reflected in the anthropological records in the region where men were migrating into the Negev during the wetter periods such as the Upper Palaeolithic and the Epipalaeolithic periods.

In conclusion evidence for relative large climatic changes are recorded in the sediments of the desert belt boundary in the northern Negev. Dry periods are

In conclusion evidence for relative large climatic changes are recorded in the sediments of the desert belt boundary in the northern Negev. Dry periods are represented by dune migration, blockage of drainage system and burial of soils, while wet periods are characterized by the stabilization of sand dune fields and soil development.

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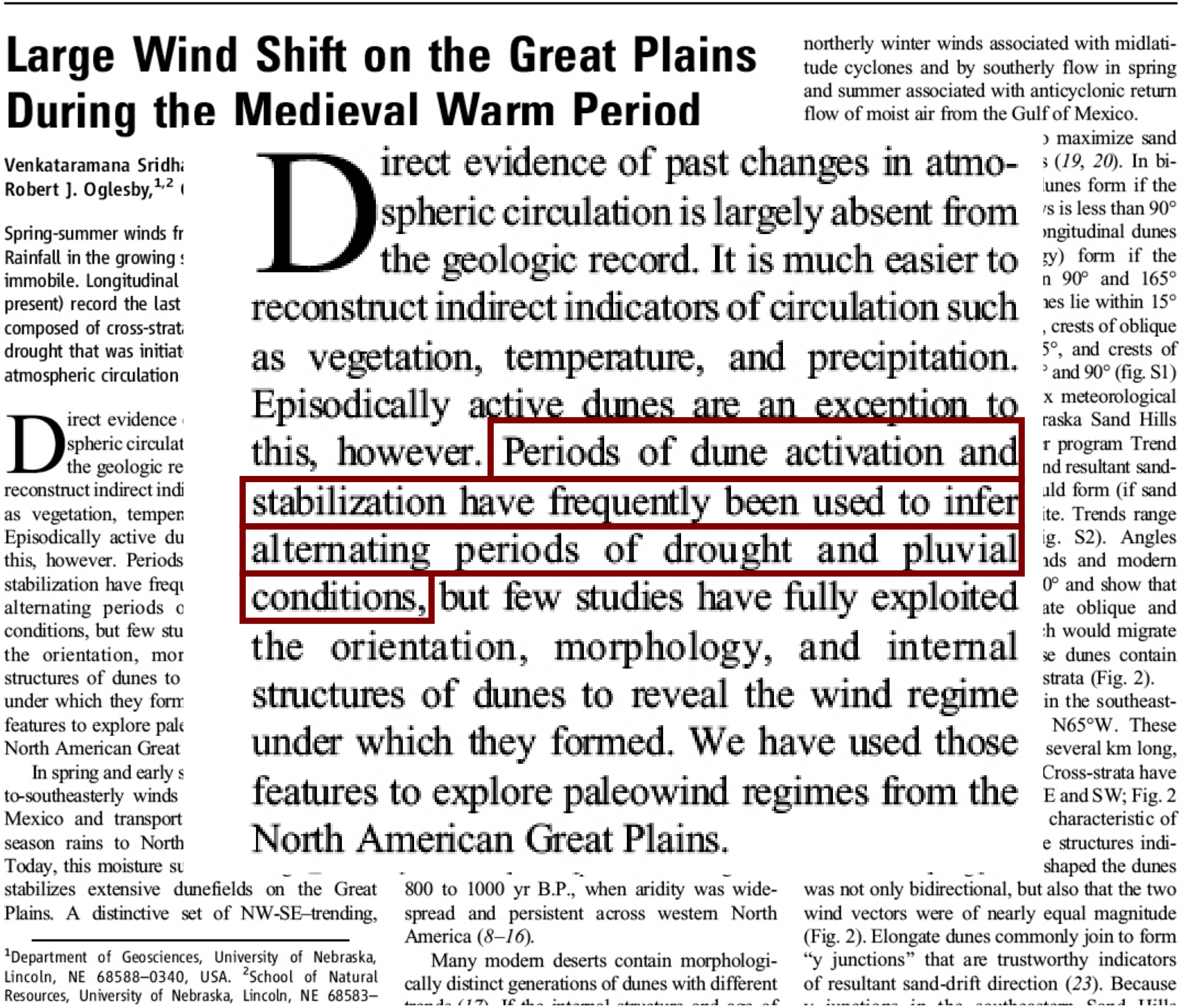

Large Wind Shift on the Great Plains During the Medieval Warm Period

Venkataramana Sridh
Robert J. Oglesby,[1,2]

Spring-summer winds fr
Rainfall in the growing
immobile. Longitudinal
present) record the last
composed of cross-strat
drought that was initiat
atmospheric circulation

Direct evidence of past changes in atmospheric circulation is largely absent from the geologic record. It is much easier to reconstruct indirect indicators of circulation such as vegetation, temperature, and precipitation. Episodically active dunes are an exception to this, however. **Periods of dune activation and stabilization have frequently been used to infer alternating periods of drought and pluvial conditions,** but few studies have fully exploited the orientation, morphology, and internal structures of dunes to reveal the wind regime under which they formed. We have used those features to explore paleowind regimes from the North American Great Plains.

In spring and early s
to-southeasterly winds
Mexico and transport
season rains to North
Today, this moisture su
stabilizes extensive dunefields on the Great Plains. A distinctive set of NW-SE–trending,

800 to 1000 yr B.P., when aridity was widespread and persistent across western North America (*8*–*16*).

Many modern deserts contain morphologically distinct generations of dunes with different

northerly winter winds associated with midlatitude cyclones and by southerly flow in spring and summer associated with anticyclonic return flow of moist air from the Gulf of Mexico.

maximize sand
(*19*, *20*). In bi-
lunes form if the
s is less than 90°
ongitudinal dunes
y) form if the
n 90° and 165°
es lie within 15°
, crests of oblique
5°, and crests of
and 90° (fig. S1)
x meteorological
raska Sand Hills
r program Trend
nd resultant sand-
uld form (if sand
ite. Trends range
ig. S2). Angles
nds and modern
0° and show that
ate oblique and
h would migrate
e dunes contain
strata (Fig. 2).
in the southeast-
N65°W. These
several km long,
Cross-strata have
E and SW; Fig. 2
characteristic of
e structures indi-
shaped the dunes
was not only bidirectional, but also that the two wind vectors were of nearly equal magnitude (Fig. 2). Elongate dunes commonly join to form "y junctions" that are trustworthy indicators of resultant sand-drift direction (*23*). Because

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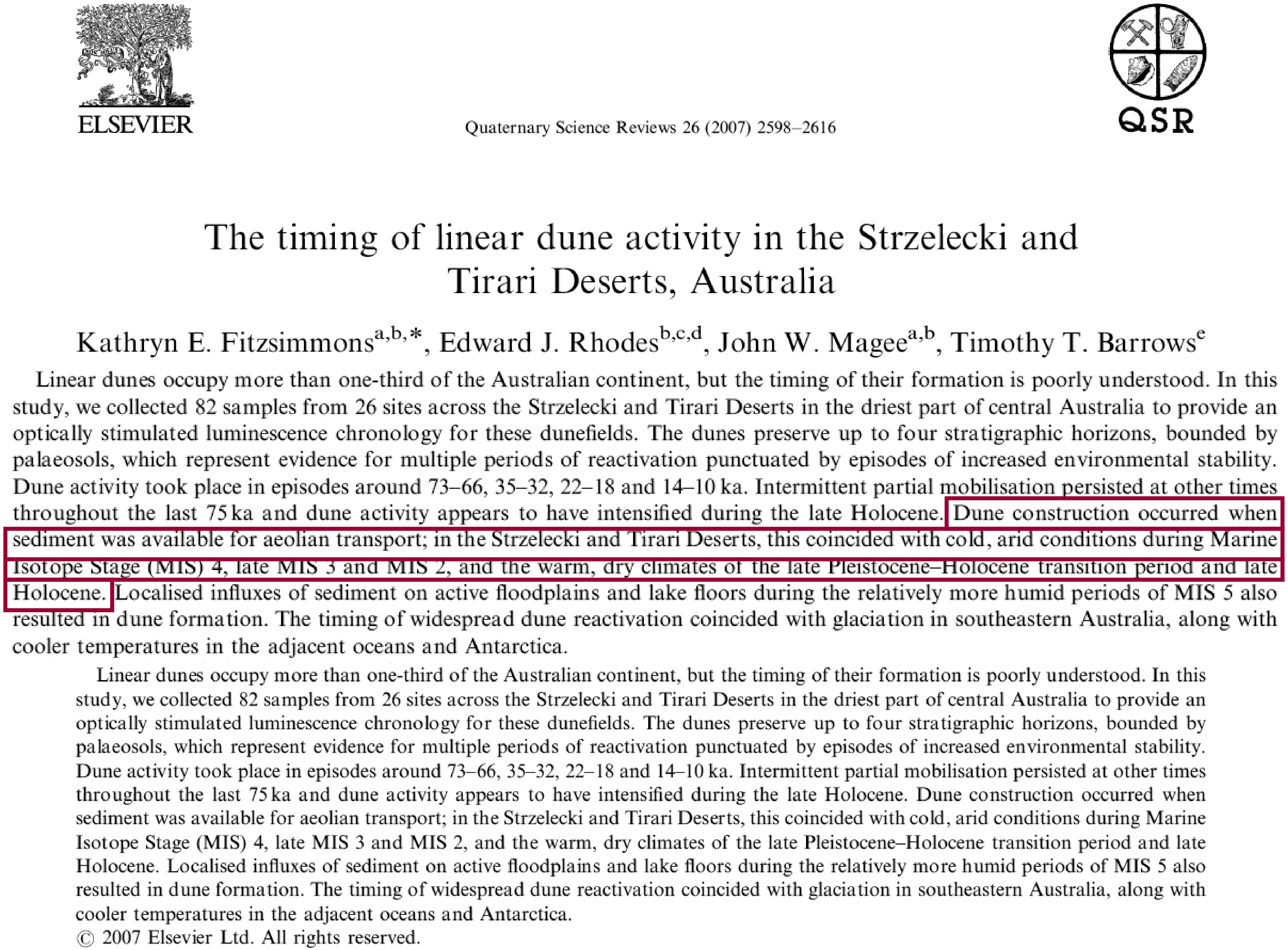
[1]Department of Geosciences, University of Nebraska, Lincoln, NE 68588–0340, USA. [2]School of Natural Resources, University of Nebraska, Lincoln, NE 68583–

Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J. and Rowe, C.M. 2006. Large wind shift on the Great Plains during the Medieval Warm Period. ***Science*, 313**: 345-347.



ELSEVIER

Quaternary Science Reviews 26 (2007) 2598–2616

QSR

The timing of linear dune activity in the Strzelecki and Tirari Deserts, Australia

Kathryn E. Fitzsimmons[a,b,*], Edward J. Rhodes[b,c,d], John W. Magee[a,b], Timothy T. Barrows[e]

Linear dunes occupy more than one-third of the Australian continent, but the timing of their formation is poorly understood. In this study, we collected 82 samples from 26 sites across the Strzelecki and Tirari Deserts in the driest part of central Australia to provide an optically stimulated luminescence chronology for these dunefields. The dunes preserve up to four stratigraphic horizons, bounded by palaeosols, which represent evidence for multiple periods of reactivation punctuated by episodes of increased environmental stability. Dune activity took place in episodes around 73–66, 35–32, 22–18 and 14–10 ka. Intermittent partial mobilisation persisted at other times throughout the last 75 ka and dune activity appears to have intensified during the late Holocene. Dune construction occurred when sediment was available for aeolian transport; in the Strzelecki and Tirari Deserts, this coincided with cold, arid conditions during Marine Isotope Stage (MIS) 4, late MIS 3 and MIS 2, and the warm, dry climates of the late Pleistocene–Holocene transition period and late Holocene. Localised influxes of sediment on active floodplains and lake floors during the relatively more humid periods of MIS 5 also resulted in dune formation. The timing of widespread dune reactivation coincided with glaciation in southeastern Australia, along with cooler temperatures in the adjacent oceans and Antarctica.

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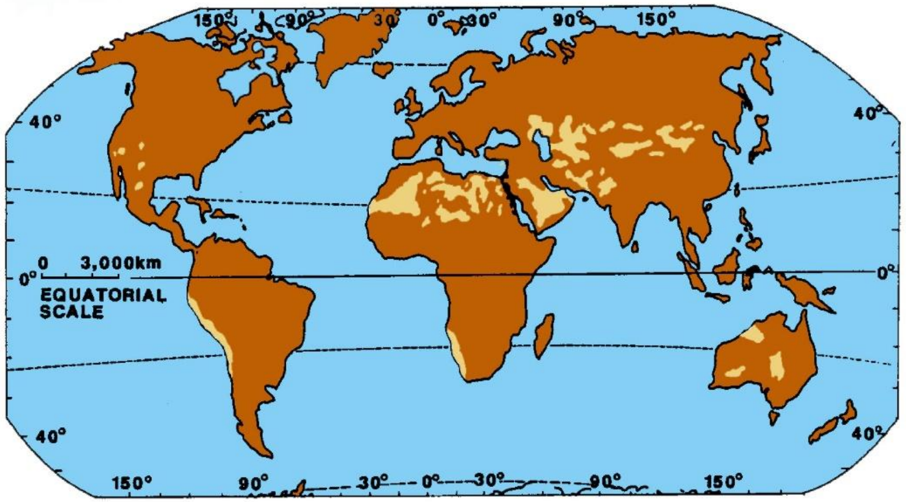
Active dunes – dry period

Stabilized dunes – wet period

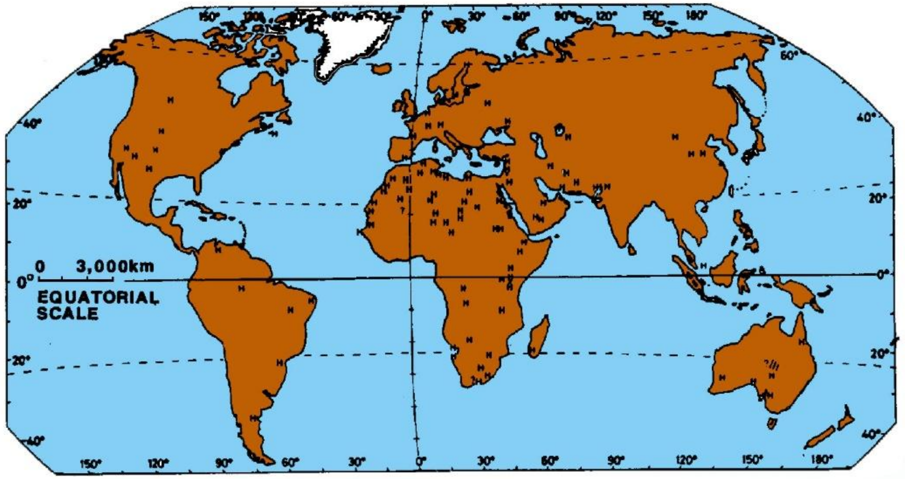


TODAY

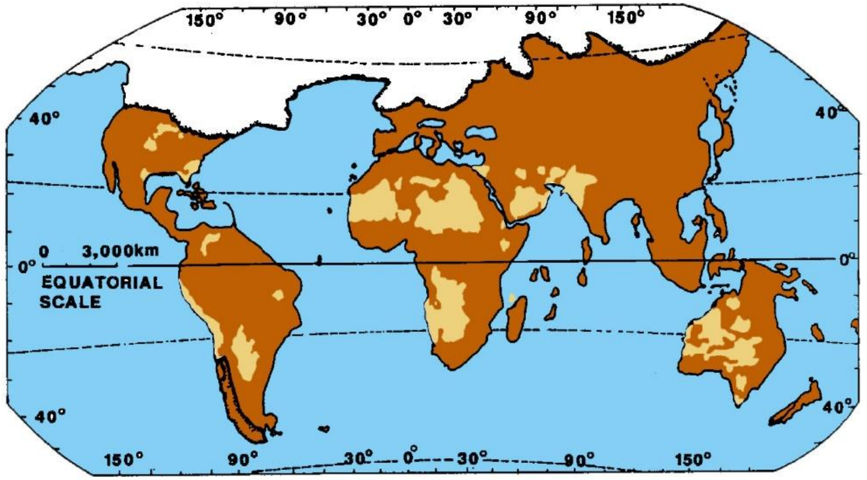
- ▨ **Sand-dune areas**
- **H** **Wet conditions**
- **Ice caps**

Source:

