Coastal Dunes

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UAlg UNIVERSIDADE DO ALGARVE
AR NET AQUATIC RESEARCH NETwork
CiMA Centre for Marine and Environmental Research
Universidad Católica de Valencia San Vicente Mártir
EU CONEXUS European University for Smart Urban Coastal Sustainability

Outline

1. Types and relevance of (coastal) dunes

2. The basics of dune formation: aeolian processes

3. The basics of dune evolution

4. Human interference

Relevance of coastal dunes

Why do we care about coastal dunes?

Protective barrier

Coastal protection against storm surge and high waves, preventing coastal flooding and structural damage

Biodiversity

Provide important ecological habitats

Leisure



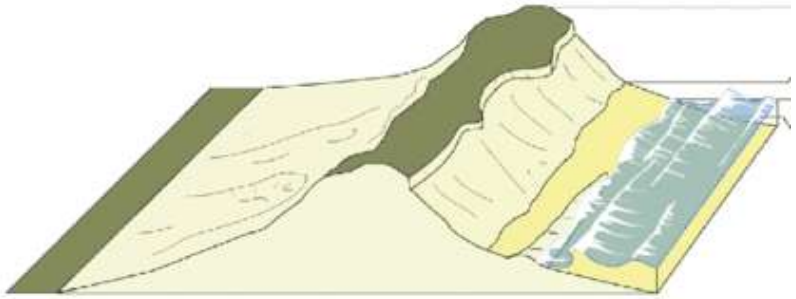


Relevance of coastal dunes

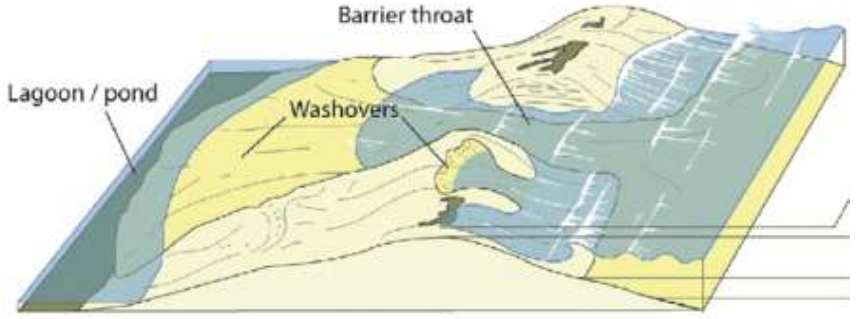
Why do we care about coastal dunes?

Coastal dunes are the first line of defence wave attack

SWASH REGIME



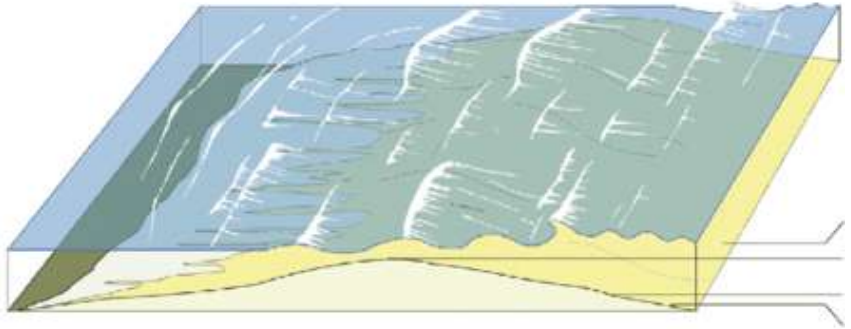
OVERWASH REGIME



COLLISION REGIME



INUNDATION REGIME

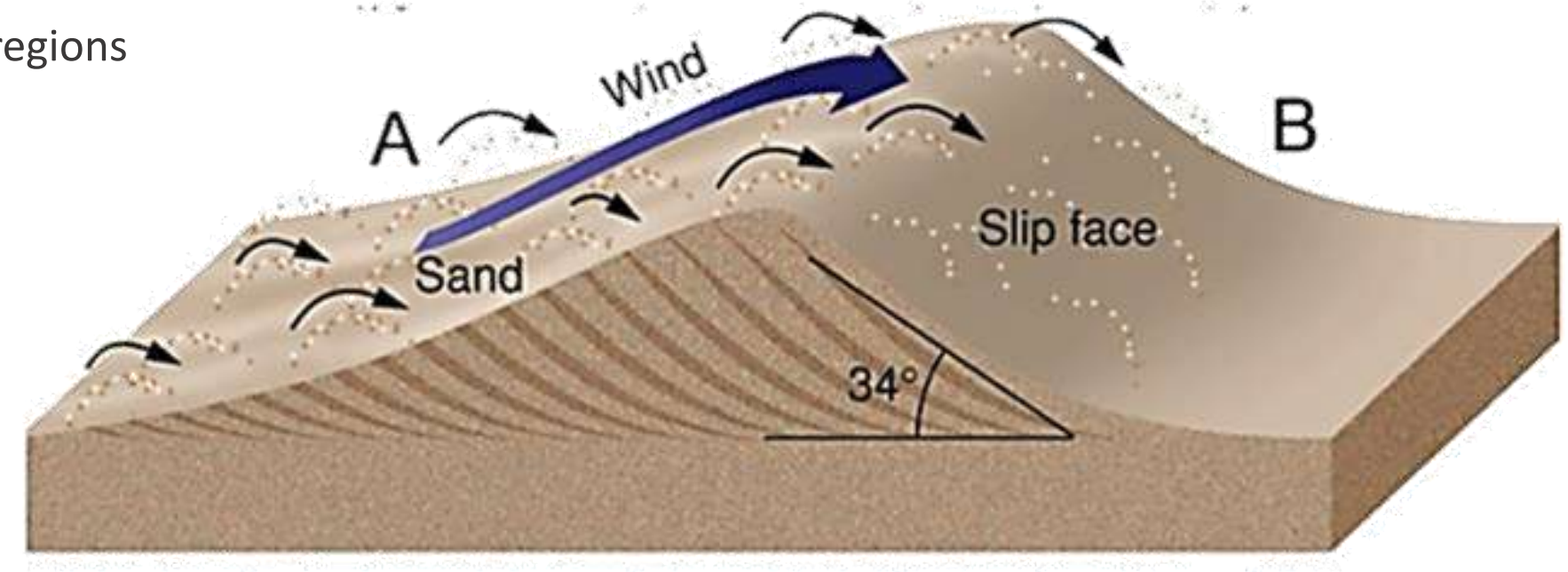


Storm impact regimes by Sallenger (2000), from Goslin and Clemmensen (2017).

Relevance of coastal dunes

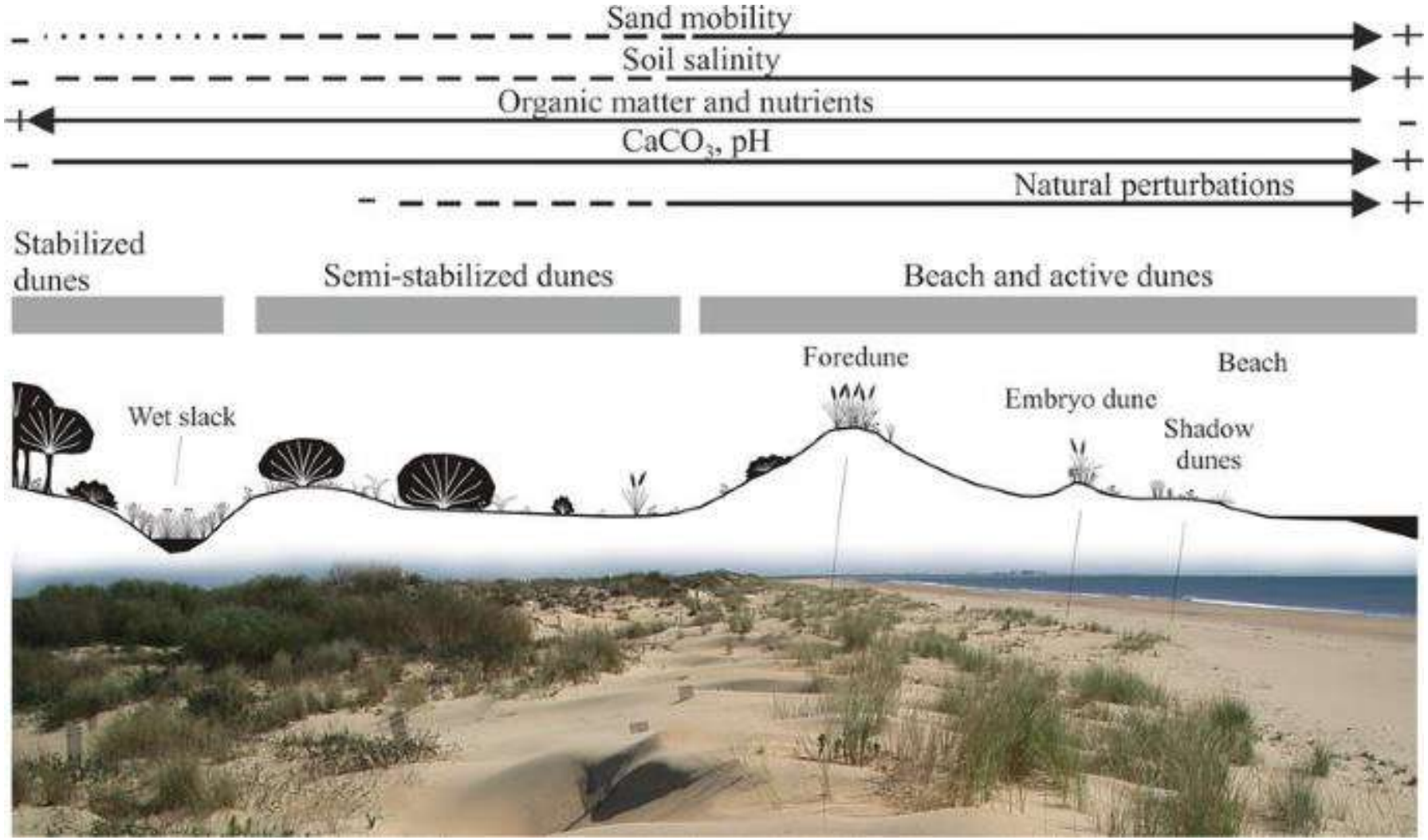
What is a dune?