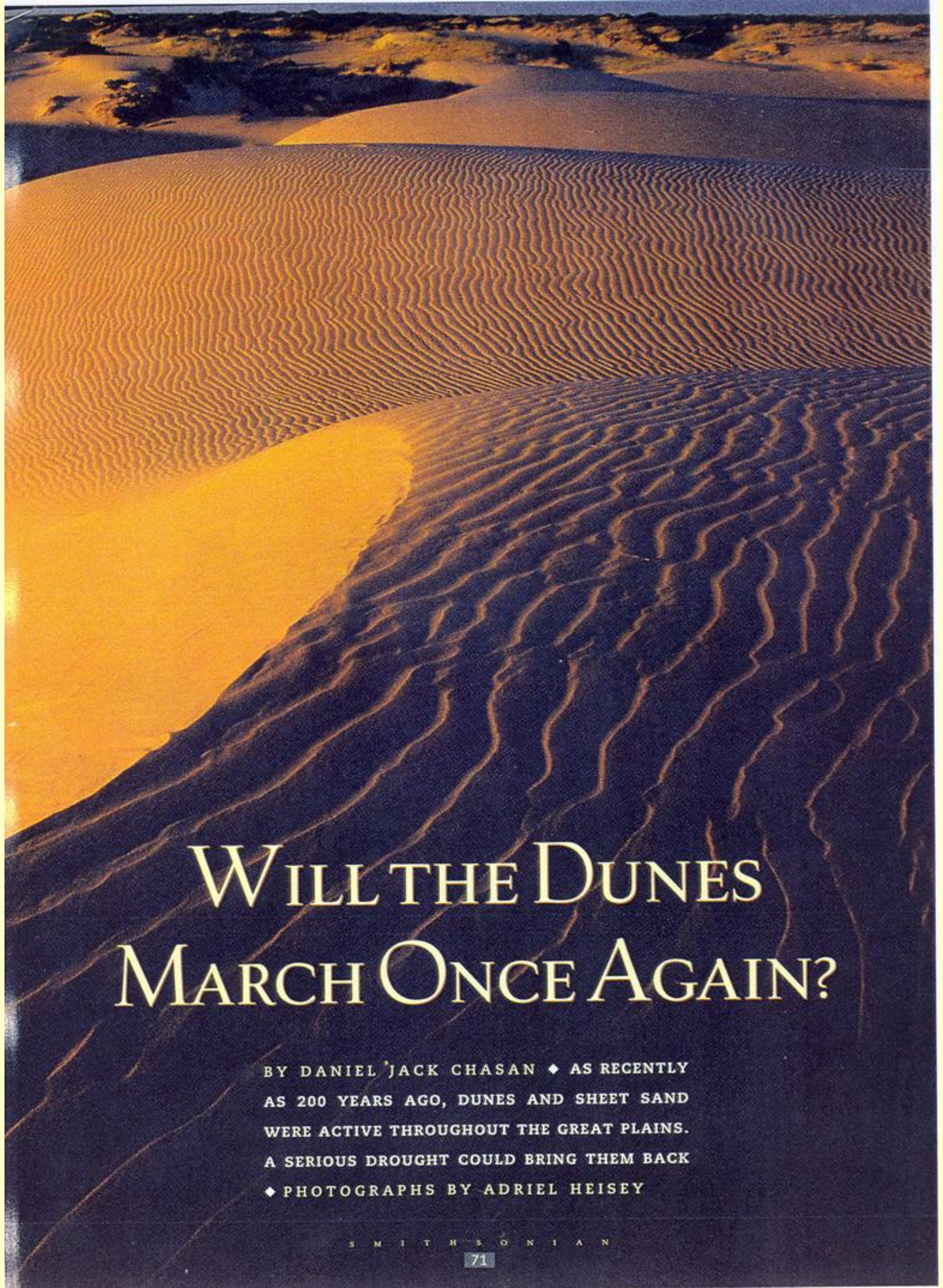
Sarnthein, M. 1978. Sand deserts during glacial maximum and climatic optimum. ***Nature***, **272**: 43-46.



6,000 BP



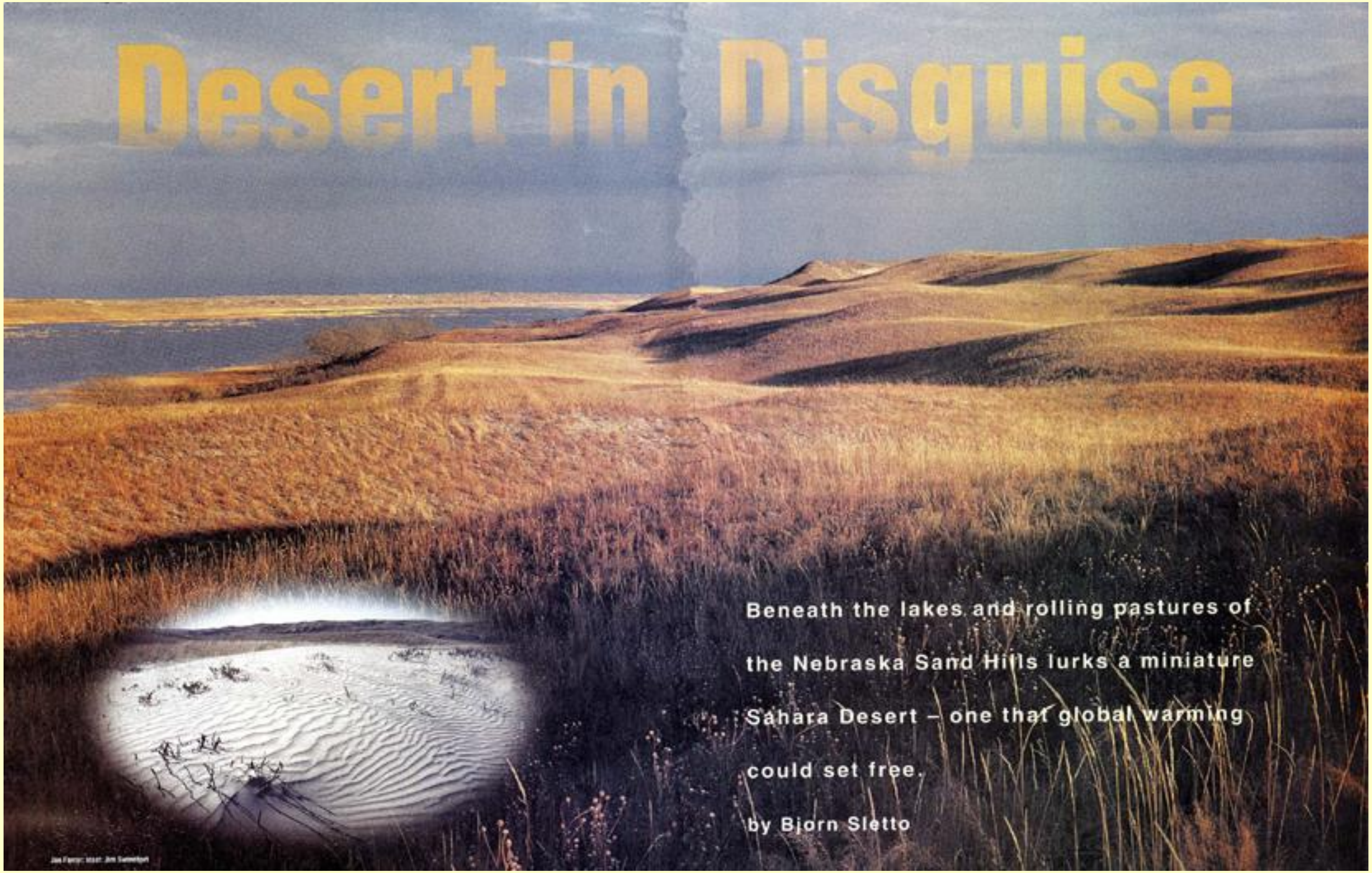
18,000 BP



WILL THE DUNES MARCH ONCE AGAIN?

BY DANIEL JACK CHASAN ◆ AS RECENTLY AS 200 YEARS AGO, DUNES AND SHEET SAND WERE ACTIVE THROUGHOUT THE GREAT PLAINS. A SERIOUS DROUGHT COULD BRING THEM BACK ◆ PHOTOGRAPHS BY ADRIEL HEISEY

Chasan, D. J. (1997). "Will the dunes march again." Smithsonian Magazine **December 1997**: 71-80.



Desert in Disguise

Beneath the lakes and rolling pastures of the Nebraska Sand Hills lurks a miniature Sahara Desert – one that global warming could set free.

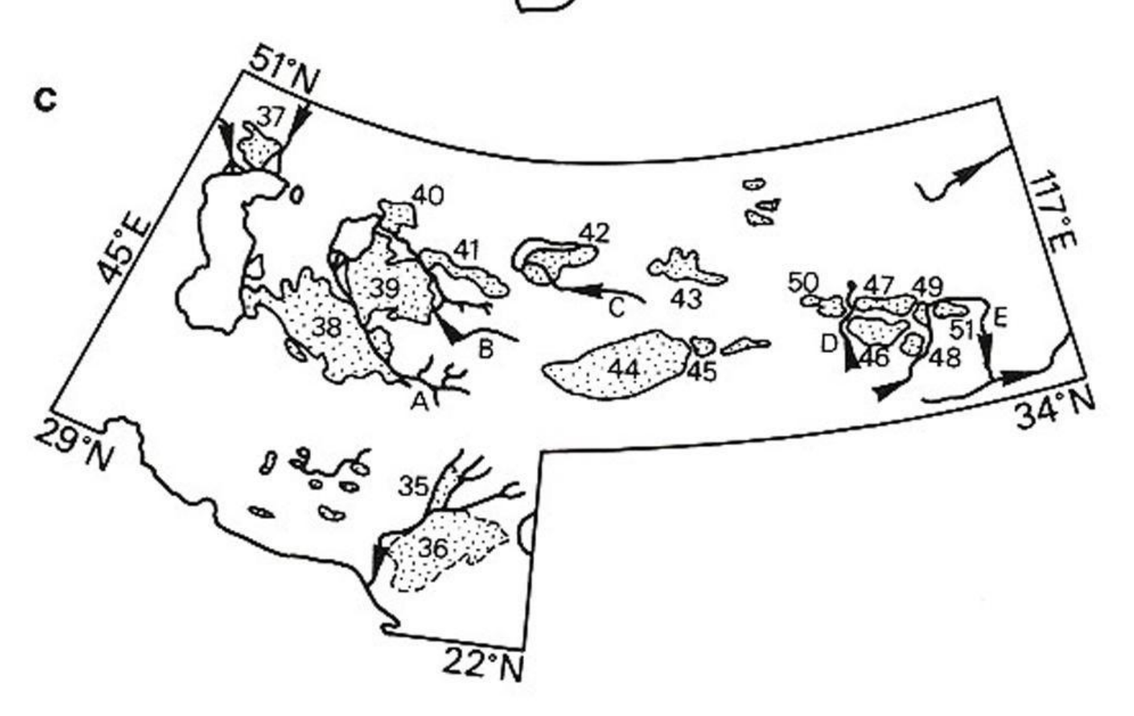
by Bjorn Sletto

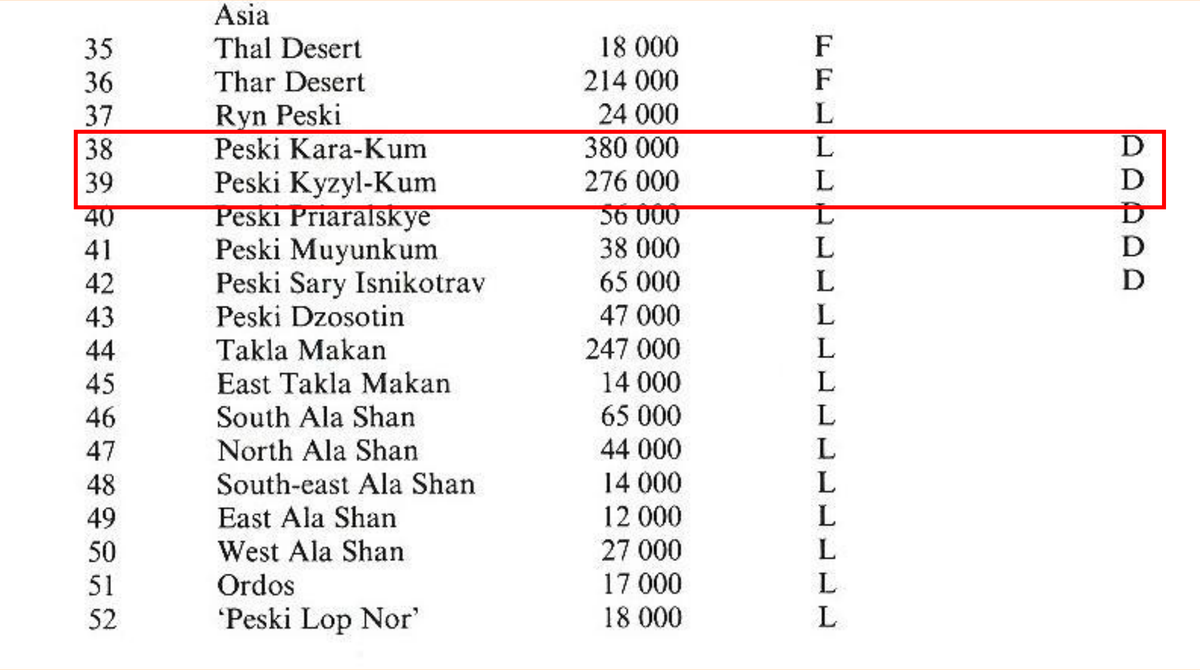
Earth, February 1997

Isohyet of 150 mm - . - . - . - . - . - . - . - . - . -

After Wilson, 1970

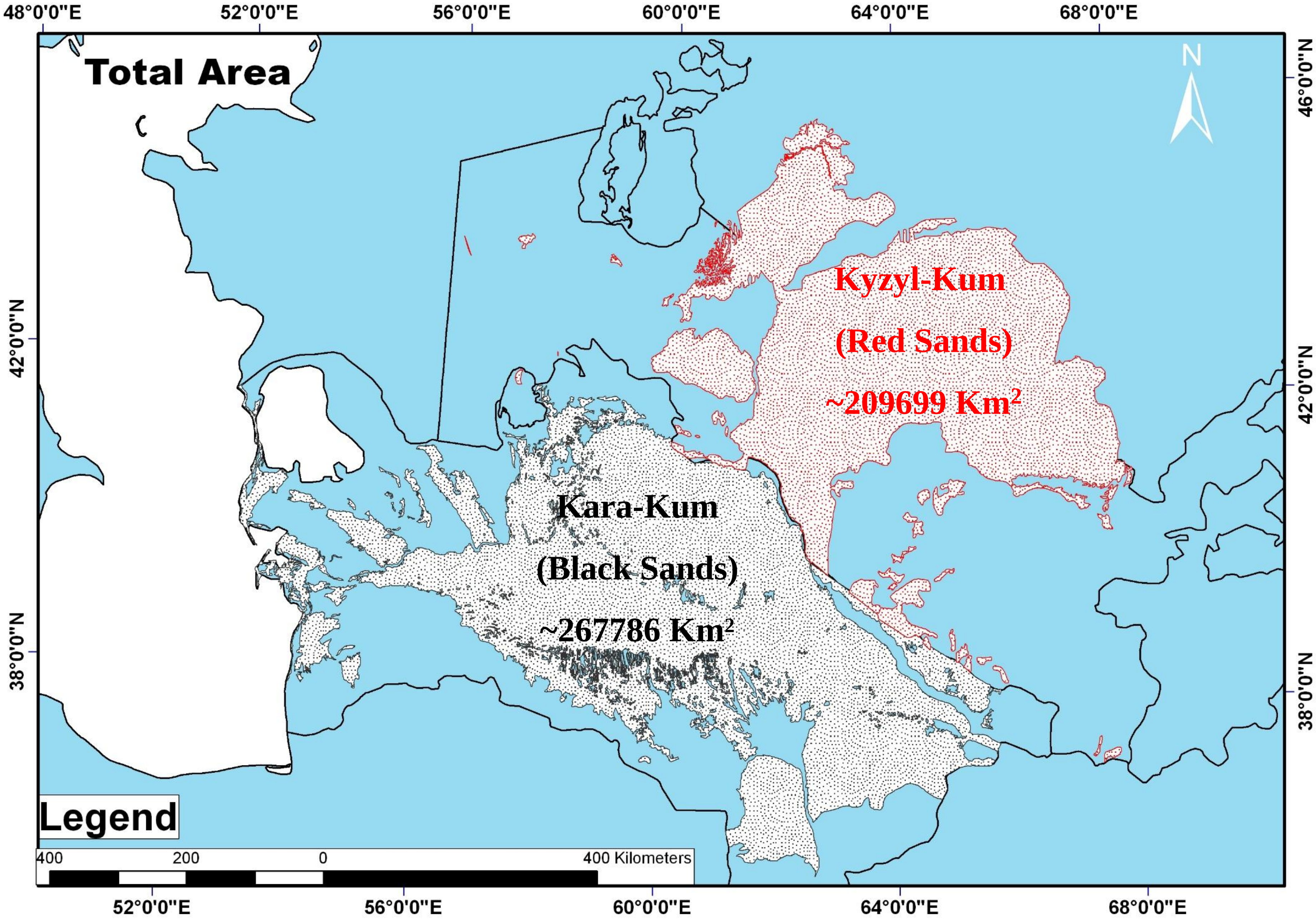
Ian Wilson, 1970, The external morphology of wind-laid bodies, PhD thesis, University of Reading.