- Mounds of loose sand accumulated by wind
- Are found in all continentes and climates
- Cover approximately 20% world surface
- 99% are located in arid regions



Relevance of coastal dunes

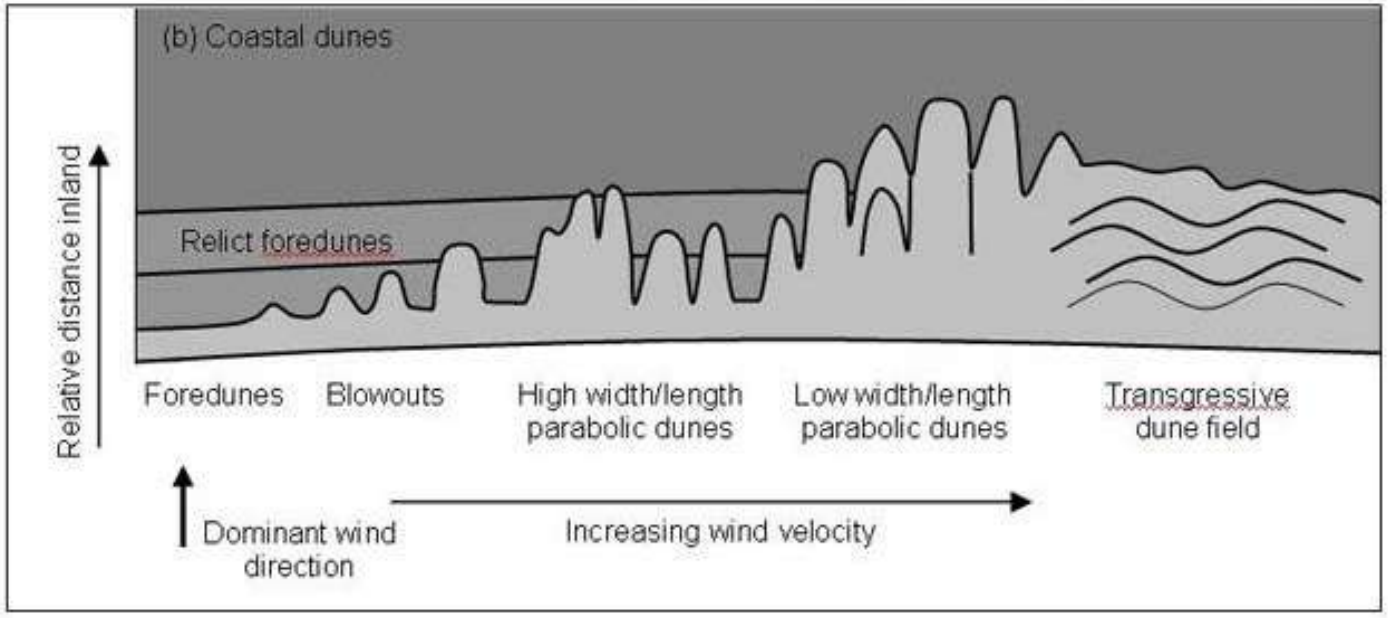
Main environmental gradients on coastal dunes

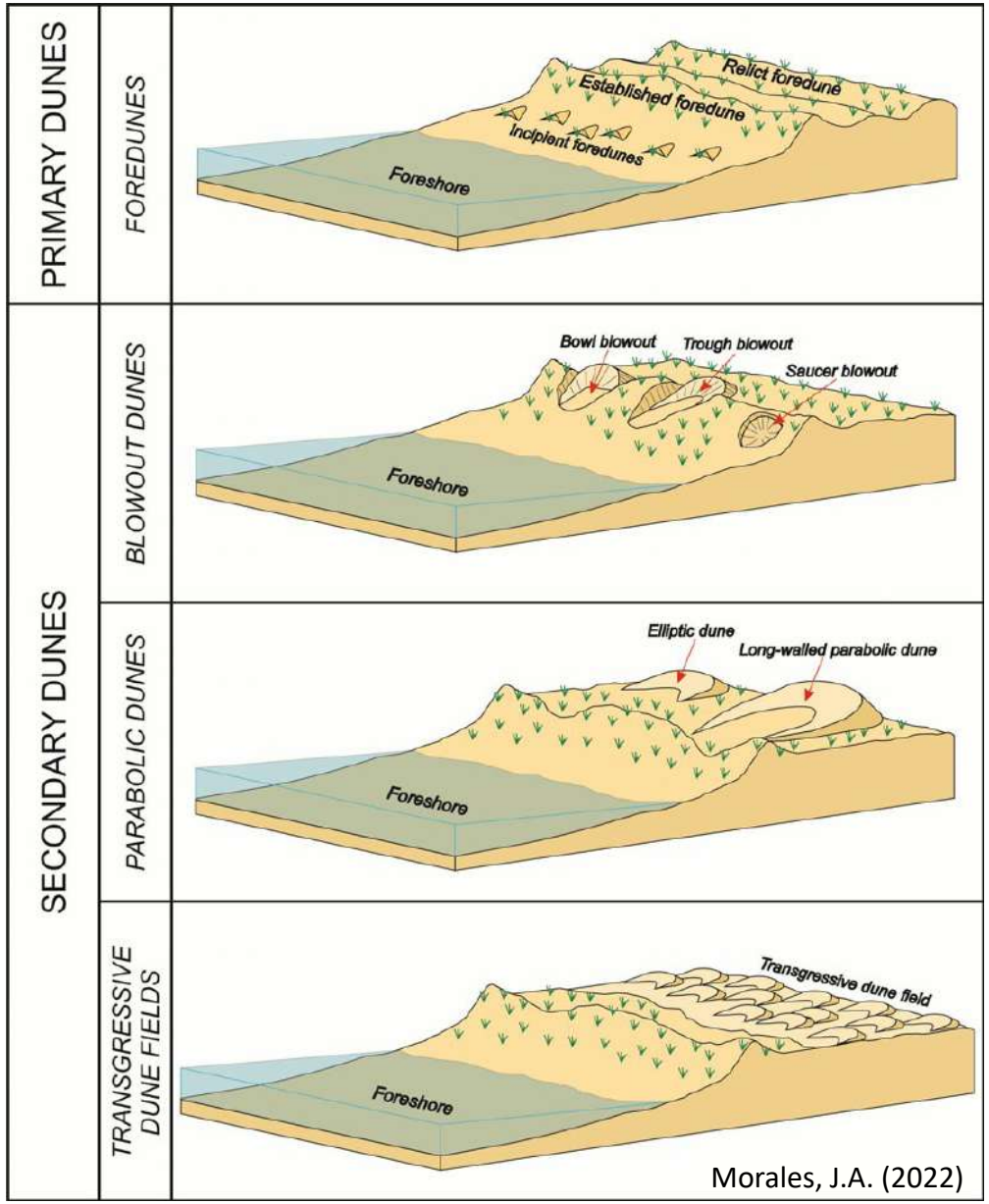


Muñoz-Vallés, S., Cambrollé, J. (2015)

Types of coastal dunes

Coastal dune types as a function of the **migration direction**



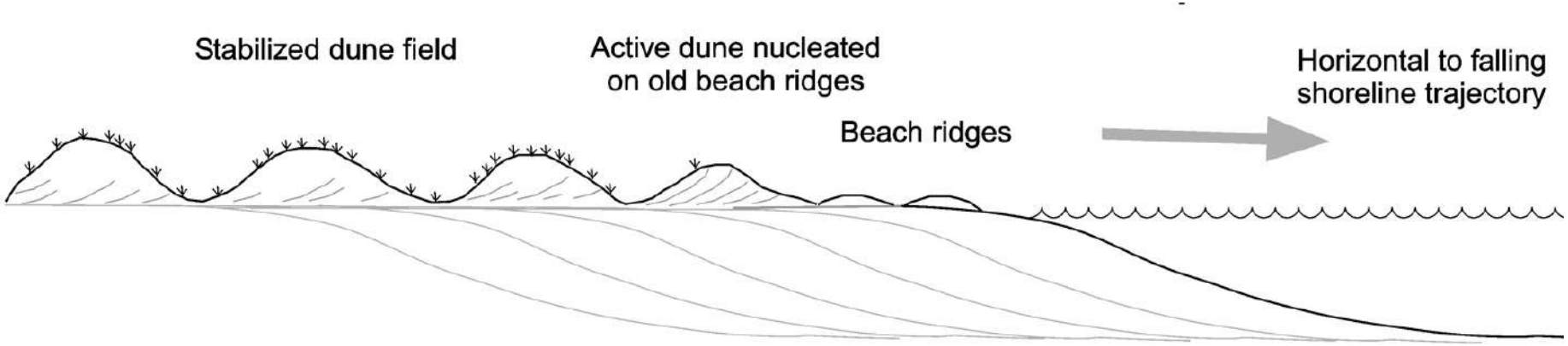


Morales, J.A. (2022)