	Asia			
35	Thal Desert	18 000	F	
36	Thar Desert	214 000	F	
37	Ryn Peski	24 000	L	
38	Peski Kara-Kum	380 000	L	D
39	Peski Kyzyl-Kum	276 000	L	D
40	Peski Priaralskye	56 000	L	D
41	Peski Muyunkum	38 000	L	D
42	Peski Sary Isnikotrav	65 000	L	D
43	Peski Dzosotin	47 000	L	
44	Takla Makan	247 000	L	
45	East Takla Makan	14 000	L	
46	South Ala Shan	65 000	L	
47	North Ala Shan	44 000	L	
48	South-east Ala Shan	14 000	L	
49	East Ala Shan	12 000	L	
50	West Ala Shan	27 000	L	
51	Ordos	17 000	L	
52	‘Peski Lop Nor’	18 000	L	

After Wilson, 1973


Total Area
Kyzyl-Kum
(Red Sands)
~209699 Km²
Kara-Kum
(Black Sands)
~267786 Km²
N
Legend
400
200
0
400 Kilometers
48°0'0"E
52°0'0"E
56°0'0"E
60°0'0"E
64°0'0"E
68°0'0"E
46°0'0"N
42°0'0"N
38°0'0"N

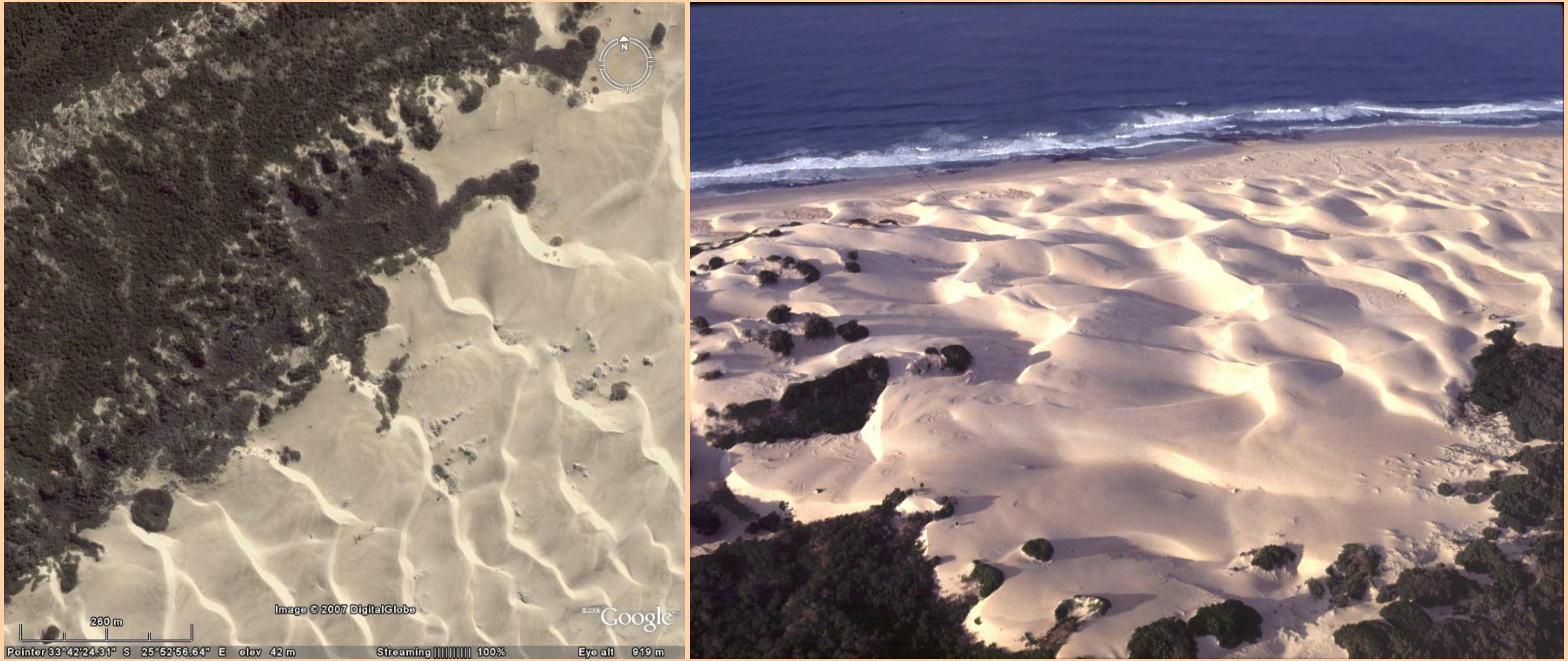
Kyzyl-Kum

Kara-Kum

P=114 mm PE=2100 mm

P/PE=0.05

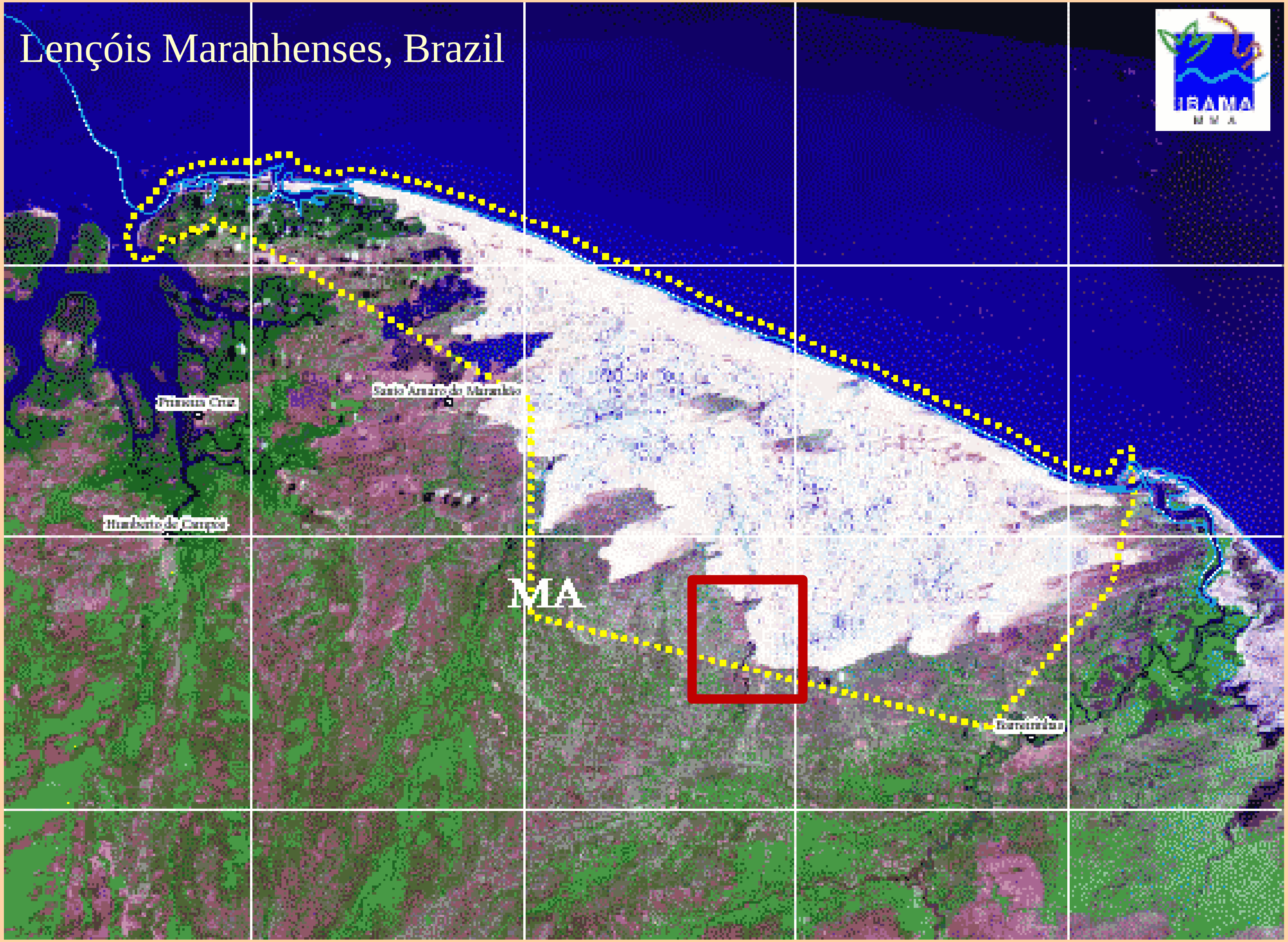
Negev Desert (Israel)



P=624mm

Port Elizabeth, South Africa

Lençóis Maranhenses, Brazil

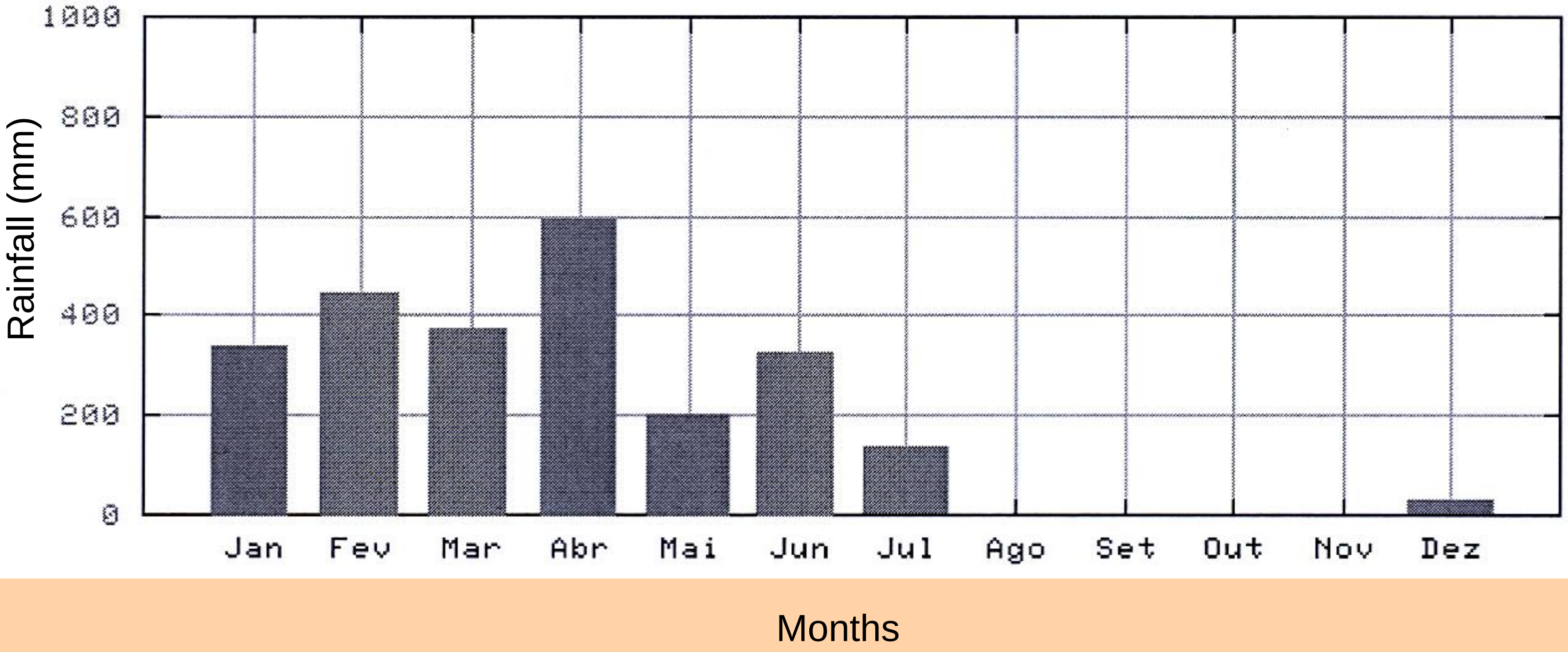


Lençóis Maranhenses, Brazil

Lençóis Maranhenses, Brazil

Lençóis Maranhenses, Brazil

Rainfall at Lençóis Maranhenses, Brazil



Average yearly rainfall 2400 mm

What are the limiting factors for vegetation on sand dunes?

Lençóis Maranhenses, Brazil

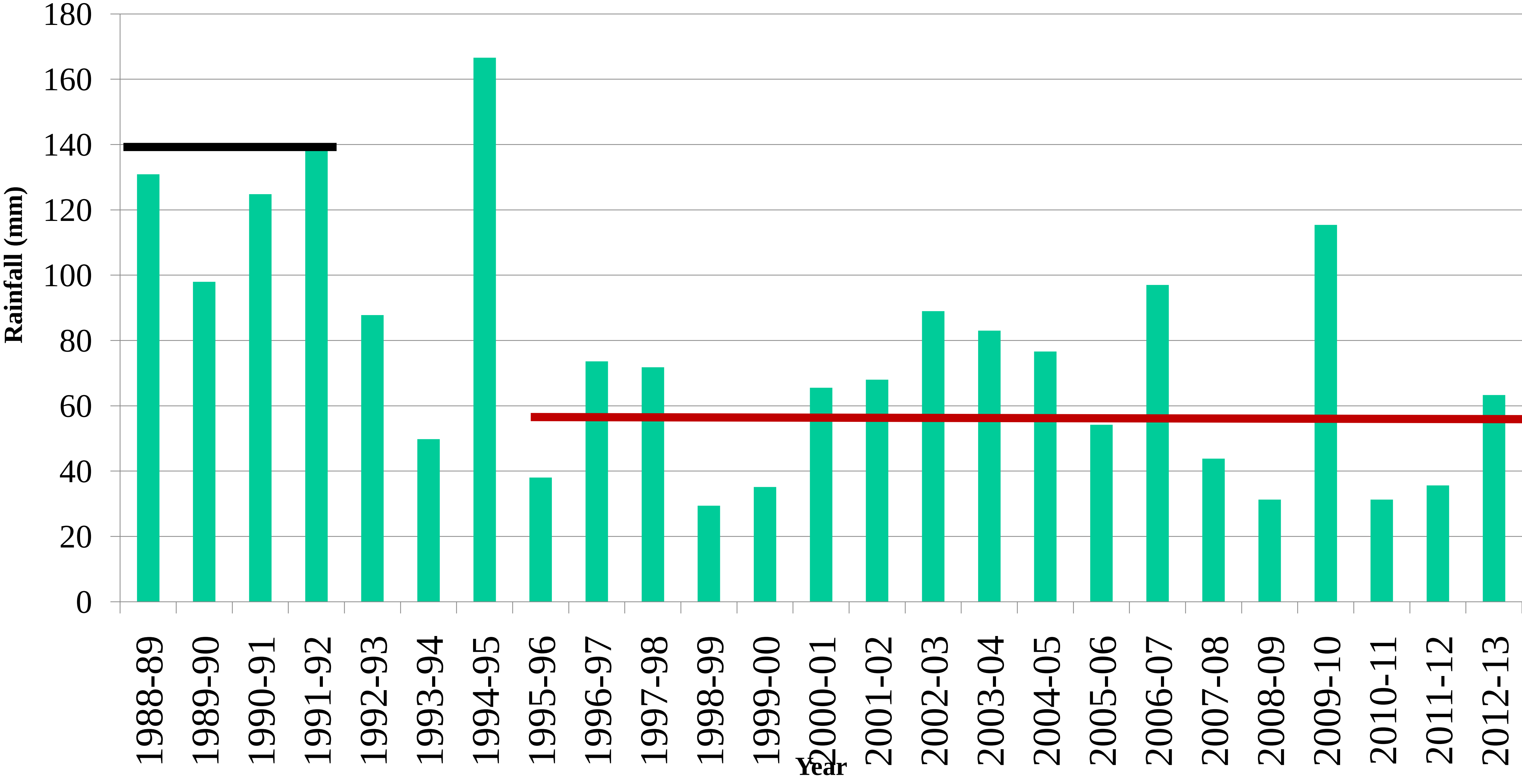
NE France

NE France

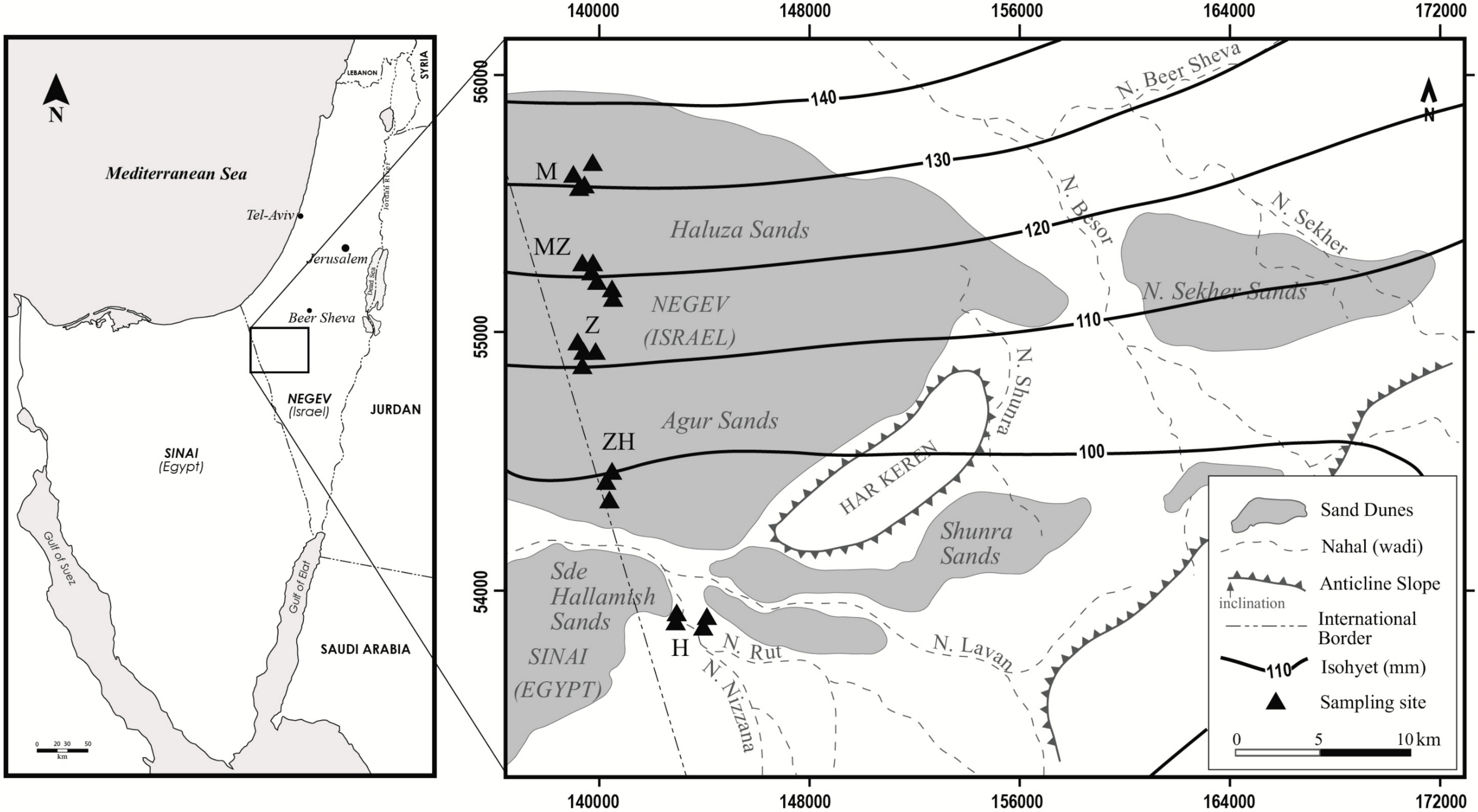
One of the limiting factors for vegetation on dune sand is wind erosion

- How much is the minimum precipitation needed in order for vegetation growth on dunes to stabilize the sand dunes?
- How can wind erosion’s effect on the prevention of vegetation growth or the mobility of sand dunes be quantified?
- How does the combined effect of wind erosion and precipitation determine the mobility and stability of sand dunes?