Types of coastal dunes

Coastal dune types as a function of **migration direction**

❖ **Primary or regressive dunes – Foredunes**



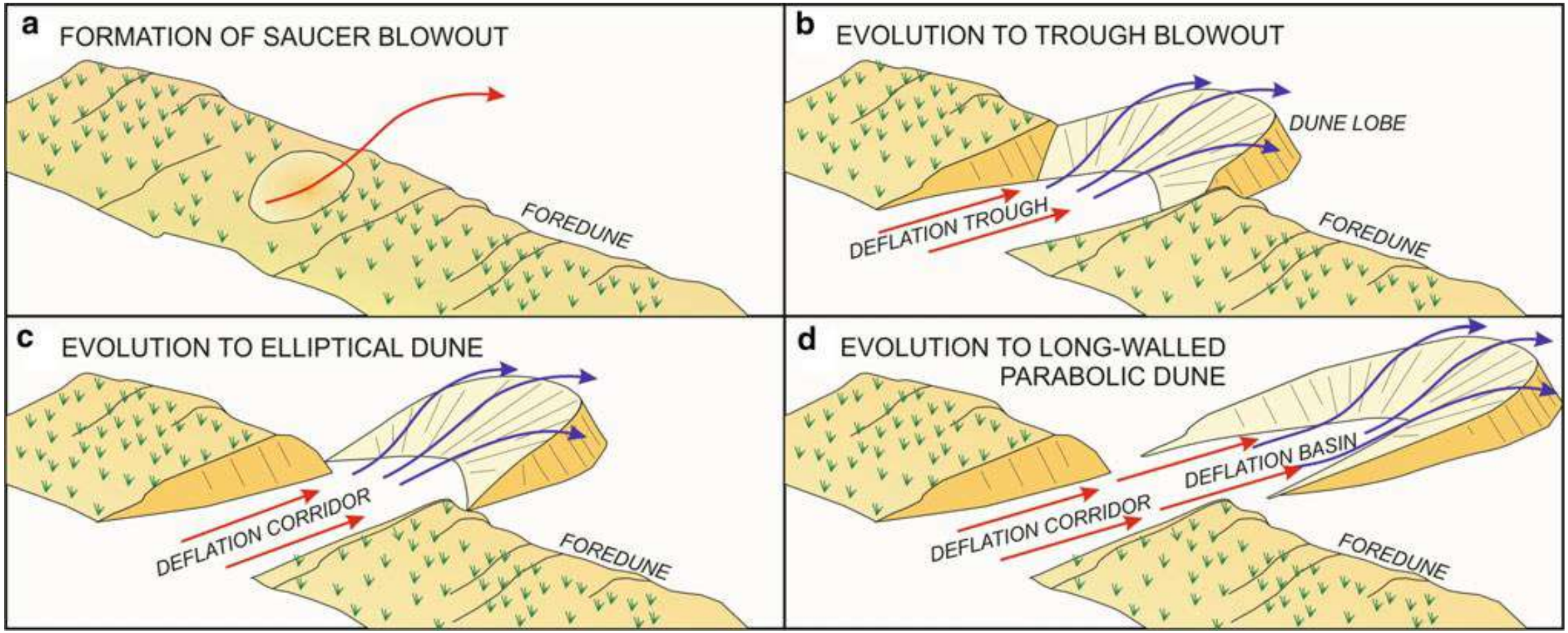




Types of coastal dunes

Coastal dune types as a function of **migration direction**

❖ Blowouts and parabolic dunes

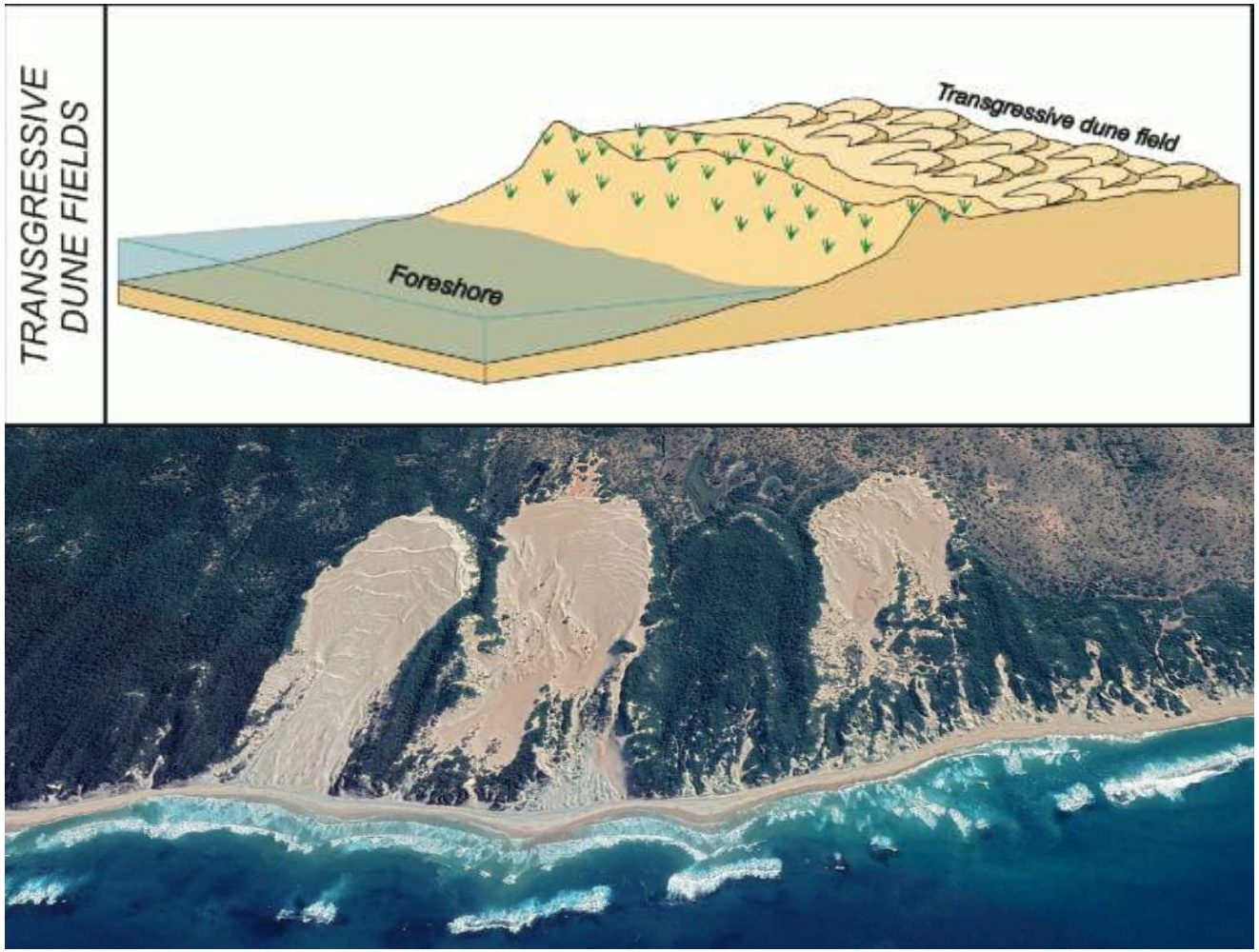


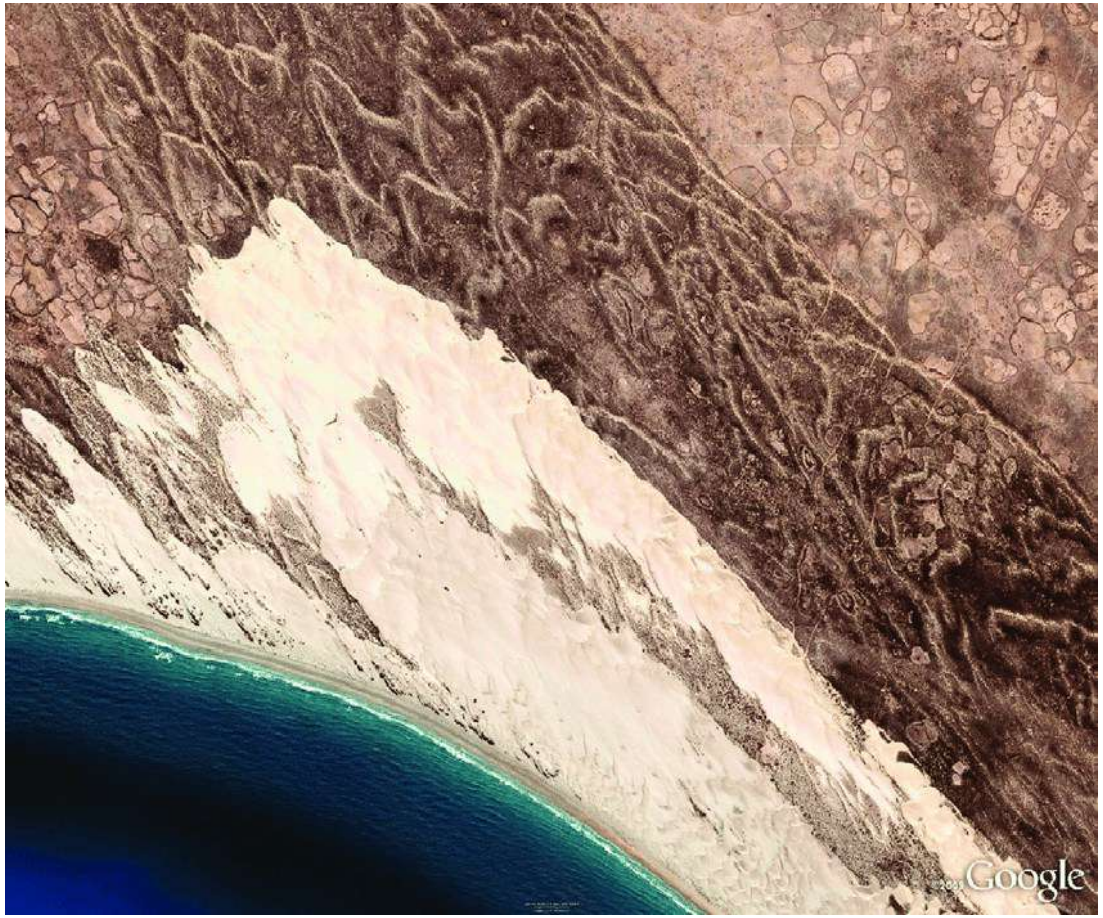
Morales, J.A. (2022)

Types of coastal dunes

Coastal dune types as a function of **migration direction**

❖ **Transgressive dunefield**





Types of coastal dunes

Coastal dune types as a function of **vegetation cover and mobility**



Mixed system:

- Parts are fully vegetated and fixed
- Parts are partly vegetated and active



- Partially vegetated and mobile

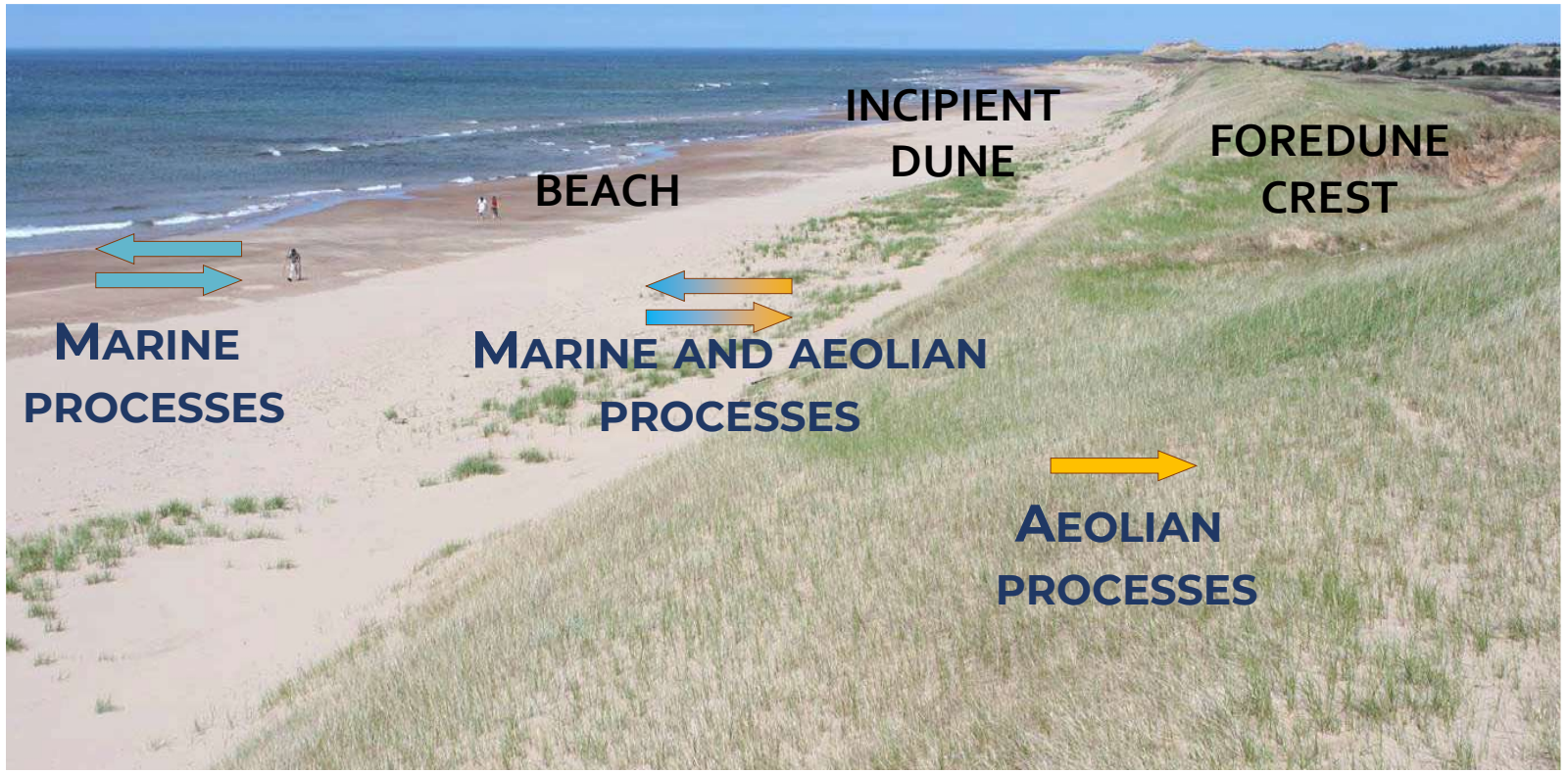


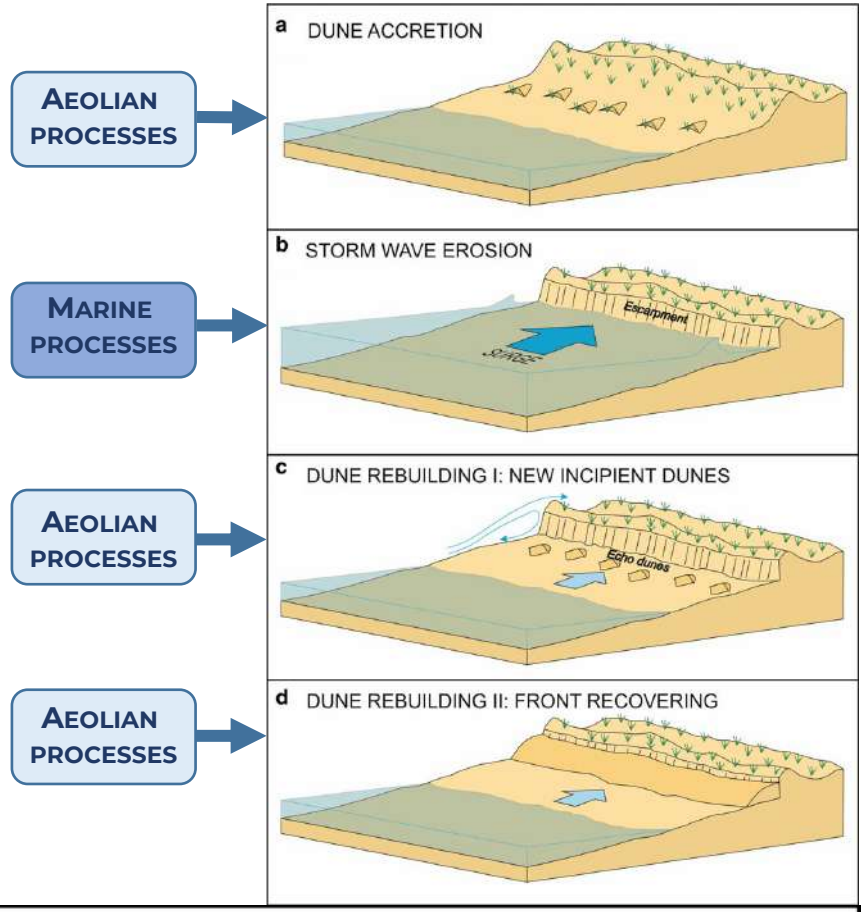
- Free of vegetation and active

Dune formation

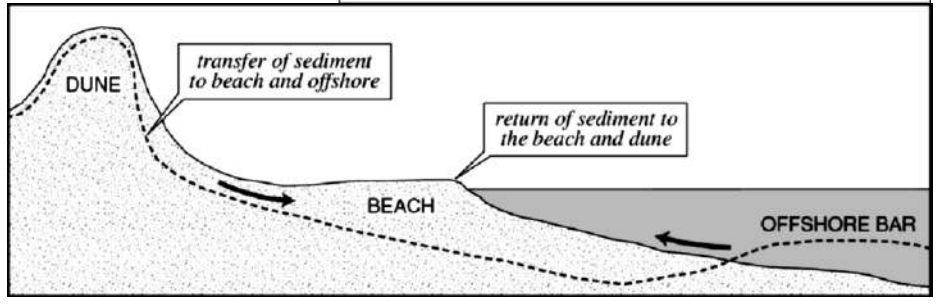
Dune formation

Beach-dune interaction elements and processes





- Dunes are very important elements in low-lying sandy coasts.
- They are part of the coupled beach-dune system.
- **They form through the accumulation of sand transported from the beach by winds and trapped by physical barriers such as vegetation.**