The effect of prolonged drought on fixed sand dunes



NW Negev Desert, Israel


N
Mediterranean Sea
LEBANON
SYRIA
Jordan River
Tel-Aviv
Jerusalem
Dead Sea
Beer Sheva
NEGEV
(Israel)
JURDAN
SINAI
(Egypt)
Gulf of Suez
Gulf of Elat
SAUDI ARABIA
0 20 30 50
km
140000
148000
156000
164000
172000
56000
55000
54000
140
130
120
110
100
N. Beer Sheva
N. Besor
N. Sekher
N. Sekher Sands
Haluza Sands
NEGEV
(ISRAEL)
Agur Sands
N. Shunra
HAR KEREN
Shunra Sands
Sde Hallamish Sands
SINAI
(EGYPT)
N. Rut
N. Nizzana
N. Lavan
M
MZ
Z
ZH
H
Sand Dunes
Nahal (wadi)
Anticline Slope
inclination
International Border
Isohyet (mm)
Sampling site
0
5
10 km

Survey method

5 sites along the rain gradient

4 samplings at each site each in an area of 5x20 meters

4 repetitions at each site

Total of 80 samples in 2007

80 samples in 2008

80 samples in 2009

Visual assessment of wilting of *Artemisia monosperma*

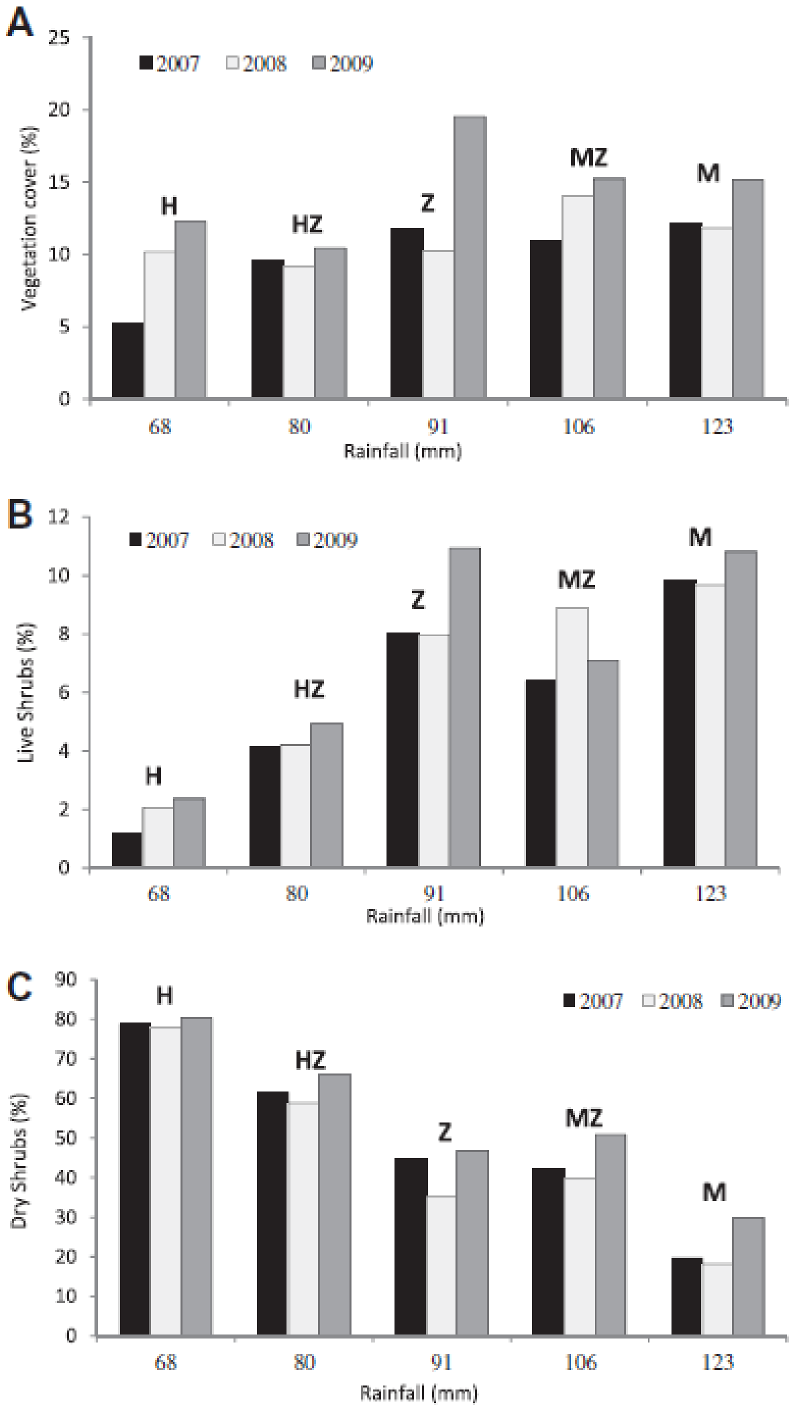

Dead *(all above-ground parts dead)*


Dead (disintegrated)


Normal (not wilted)


Slightly wilted


Wilted (nearly dead)

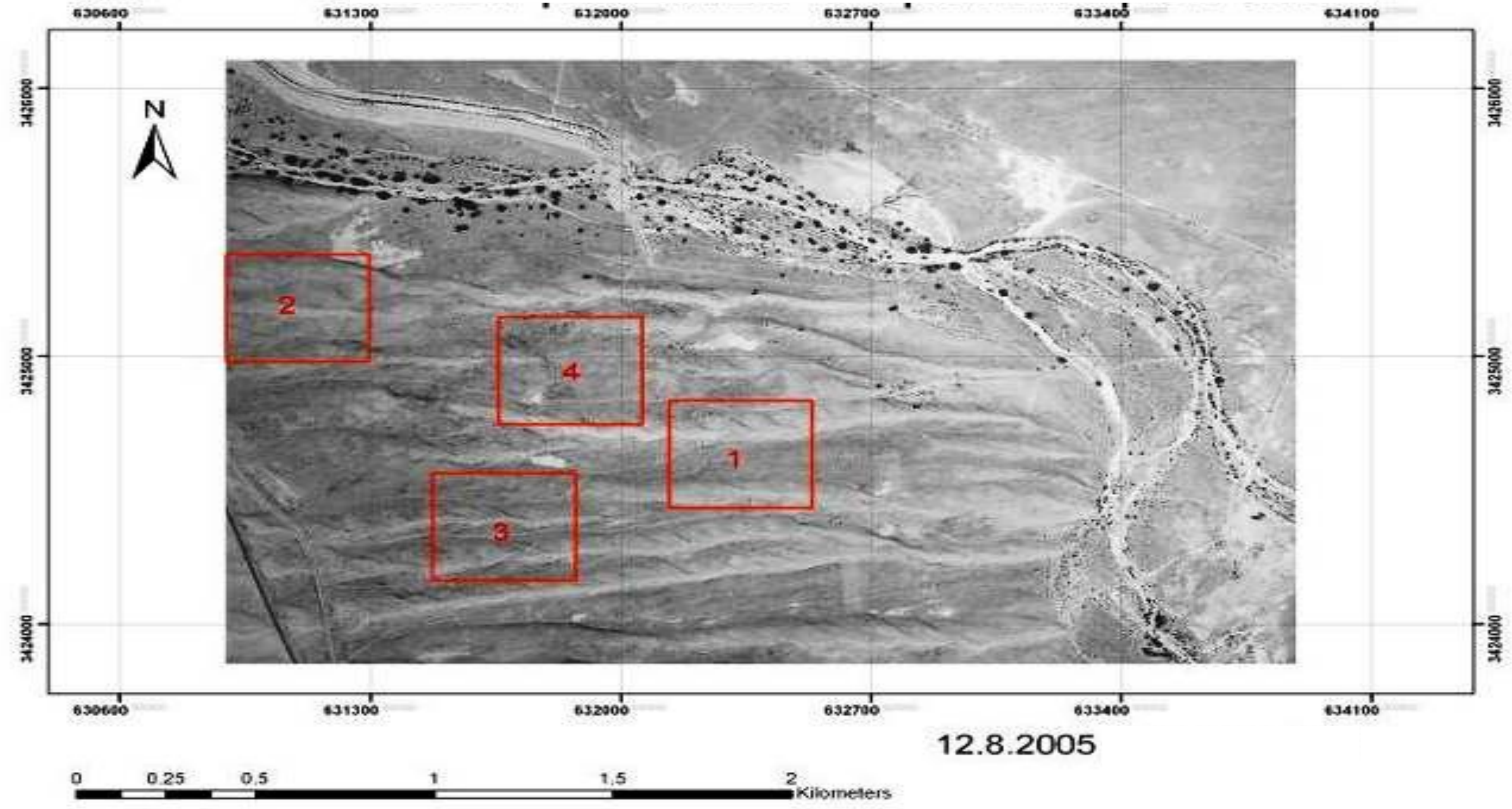

A
Vegetation cover (%)
0
5
10
15
20
25
2007
2008
2009
H
HZ
Z
MZ
M
68
80
91
106
123
Rainfall (mm)
B
Live Shrubs (%)
0
2
4
6
8
10
12
2007
2008
2009
H
HZ
Z
MZ
M
68
80
91
106
123
Rainfall (mm)
C
Dry Shrubs (%)
0
10
20
30
40
50
60
70
80
90
2007
2008
2009
H
HZ
Z
MZ
M
68
80
91
106
123
Rainfall (mm)

Aerial photo analysis

Year	Date	Resolution (m)	Scale	TRMS (m)
2005	12.8	0.63	23100	0.57
2003	not known	1	-	base
1999	4.12	0.3	13000	0.44
1994	30.4	0.68	36400	0.6
1989	4.2	0.42	13727	0.5
1982	17.4	0.51	27000	0.57
1984	20.7	0.92	27800	0.47
1976	24.4	0.47	15724	0.5
1971	12.6	0.74	28500	0.53
1968	26.7	0.58	26000	0.51
1956	24.7	0.72	30000	0.52

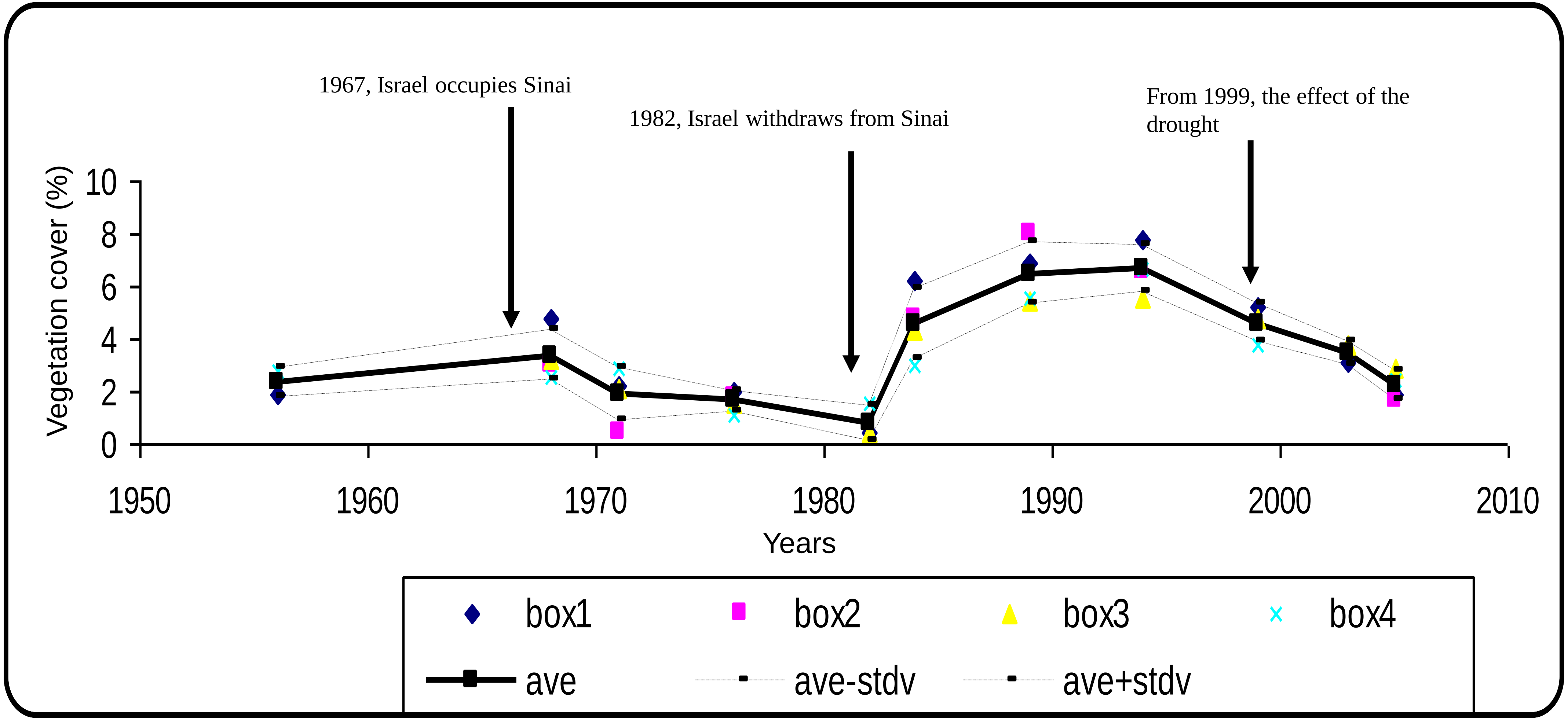
TRMS= Total Root Mean Square error

Aerial Photo Analysis (H)



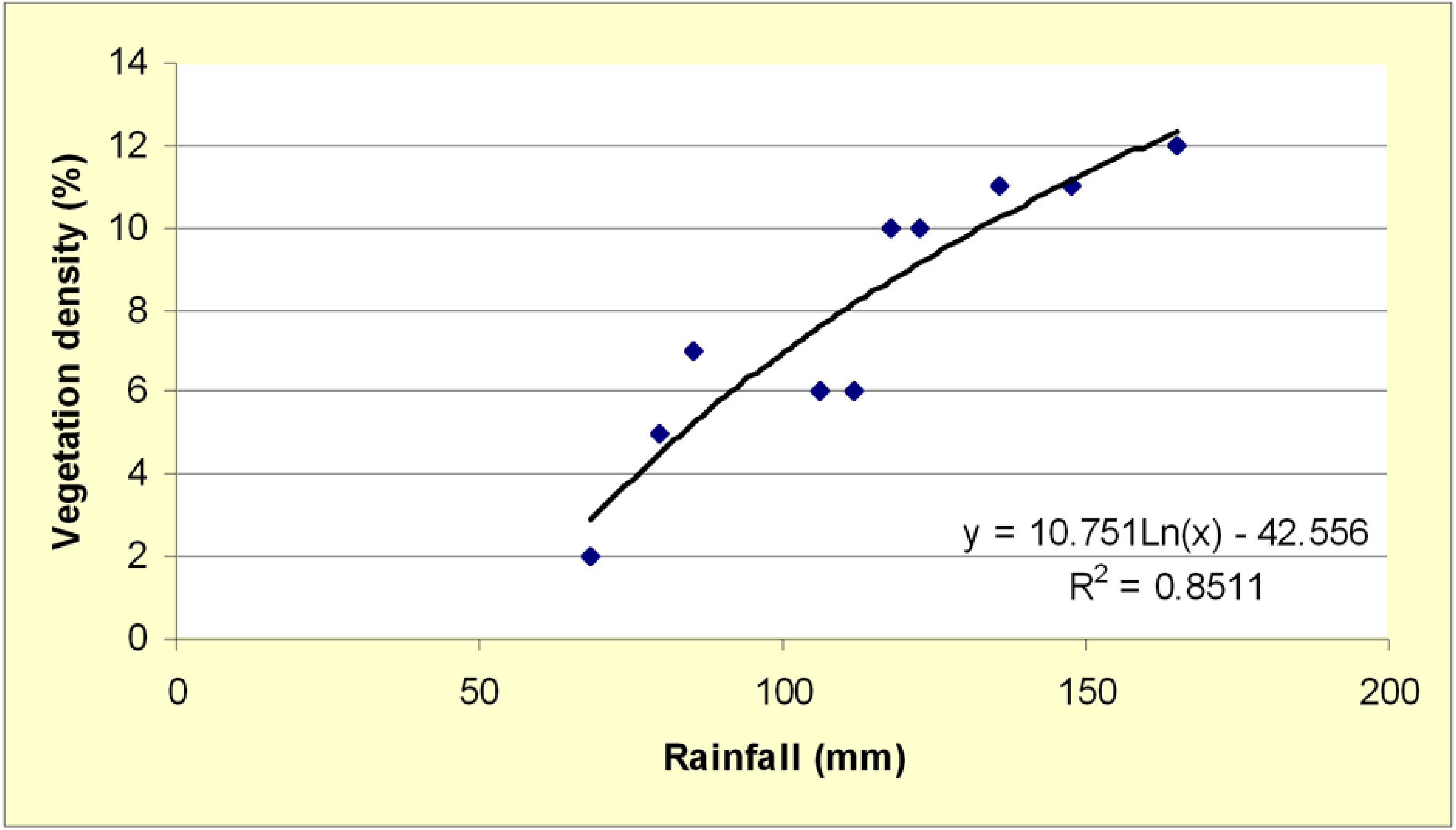
12.8.2005

Change in vegetation cover from 1956 until 2005 in Hallamish (H) field - Aerial Photo Analysis



The correlation coefficients and probabilities for the moving averages of rainfall and shrubs cover measured at site H between 1988/89 – 2004/05.