Dune formation

Beach-dune interaction elements and processes



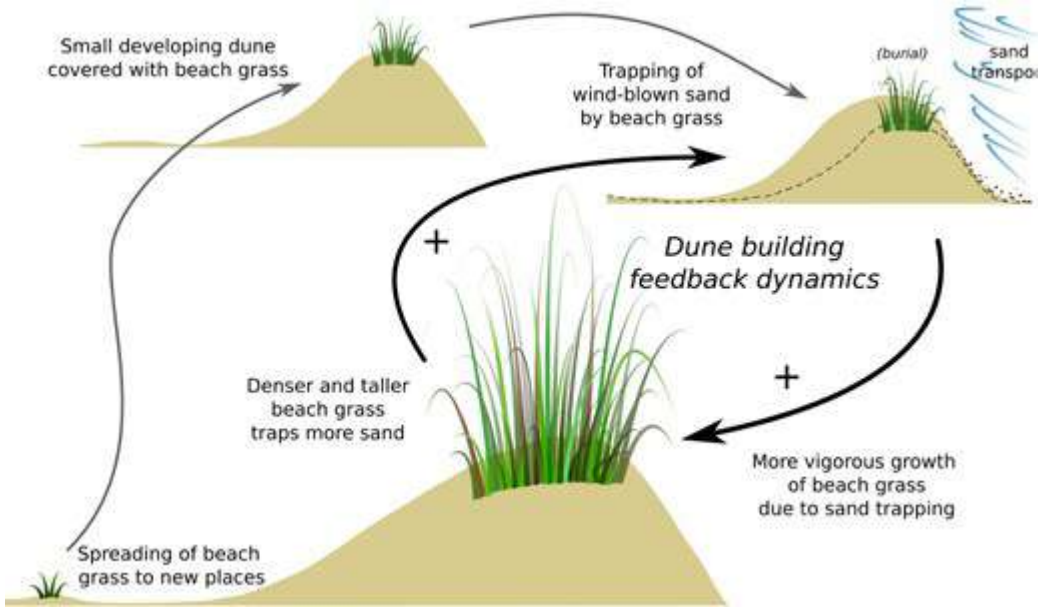
The basic conditions:

- occurrence of strong onshore winds (**transport limiting condition**);
- available supply of beach sediments (**supply limiting condition**);
- sufficient fetch for the transport of sediment from the backshore to the dune (**supply limiting condition**);
- vegetation (seeds) to capture the sediment (**supply limiting condition**).

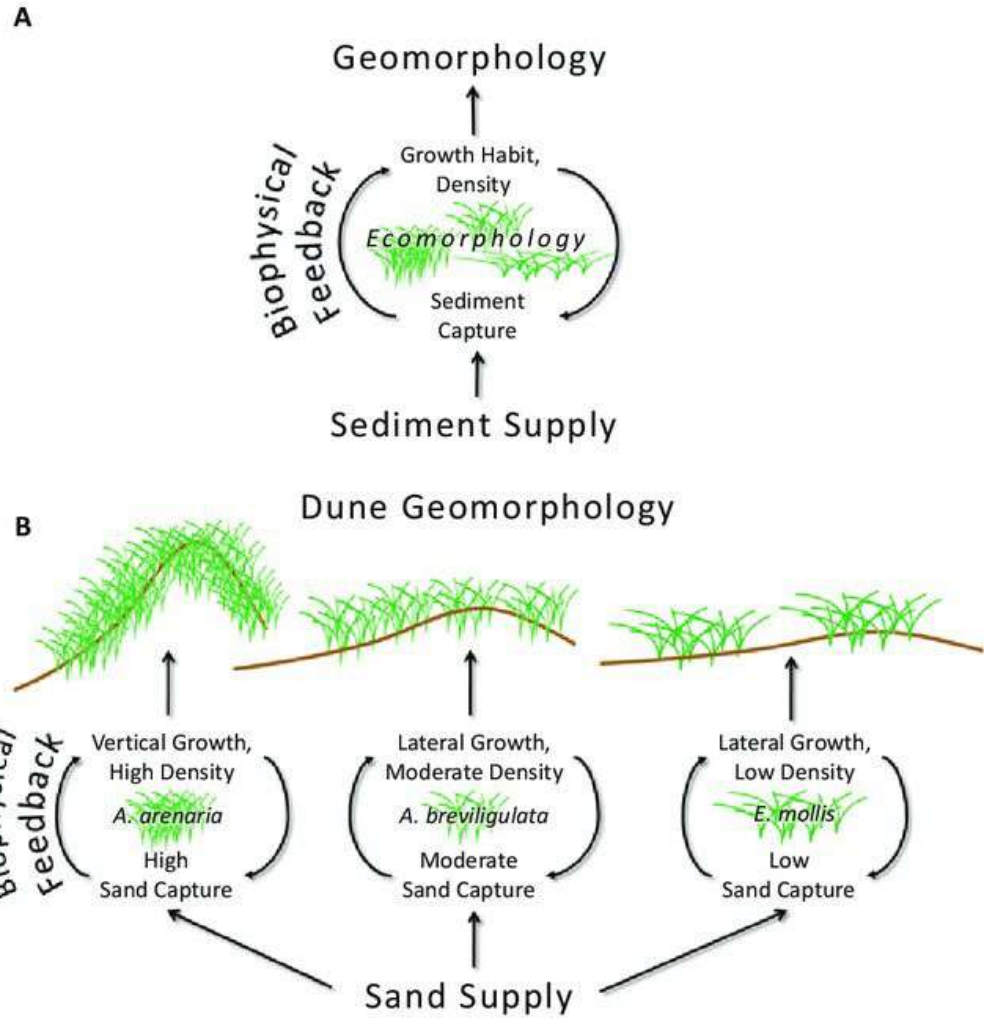
Dune formation

Coastal dunes and vegetation

Biophysical feedback between vegetation and sediment in coastal foredune systems.

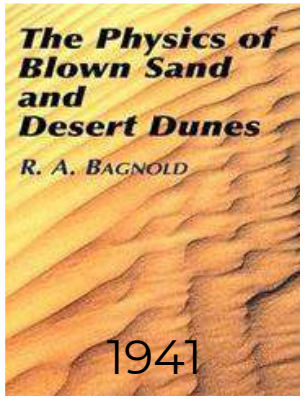


Luijendijk et al. (2019)



Ruggiero et al. (2018)

Dune formation



Aeolian processes

- The field remains grounded in the classical work of Ralph A. Bagnold, especially with regard to the transport of sand
- Wind transport mechanics are addressed from:

  a) **transport limited perspective**: transport is a function of wind speed and sediment properties; incorporates velocity threshold

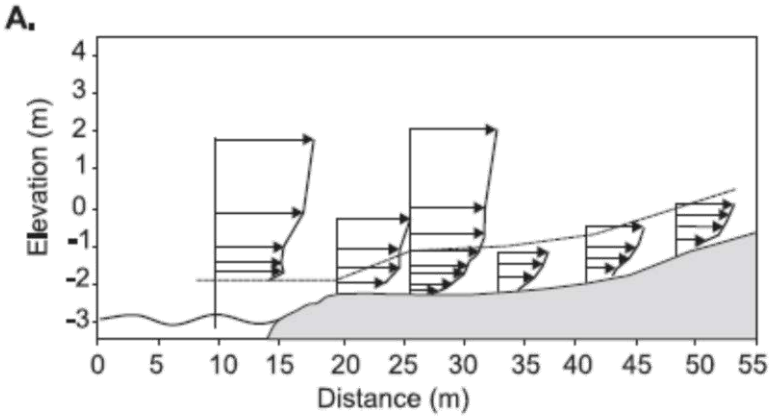
  b) **supply limited perspective**: ability of the surface to supply grains to the air stream, often resulting in lower total transport rates than would be predicted given wind speed; incorporates surficial factors (e.g., surface crusts, vegetation, surface moisture, fetch)

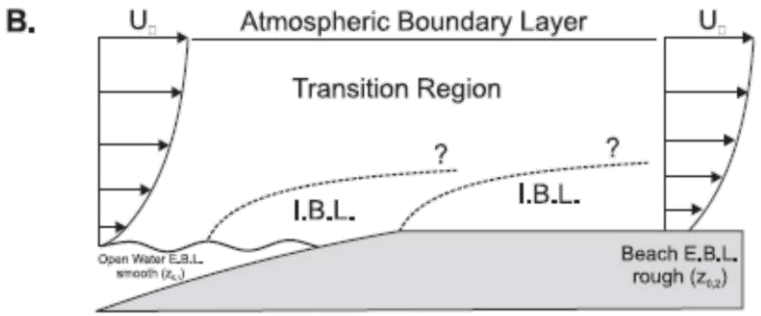
Dune formation

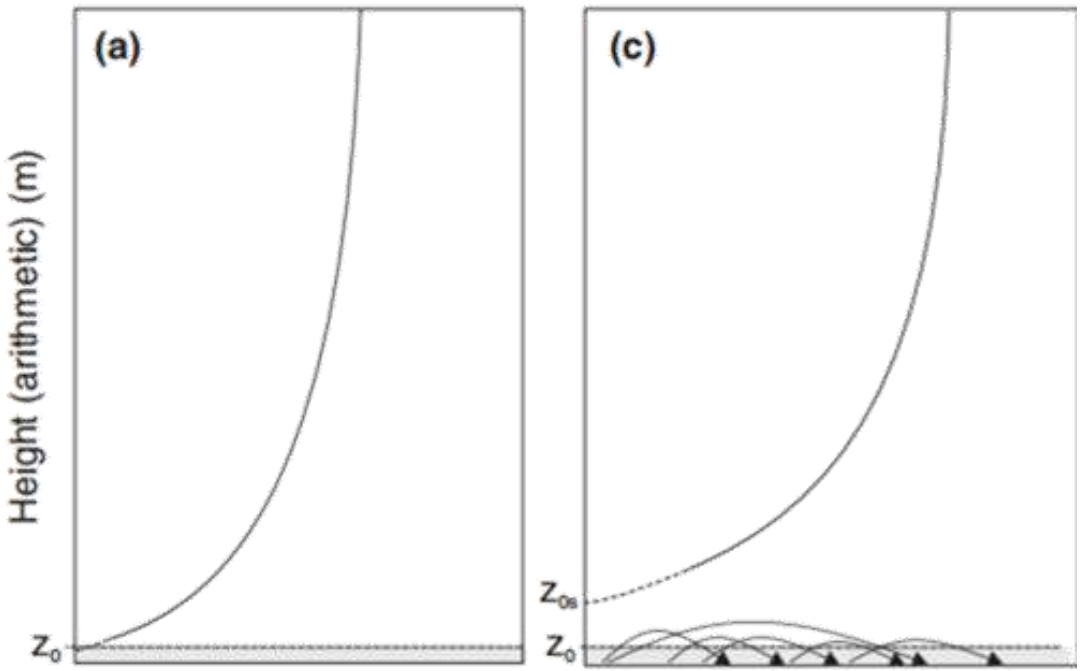
Aeolian processes

The horizontal wind speed near the bed is retarded giving rise to a distinctive log-linear change in wind speed with height. The velocity profile above the viscous sublayer for aerodynamically rough surfaces is characterized by the Prandtl–von Karman equation:

Law of the Wall: $\frac{u}{u_*} = \left(\frac{1}{k}\right) log_{10}(z/z_0)$





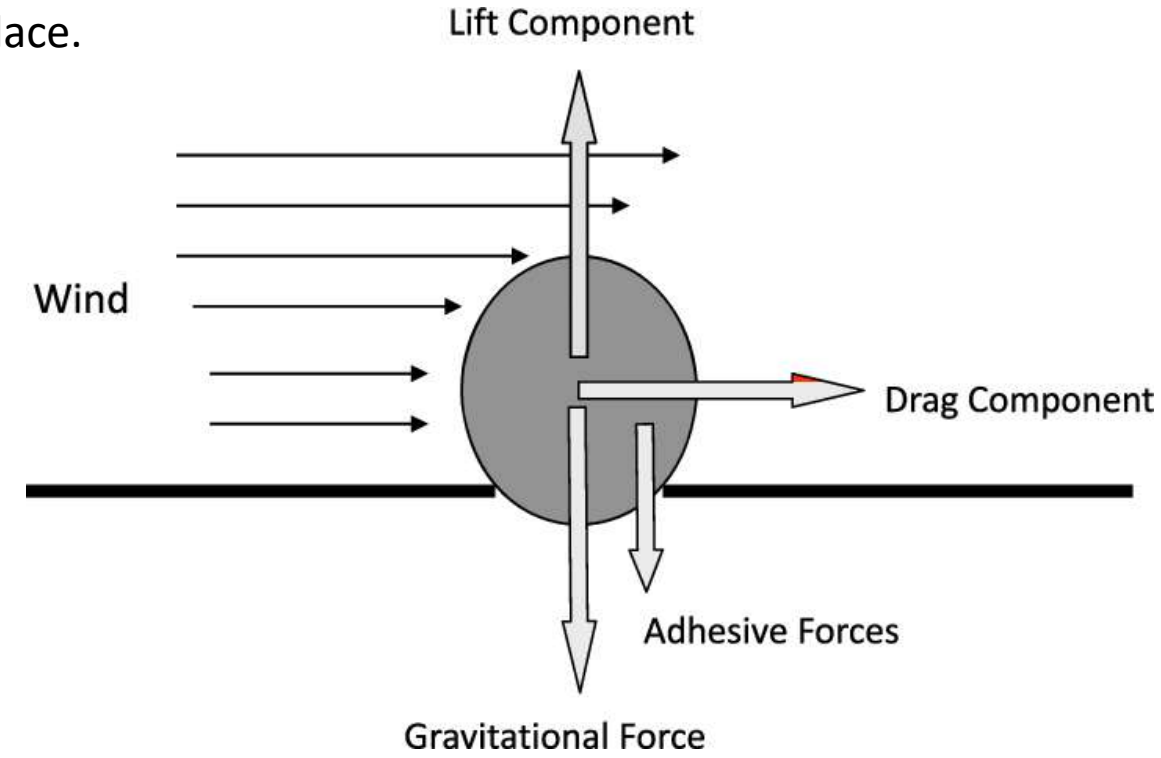


Dune formation

Aeolian processes – transport limiting conditions

Wind blowing over a sand surface will initiate sediment transport when the forces acting on an individual grain overcome the gravitational and frictional forces holding the grain in place.

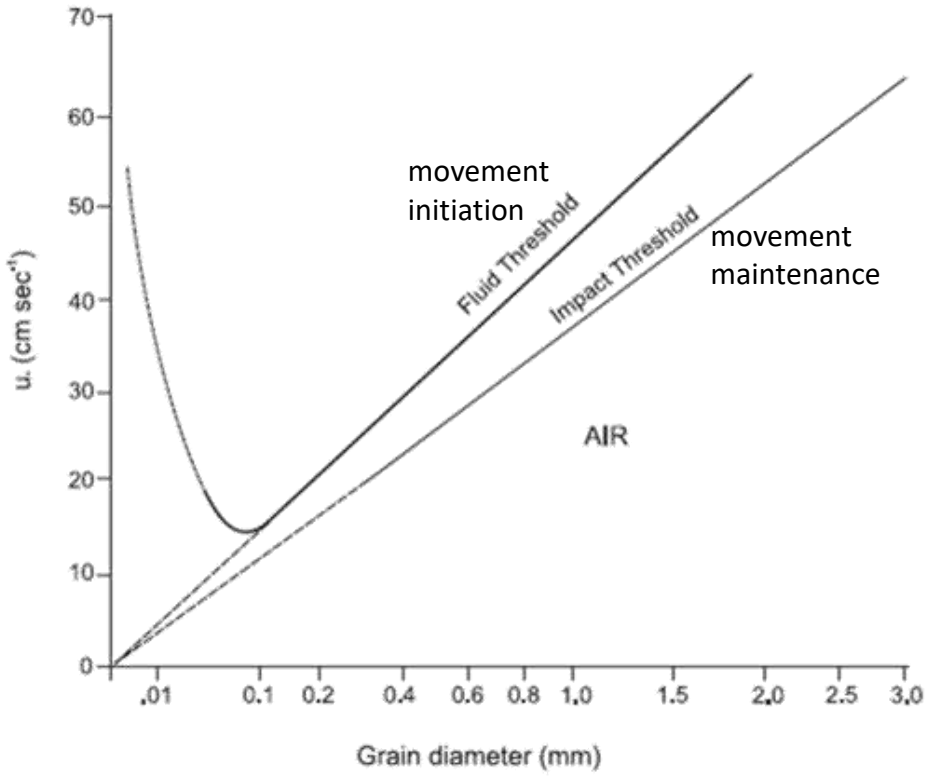
Forces acting on a particle on the bed:



Dune formation

Aeolian processes – transport limiting conditions

Wind blowing over a sand surface will initiate sediment transport when the forces acting on an individual grain overcome the gravitational and frictional forces holding the grain in place.