Moving average (years)	**R^2**	**P Value**
5	0.33	0.3
6	0.62	0.1
7	**0.84**	**0.02**
8	**0.83**	**0.03**
9	**0.88**	**0.01**
10	**0.79**	**0.04**
11	**0.67**	**0.08**



Accordingly, when the annual average rainfall is **52 mm**, the shrub cover (in the Negev Desert) is zero (After: Siegal, Z., Tsoar, H., Karnieli, A. 2013, Effects of prolonged drought on the vegetation cover of sand dunes in the NW Negev Desert: Field survey, remote sensing and conceptual modeling. *Aeolian Research* 9, 161–173).

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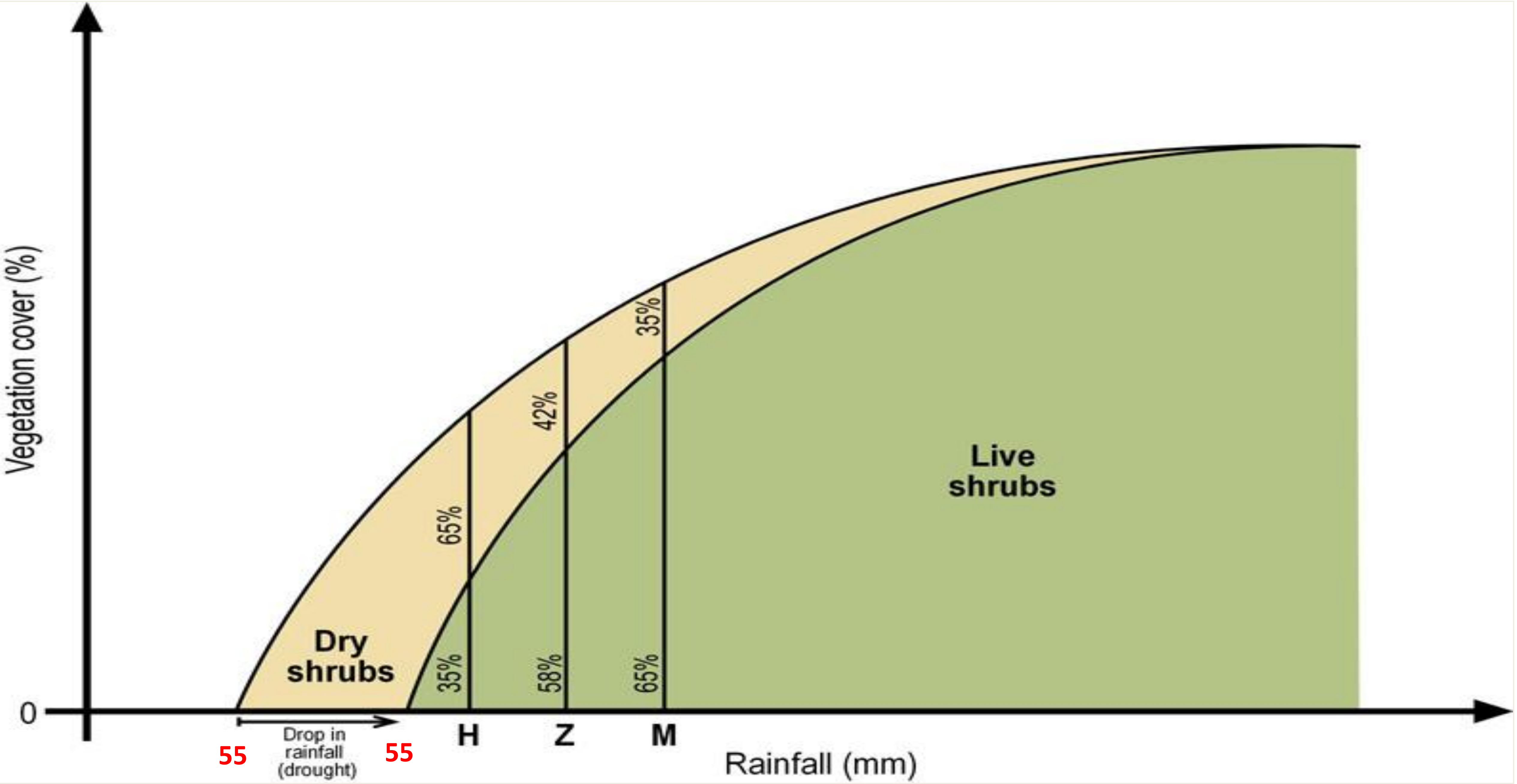

Vegetation cover (%)
0
Dry shrubs
Live shrubs
65%
35%
42%
58%
35%
65%
H
Z
M
Drop in rainfall (drought)
55
55
Rainfall (mm)

How can wind erosion’s effect on the prevention of vegetation growth or the mobility of sand dunes be quantified?

The limiting factor for vegetation on dune sand is wind erosion (power)

Power is defined as the amount of energy consumed per unit of time. The unit of power is joule per second (*J/s*), known as watt (*W*).

$$Q = C(d/D)^{0.5}\left(\frac{\rho}{g}\right)U_*^3$$

WIND POWER EQUATIONS

$$E_K = \frac{1}{2} m U^2$$

Where: E_K is the kinetic energy, m is the mass and U is the speed.

$$\rho = \frac{m}{V} \quad \text{or} \quad m = \rho V \quad \text{Hence:} \quad E_K = \frac{1}{2} \rho V U^2$$

Where: ρ is the density of the air, V is the volume of air parcel.

$$V = AL \quad \text{hence:} \quad E_K = \frac{1}{2} \rho A L U^2$$

Where: A is the area of air parcel and L is its thickness.

$$U = \frac{L}{t} \quad \text{or} \quad L = tU$$ where t is the time.

$$E_K = \frac{1}{2}\rho A t U^3$$

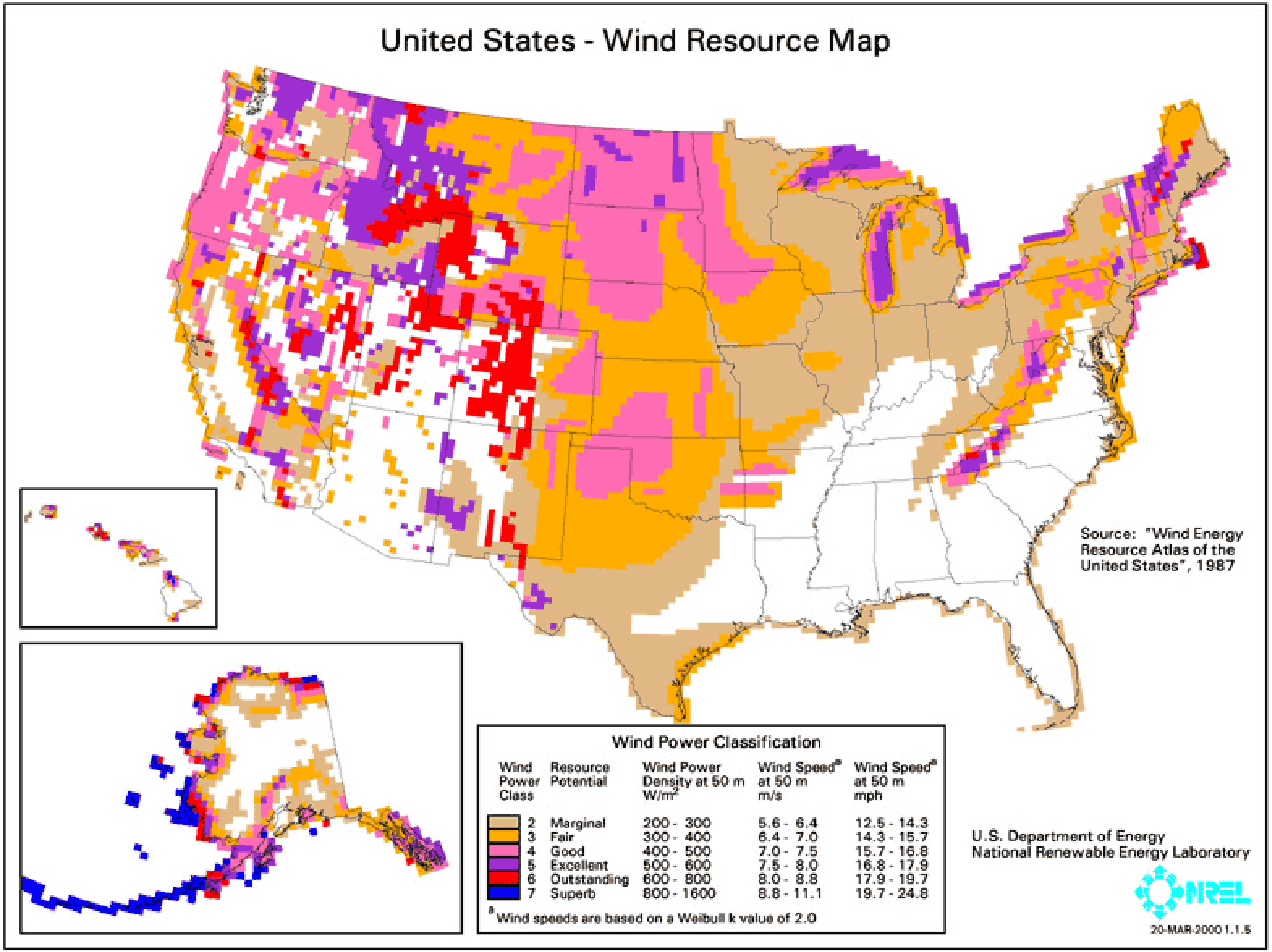
$$P_W = \frac{E_K}{t} = \frac{1}{2}\rho A U^3 \left(P_W = \frac{J}{\sec} = W \right)$$

Where: P_W = wind power, J is joule and W is watt. Hence: $P_W = \frac{1}{2}\rho A U^3$

Wind power density $\longrightarrow$ $\frac{P_W}{A} = \frac{1}{2}\rho U^3$

Where $\frac{P_W}{A}$ is the wind power density. $\left(\frac{P_W}{A}\, is\, \frac{W}{m^2} \right)$ m^2 is square meter

United States - Wind Resource Map



Source: "Wind Energy Resource Atlas of the United States", 1987

Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
🟫	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
🟧	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
🟪	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
🟪	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
🟥	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
🟦	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory

NREL

20-MAR-2000 1.1.5

Potential sand transporting power of the wind (Fryberger 1979)

$$q \propto U_*^3 t$$

$$DP = \sum q = \frac{U^2 (U - U_t)}{100} t$$

q- rate of sand drift

U_*-shear velocity

t-time wind blew (%)

U-wind velocity

U_t-threshold velocity

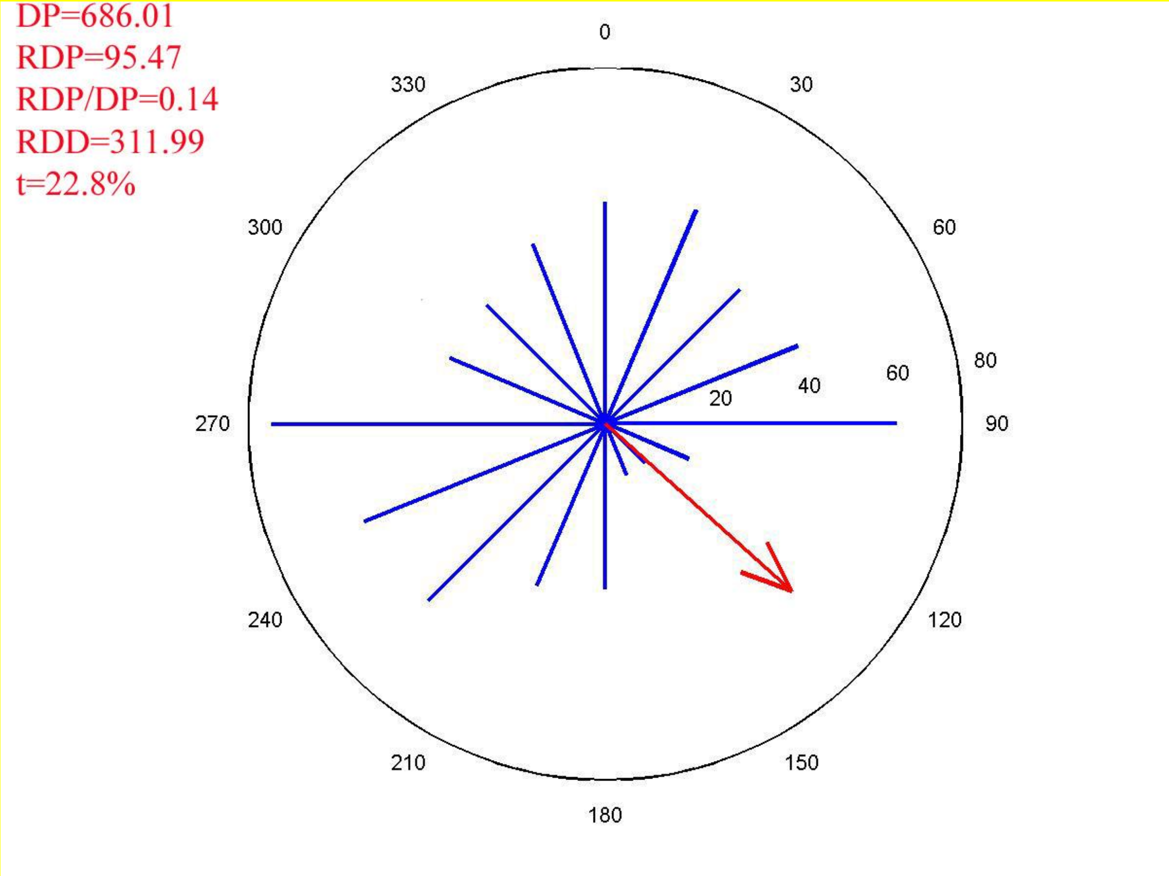
DP-drift potential

Index of directional variability of the wind

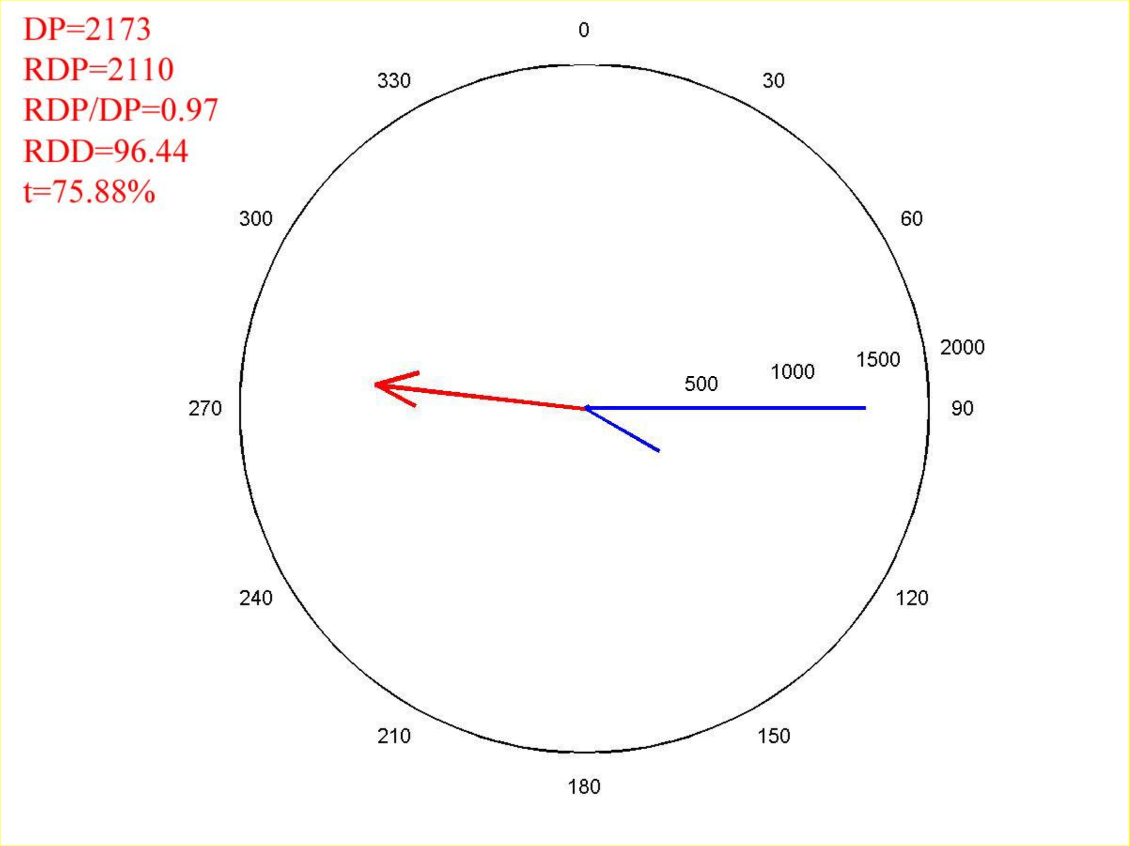
RDP/DP

RDP = the magnitude of the resultant vector (the Resultant Drift Potential).

RDP/DP approaches **unity** when the wind comes from the same direction and **zero** when the wind is multidirectional with symmetric distribution of **DP** for each direction.

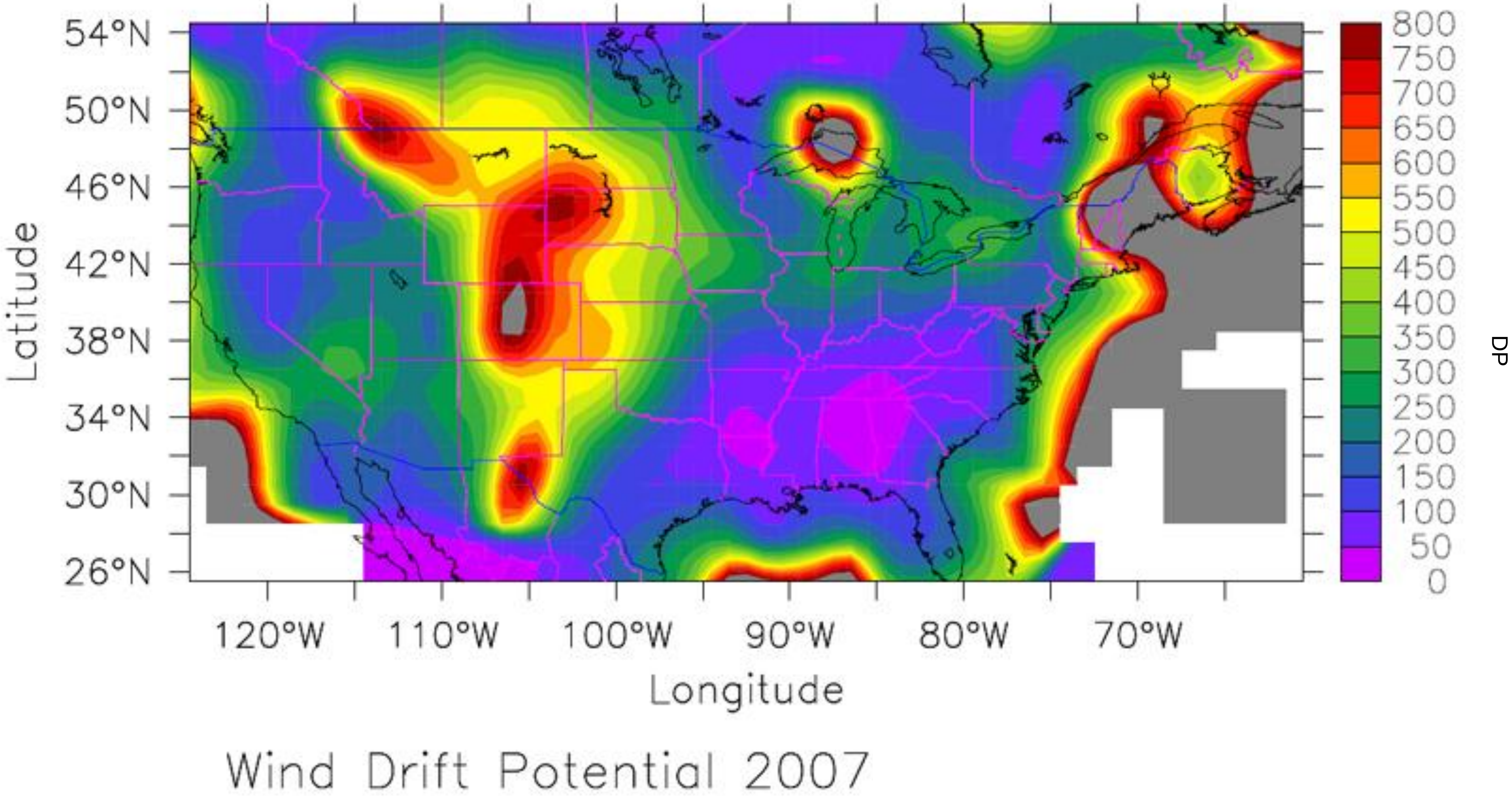


El-Golea, Algeria



Aranau, NE Brazil

NCDC (National Climatic Data Center)



Wind Drift Potential 2007

A simple model for dunes` vegetation cover.

$$\frac{dv}{dt} = \overbrace{\alpha(v+\eta)\left(1-\frac{v}{v_{\max}}\right)}^{\text{Logistic growth}} - \overbrace{\varepsilon \mathrm{DP}\,\theta(v_c - v)v}^{\text{Vegetation suppression due to sand mobility}} - \overbrace{\gamma \mathrm{DP}^{2/3} v}^{\text{Vegetation suppression due to wind}}$$

$$\theta(v_c - v) = \begin{cases} 1 & v < v_c \\ 0 & v \geq v_c \end{cases}$$

v – vegetation coverage $(0 < v < v_{\max})$

v_c – vegetation critical density

from 0.14 (Kalahari) to 0.35 (Australia)

η – spontaneous growth

From: Yizhaq, H., Ashkenazy, Y., and Tsoar, H., 2007, Why do active and stabilized dunes coexist under the same climatic conditions? *Physical Review Letters*, 98(18): Art. No. 188001

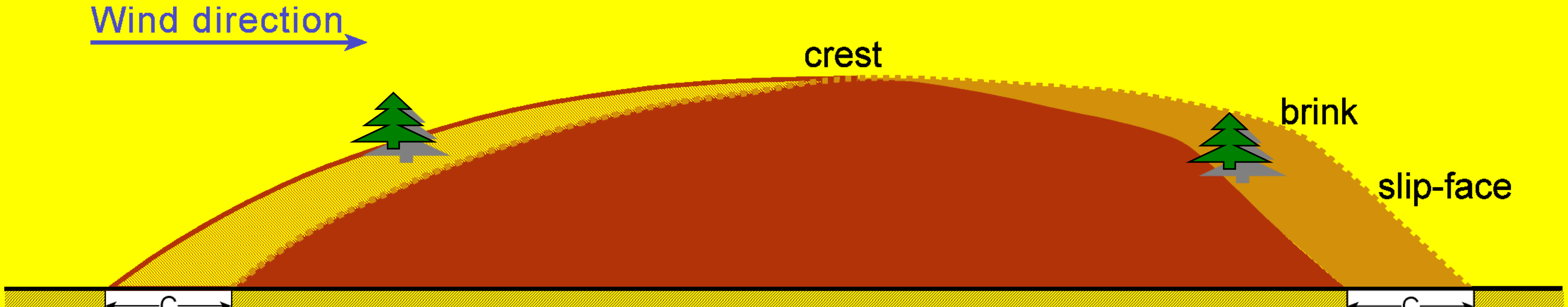
Effect of sand accumulation/erosion on vegetation

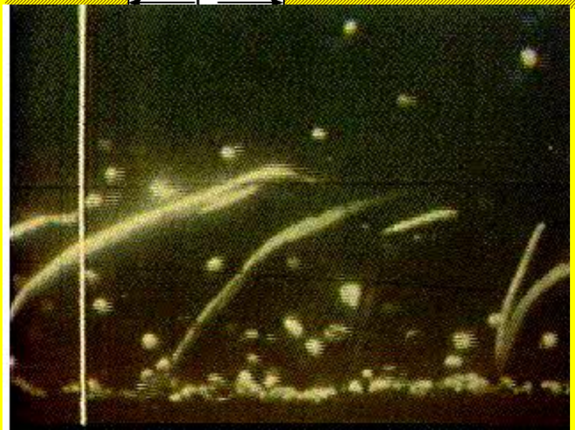
$$\frac{dv}{dt} = \alpha(v+\eta)\left(1-\frac{v}{v_{\max}}\right) - \varepsilon \mathrm{DP}\,\theta(v_c - v)v - \gamma \mathrm{DP}^{2/3} v$$

DP proportional to sand flux which is proportional to dune height.

⇒ accumulation/erosion proportional to DP.

ε depends of the plant type and quantifies the mortality





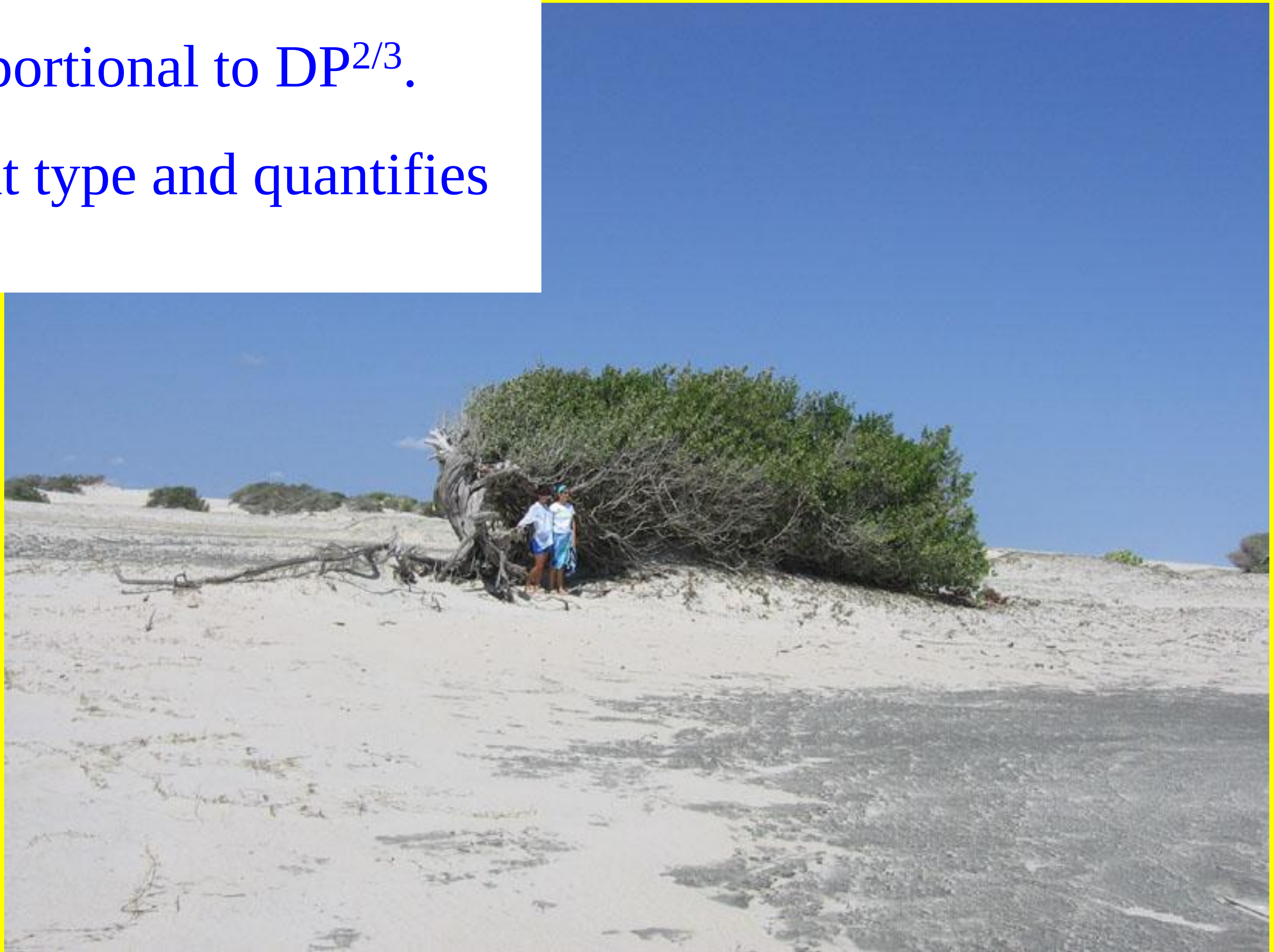
Direct effect of wind on vegetation

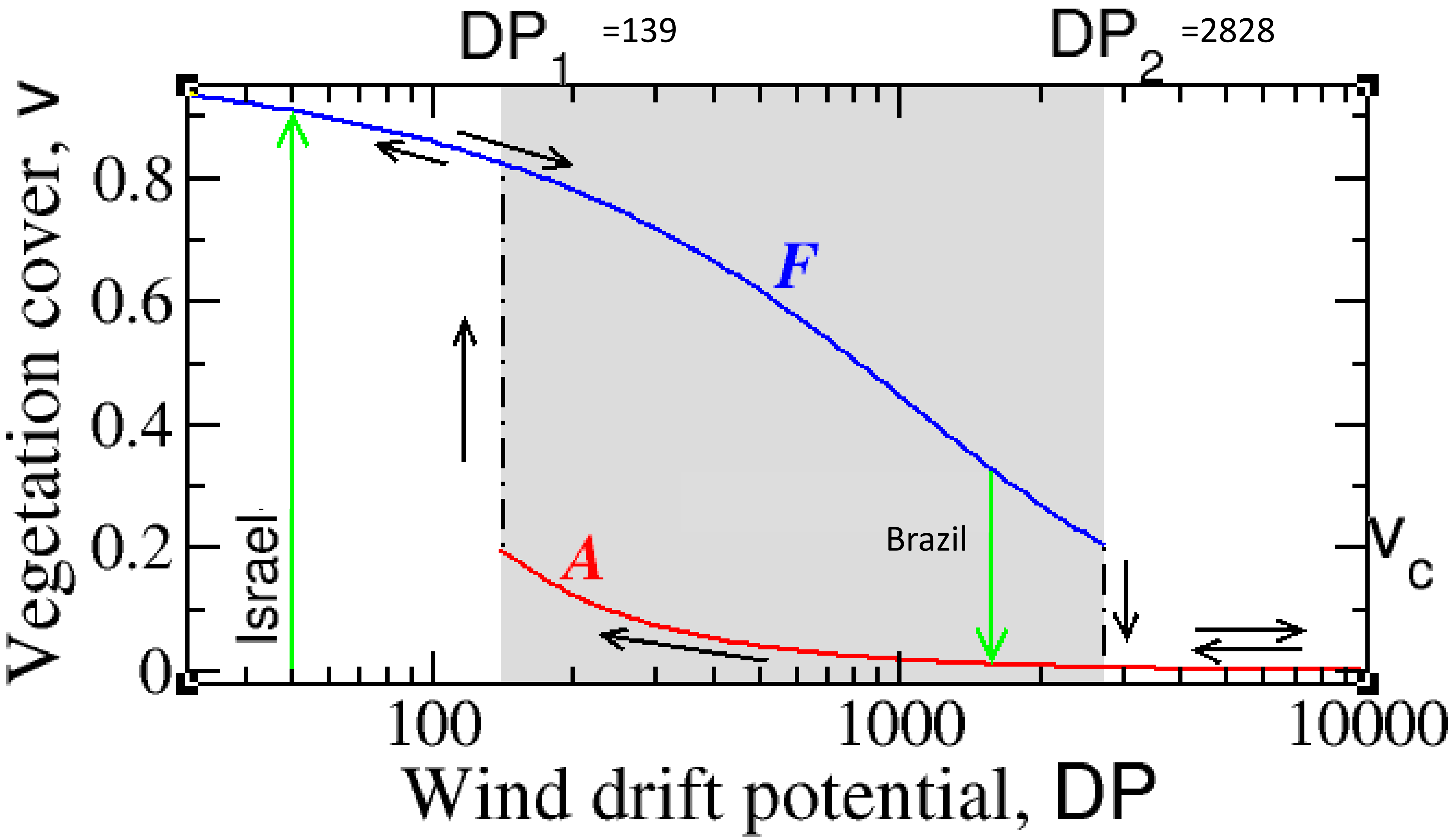
$$\boxed{\frac{dv}{dt} = \alpha(v+\eta)\left(1-\frac{v}{v_{\max}}\right) - \varepsilon \mathrm{DP}\,\theta(v_c - v)v - \enclose{circle}{\gamma \mathrm{DP}^{2/3} v}}$$

DP $\propto$ U^3 and wind drag proportional to U^2

$\Rightarrow$ wind drag proportional to $\mathrm{DP}^{2/3}$.

γ depends of the plant type and quantifies the mortality

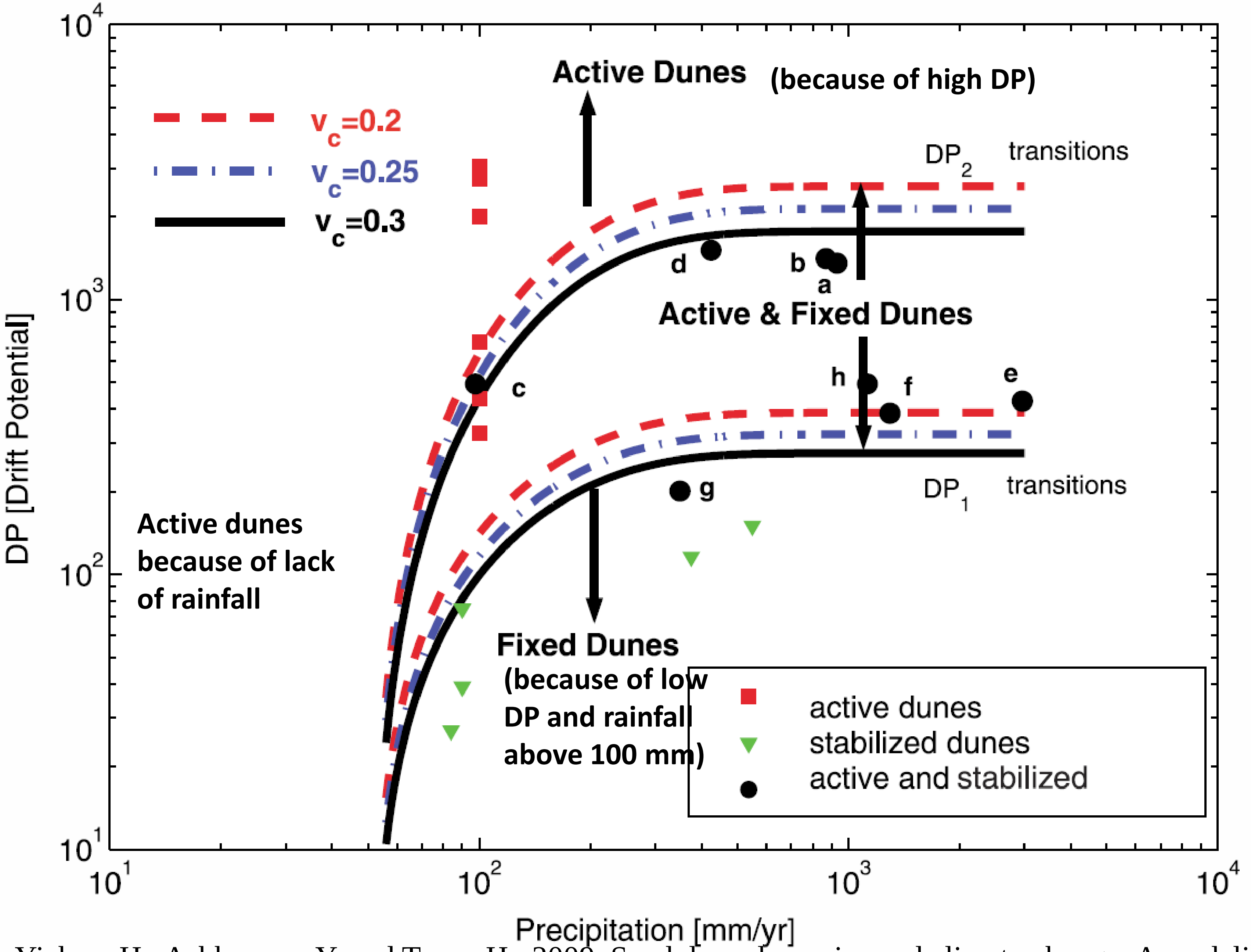




When average annual rainfall ≥ 100 mm

From: Yizhaq, H., Ashkenazy, Y. and Tsoar, H. 2007, Why do active and stabilized dunes coexist under the same climatic conditions? *Physical Review Letters*, 98(18): Art. No. 188001 MAY 4 2007

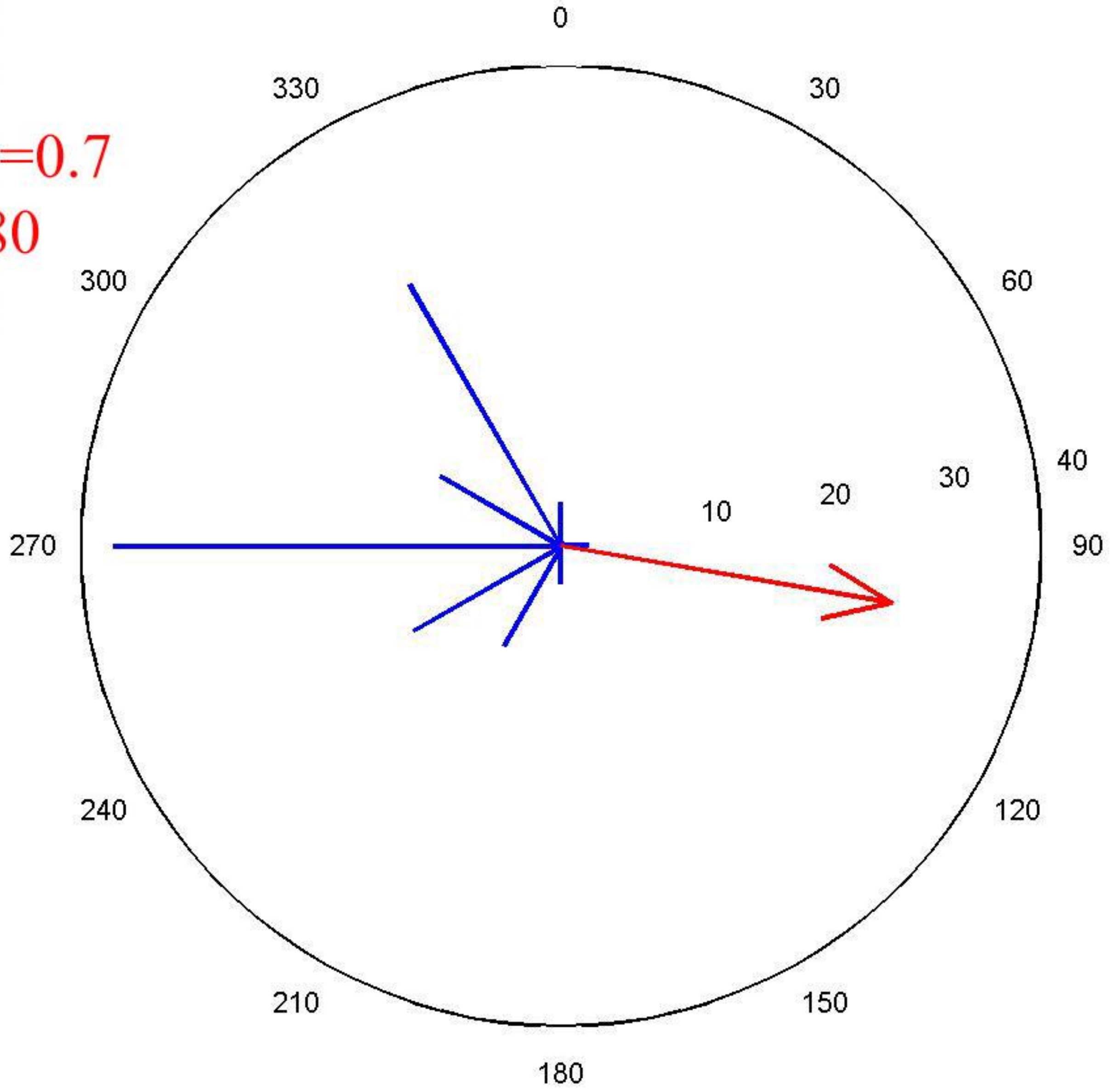
How does the combined effect of wind erosion and precipitation determine the mobility and stability of sand dunes?



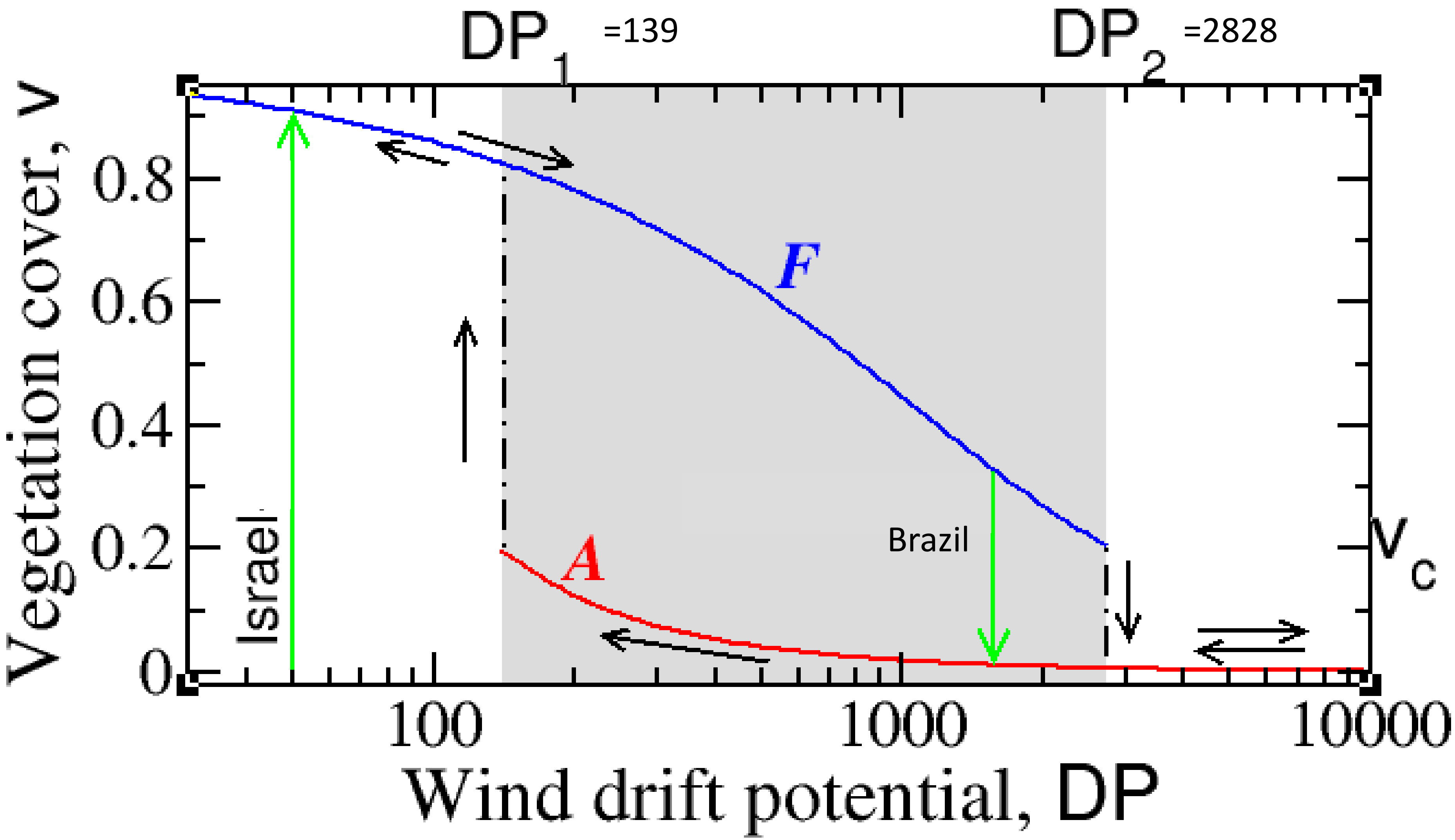
From: Yizhaq, H., Ashkenazy, Y. and Tsoar, H., 2009. Sand dune dynamics and climate change: A modeling approach. Journal of Geophysical Research-Earth Surface, 114: F01023, doi:10.1029/2008JF001138.

Human Impacts

DP=108
RDP=75
RDP/DP=0.7
RDD=280
t=16.8%

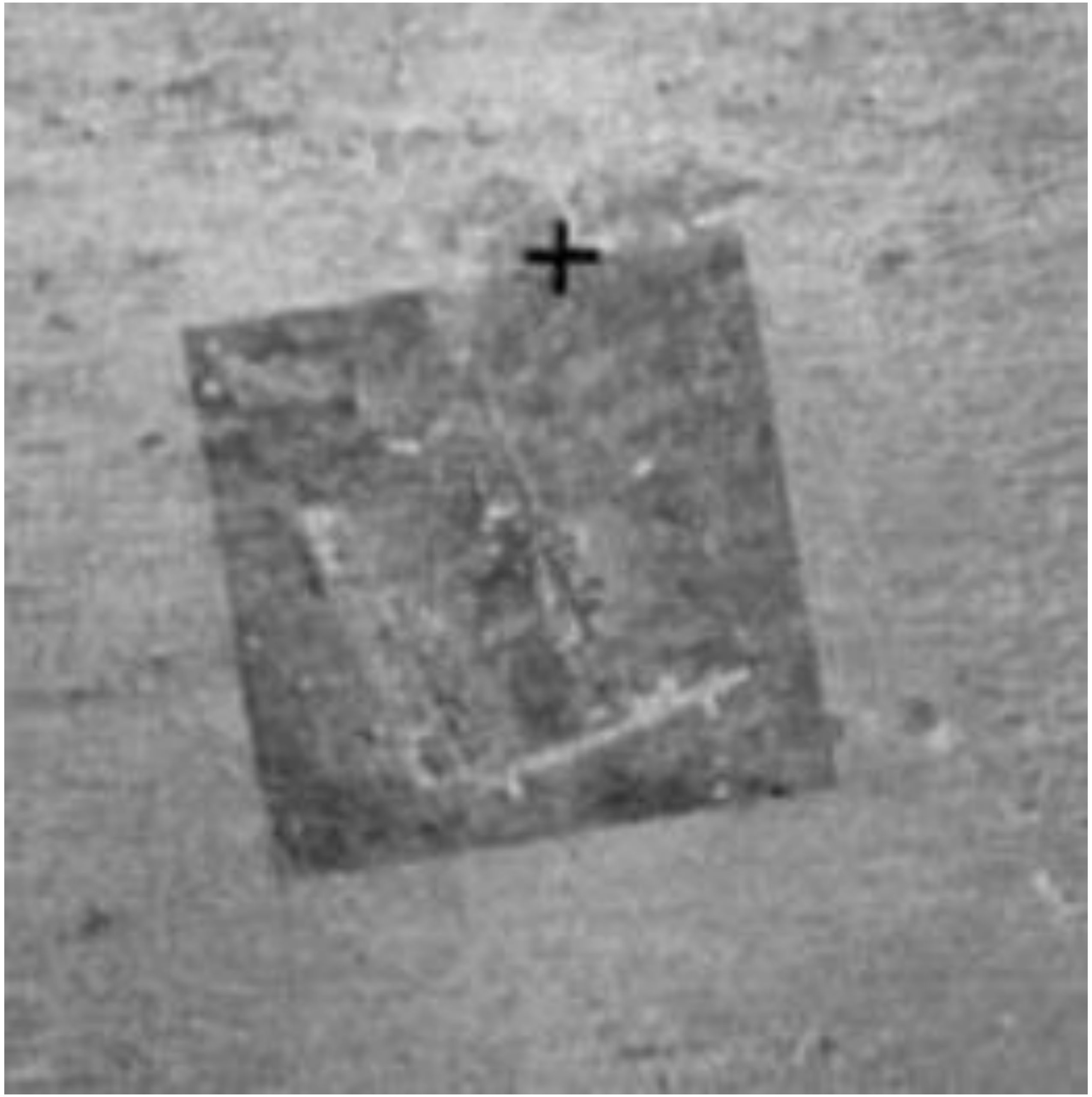


Eastern Sinai



When average annual rainfall ≥ 100 mm

From: Yizhaq, H., Ashkenazy, Y. and Tsoar, H. 2007, Why do active and stabilized dunes coexist under the same climatic conditions? *Physical Review Letters*, 98(18): Art. No. 188001 MAY 4 2007



Ashdod, Israel 1983

Ashdod, Israel 2002

Cerastes viper

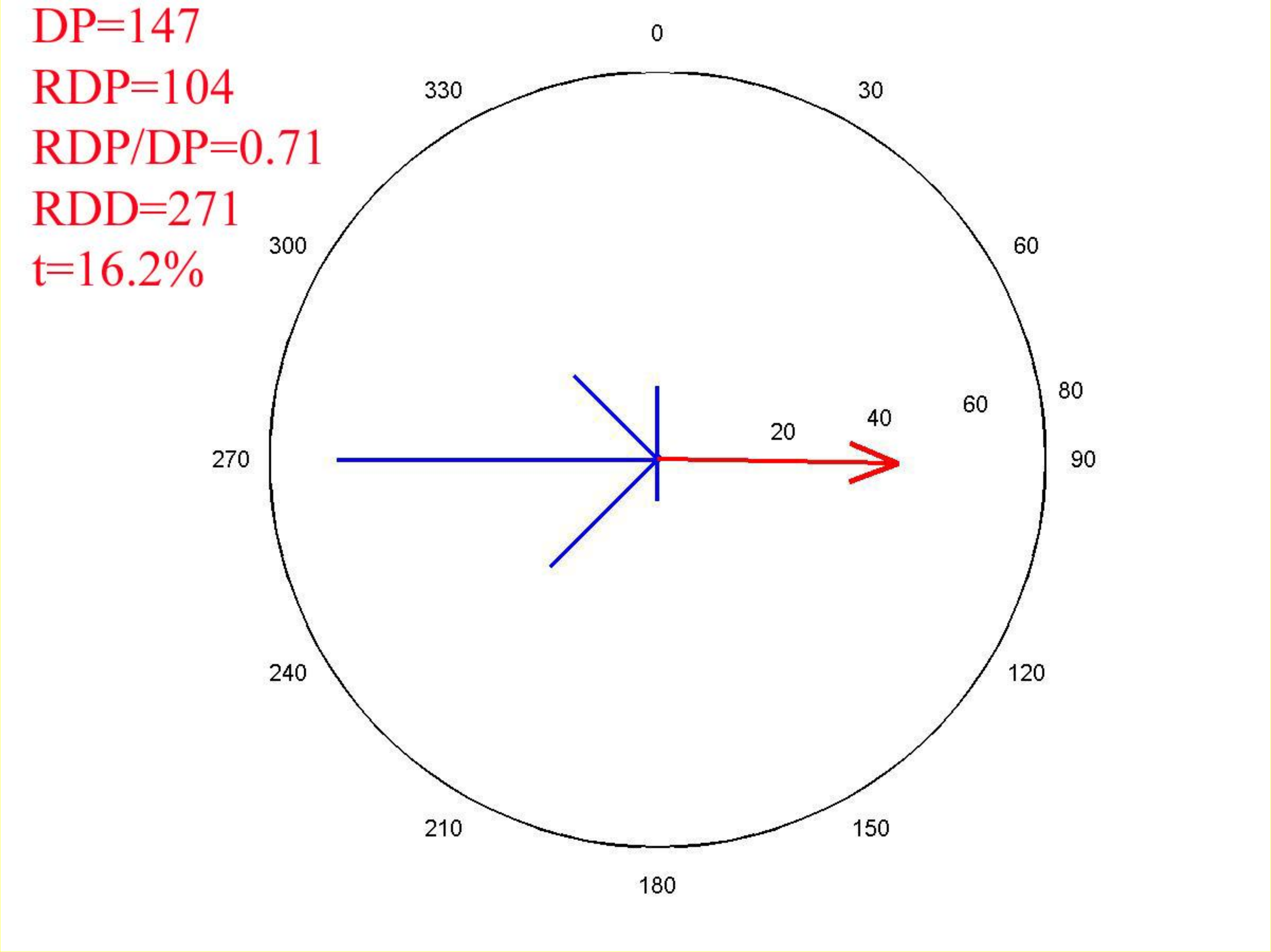
Ashdod, Israel 2001

Ashdod, Israel 2001

Ashdod, Israel 2004

Kraansvlak (The Netherlands)


300 m



DP=147

RDP=104

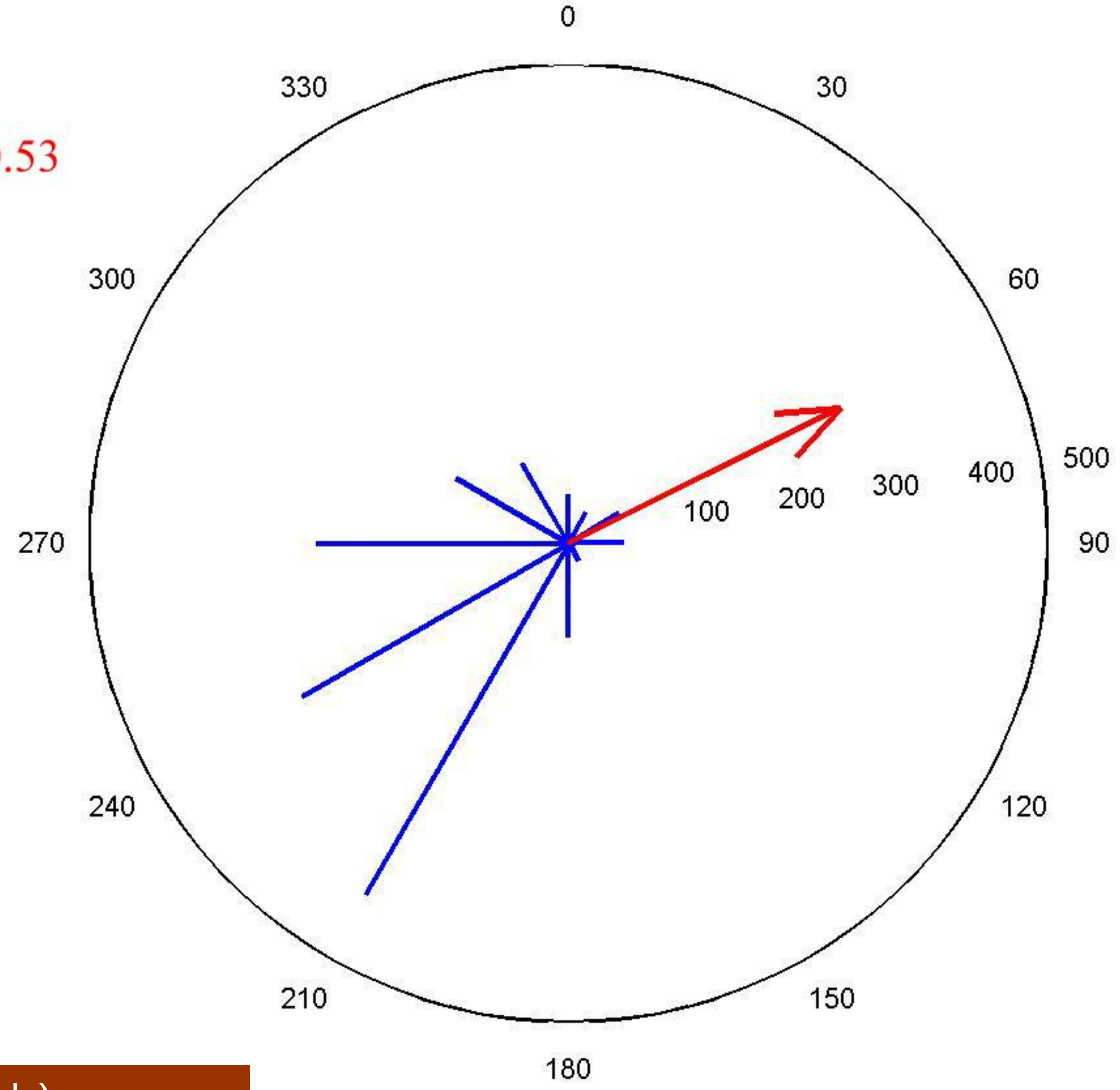
RDP/DP=0.71

RDD=271

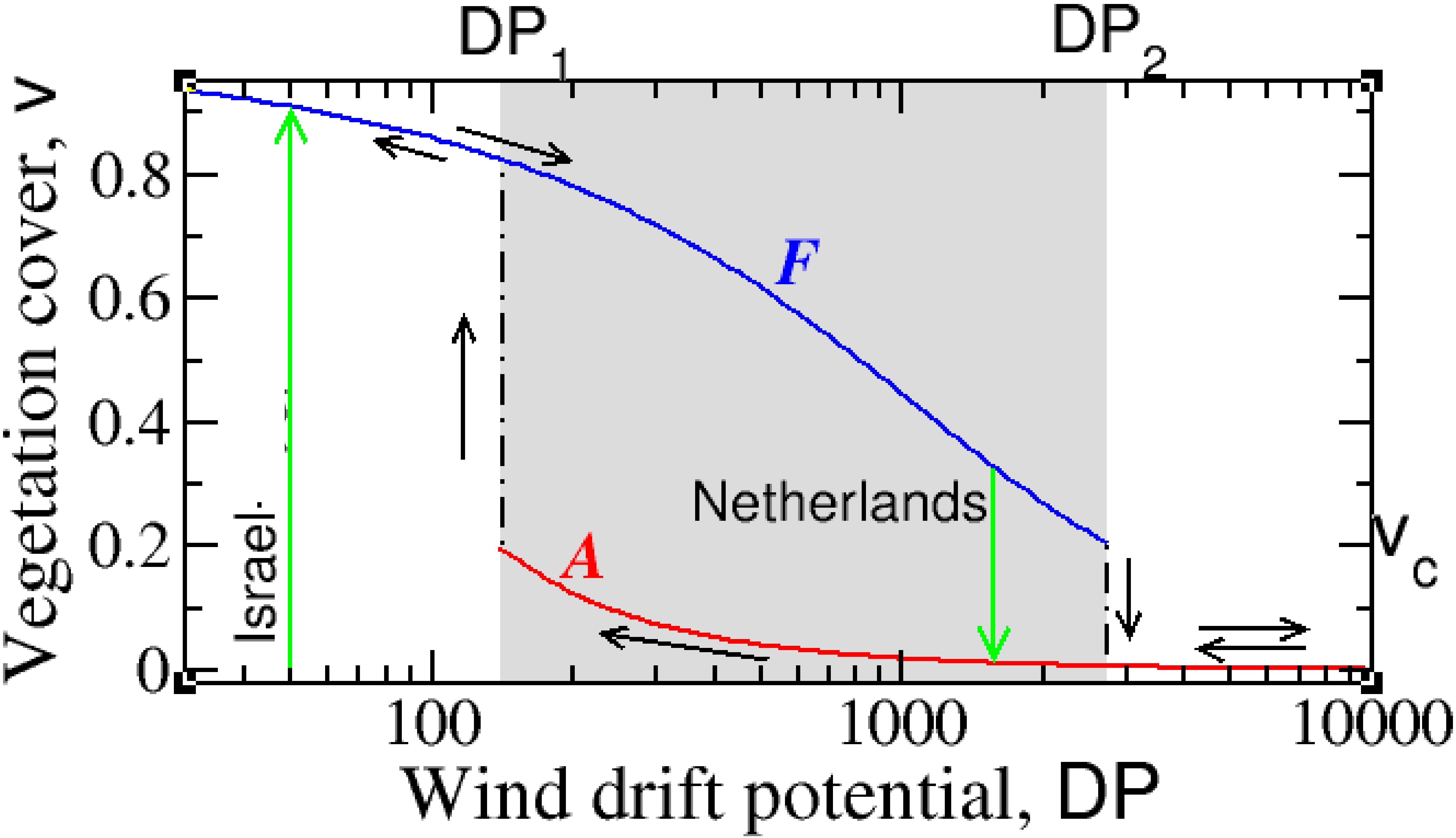
t=16.2%

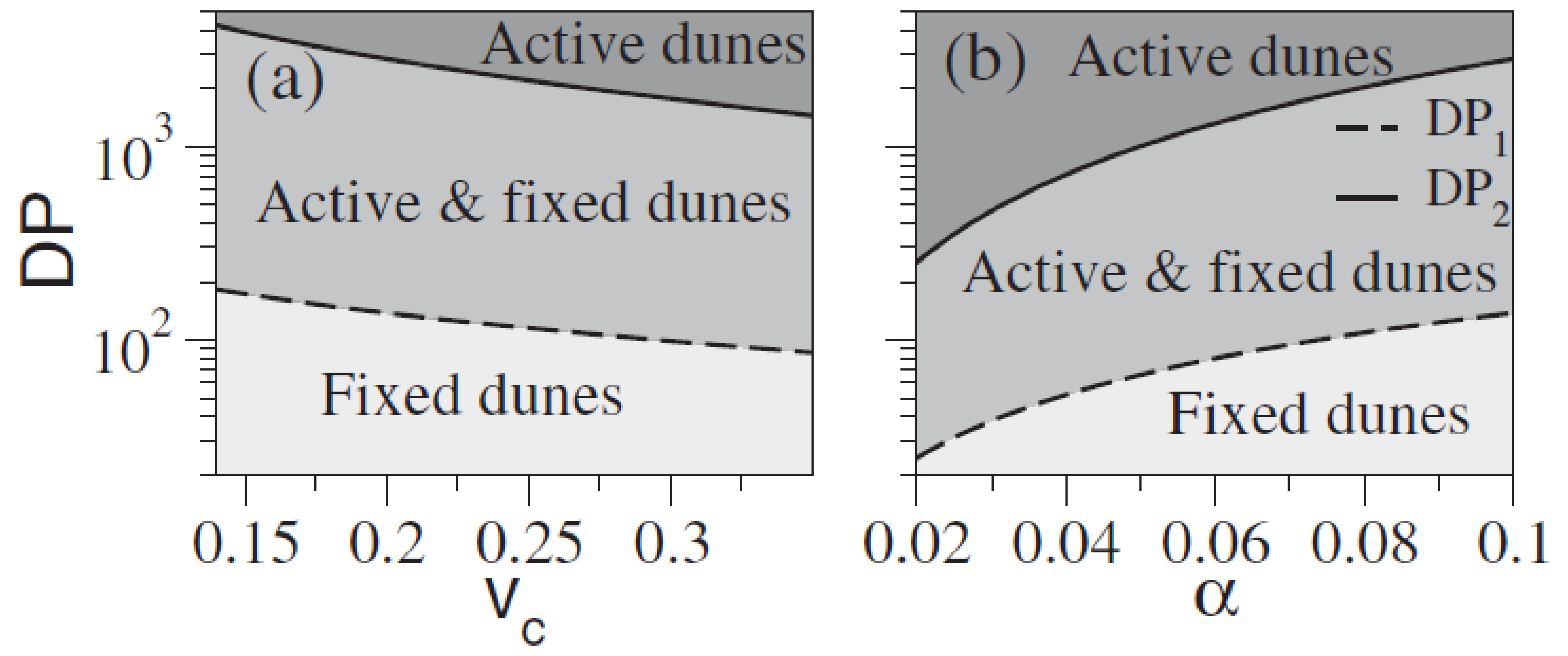
Ashdod

DP=1570
RDP=837
RDP/DP=0.53
RDD=244
t=53.86%

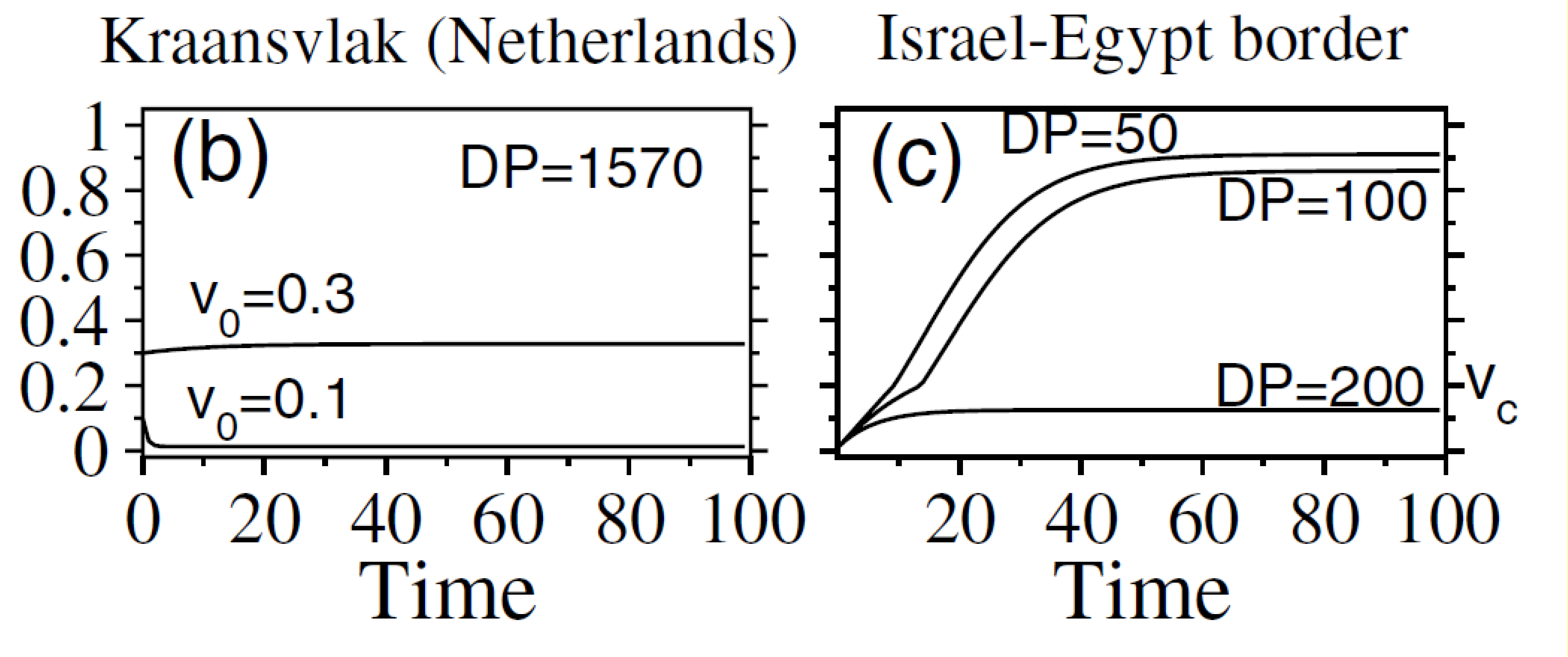


Kraansvlak (The Netherlands)


DP1
DP2
Vegetation cover, V
0.8
0.6
0.4
0.2
0
F
A
Netherlands
Israel
V
c
100
1000
10000
Wind drift potential, DP



(a) Active to fixed dune transition point and fixed to active dunes transition as a function of critical vegetation cover *Vc*. The various gray shadings represent different stability regimes. As *Vc* increases, the fix-active and active-fix dune transitions occur for weaker winds (low DP) (b) Same as (a), but for different growth rates α. As α decreases, fix-active and active-fix dune transitions occur for weaker winds (low DP), suggesting that drought conditions are more favorable for transitions from fixed to mobile dune states (desertification process).



(b) An example of transition from a fixed dune to an active dune state (the Netherlands case). Time evolution (in arbitrary time units) of vegetation cover *v* for DP=1570 for different initial conditions (*v*=0.3 and *v*=0.1). The upper curve converges into the fixed dune *F* state, while the lower curve (that is associated with large disturbance) converges into the active dune *A* state. (c) Same as b, but for different DP values, (Israel-Egypt border case), starting from *v*=0.01. For DP=50 and DP=100, the asymptotic state is the fixed dune state *F*, whereas for DP=200, it is the active dune state *A*.