Thresholds and initiation of sand transport for dry sand:

Bagnold (1941)

$$u_{*t} = A\sqrt{\left(\frac{\rho s - \rho a}{\rho a} g d\right)}$$

A = empirical parameter
(0.085 assuming active saltation)

d = grain diameter
ρs = sediment density
ρa = fluid density (air)

Condition for sediment transport (transport limiting factor):

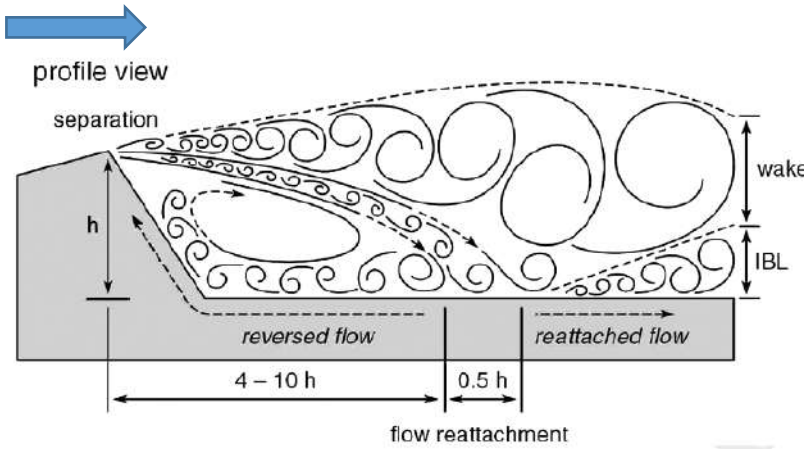
$$u_{*t} < u_*$$

u_*: friction velocity (m s^{-1})

Dune formation

Aeolian processes – transport limiting conditions

Changes in the airflow induced by topography

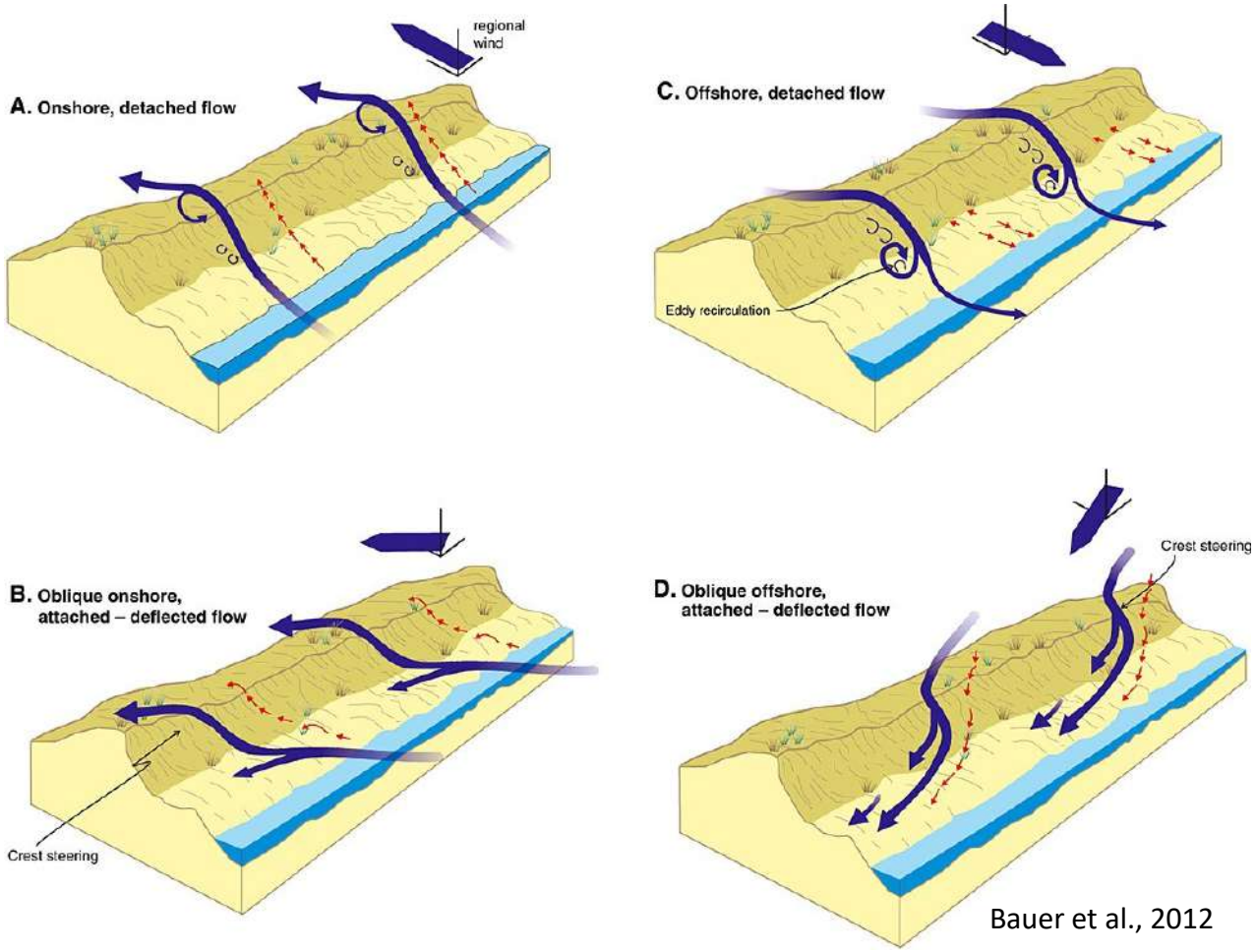


Conceptual model of flow zonation in the lee of large dunes

Walker and Nickling, 2002

Which wind conditions may enhance sediment transport to the dune?

Flow-form interactions over large (> 8 m) foredunes for variable wind approach directions.



Bauer et al., 2012

Dune formation

Aeolian processes – examples of supply limiting conditions

Transport rate is reduced because the supply of sand to the wind stream is limited by surface complexities: **Moisture, Crusting, Particle characteristics, Slope, Fetch distances, Pebble lag development, Vegetation**, etc.

$$u_{*t} = f_{u_{*t},d} \cdot f_{u_{*t},M} \cdot f_{u_{*t},\theta} \cdot f_{u_{*t},p} \cdot f_{u_{*t},veg}$$

Additional factors interfere aeolian sediment transport at coastal zones – highly complex systems

Dune formation

Aeolian processes – supply limiting conditions

Transport rate is lower than for dry sand because the supply of sand to the wind stream is limited by surface complexities:

✓ Moisture

Effect of sediment moisture: increases u_{*t}

$$u_{*tM} = A\sqrt{\left(\frac{\rho s - \rho a}{\rho a} g d\right)} + 7.5m$$

(U_{*t})

$$m = \frac{p_v \rho_w}{\rho_s (1 - p)}$$ (Hotta et al., 1984)

p_v: *volumetric Water content (percent)*

p: *porosity*

Dune formation

Aeolian processes – supply limiting conditions

Transport rate is lower than for uniform sand because the supply of sand to the wind stream is limited by surface complexities:

✓ Sparse vegetation

Effect of vegetation: reduces u_*

$$u_{*veg} = u_*(1 - kC_{veg})$$ Buckley 1987

- K vegetation shape factor
- C_{veg} vegetation cover density

Promotes both sand accumulation and retention

$$u_{*,veg} = \frac{u_*}{\sqrt{(1 + \rho_v \Gamma)}}$$ Durán & Moore 2013

- ρ_v vegetation-cover fraction
- Γ vegetation shape parameter

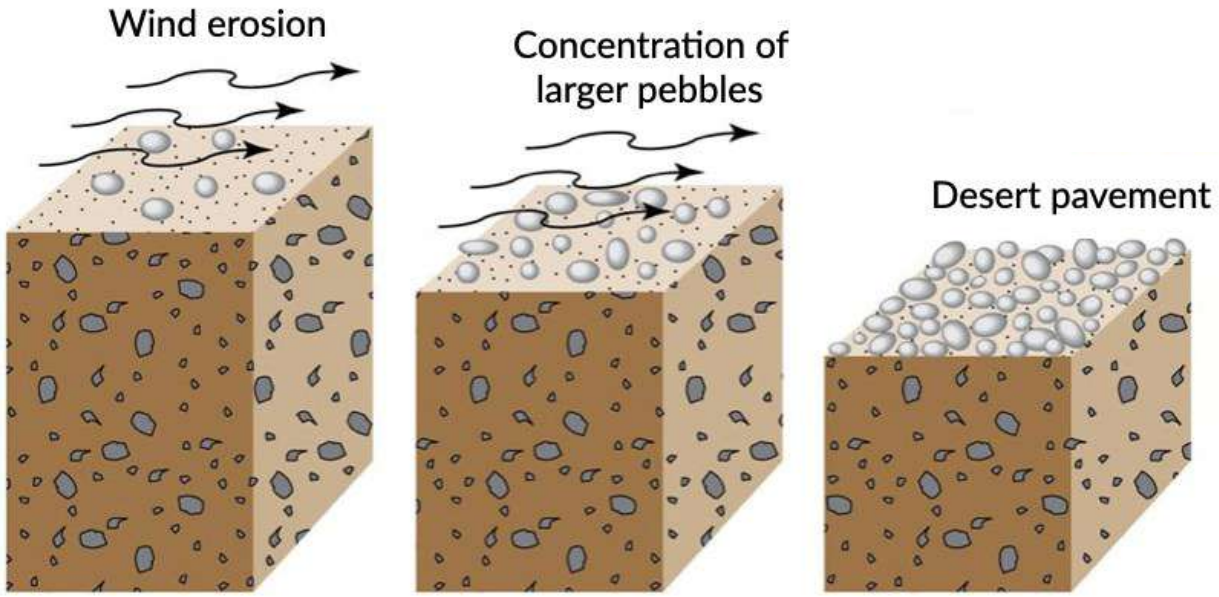
Dune formation

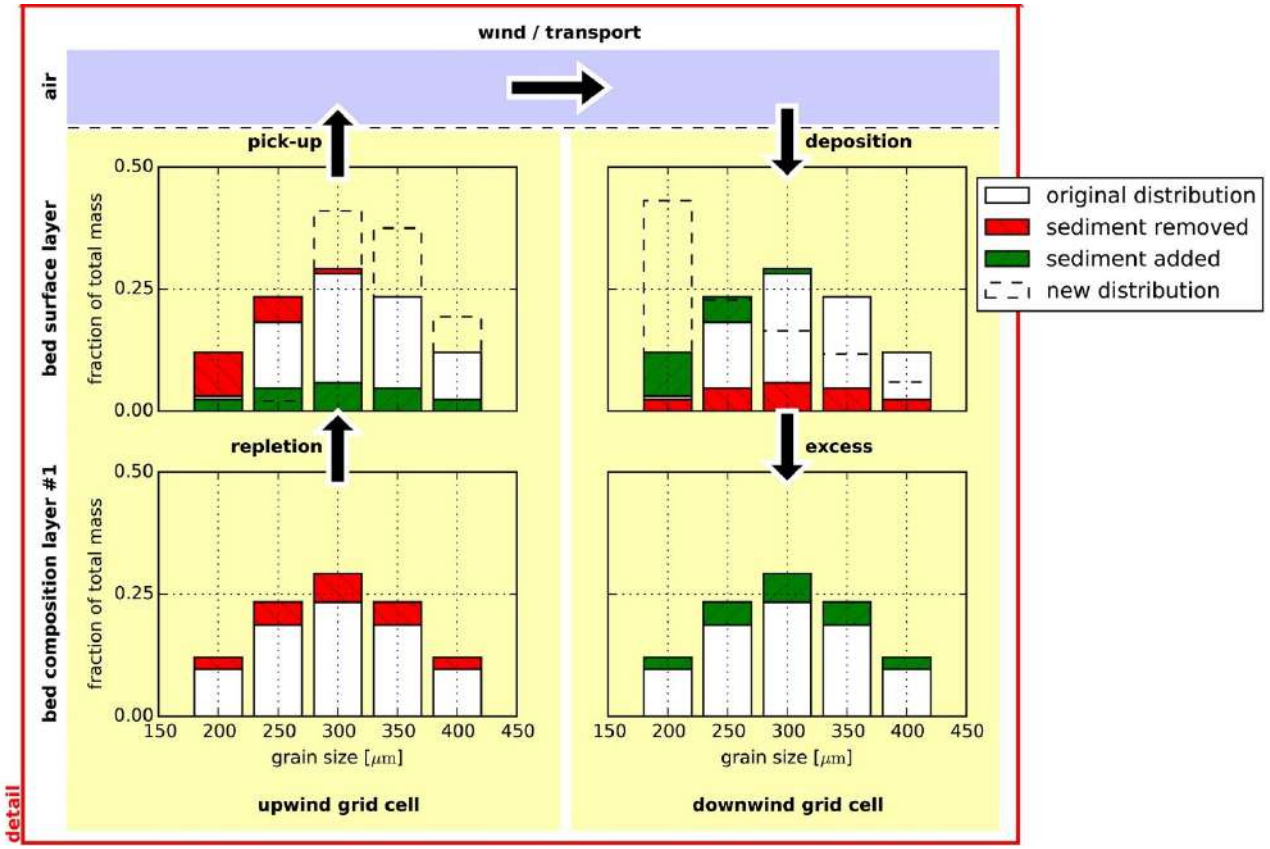
Aeolian processes – supply limiting conditions

Transport rate is lower than for uniform sand because the supply of sand to the wind stream is limited by surface complexities - beach armouring:

✓ Lag development

increases u_{*t} as grain size/density increases





Hoonhout and de Vries, 2016

Dune formation

Aeolian processes – sediment transport

Sediment transport empirical models - Instantaneous sediment transport rate

Table 17.3 Common mass transport rate expressions

Source	Dimensionless rate: $\frac{qg}{\rho u_*^3} =$
Bagnold (1941)	$C\sqrt{\frac{d}{D}}$ where C = 1.5 for uniform sand 1.8 naturally graded sand 2.8 poorly sorted sand 3.5 pebbly surface
Zingg (1953)	$C\sqrt[3]{\frac{d}{D}}, C = 0.83$
Owen (1964)	$\left(0.25 + 0.33\frac{u_{*t}}{u_*} \cdot \frac{U_F}{u_{*t}}\right)\left(1 - \left\{\frac{u_{*t}}{u_*}\right\}^2\right)$
Lettau and Lettau (1978)	$C\left(1 - \left\{\frac{u_{*t}}{u_*}\right\}\right), \mathrm{C} = 4.2$
Kawamura (1951); White (1979) Independently derived with varied values for C	$C\left(1 + \frac{u_{*t}}{u_*}\right)^2\left(1 - \frac{u_{*t}}{u_*}\right)$ where C = 2.78 (Kawamura) 2.61 (White)
Sørensen (2004)	$\left(1 - \left\{\frac{u_*}{u_{*t}}\right\}^{-2}\right)\left(\alpha + \beta\left\{\frac{u_*}{u_{*t}}\right\}^{-2} + \gamma\left\{\frac{u_*}{u_{*t}}\right\}^{-1}\right)$ where α, β and γ depend upon distributions of particle size and shape

Dune formation

Aeolian processes – sediment transport

Equilibrium transport

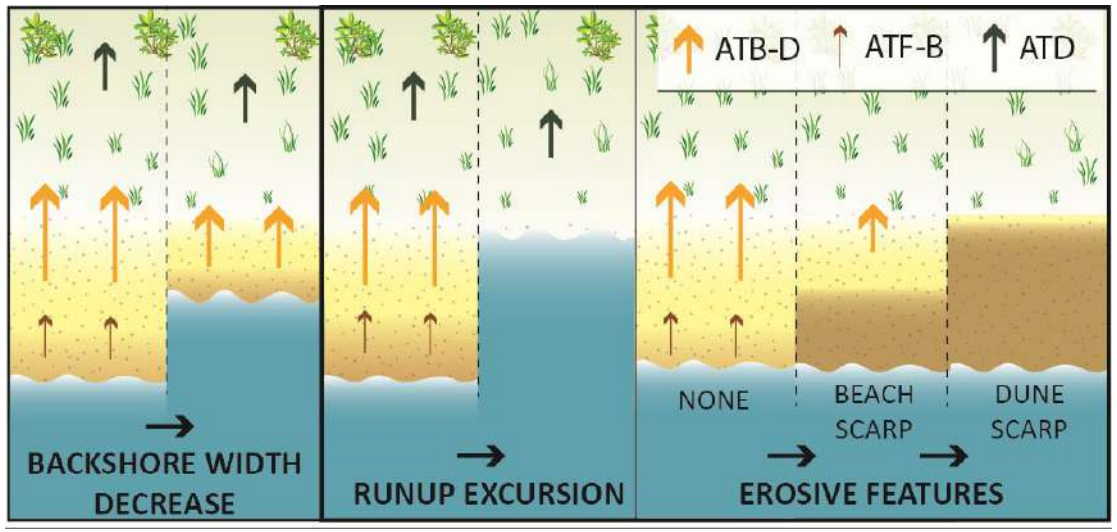
- The equations apply to conditions where there is an unlimited supply of loose, dry sand.
- There is a maximum transport capacity associated with a particular wind speed and this represents the equilibrium or transport-limited condition.

Dune formation

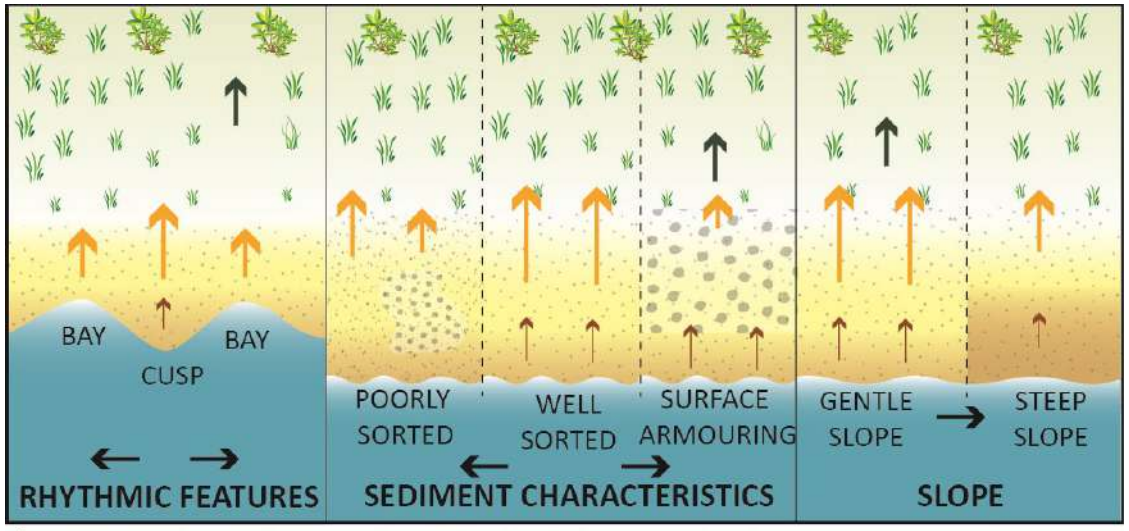
Aeolian processes – sediment transport

Equilibrium transport

- On natural beaches and coastal dune systems measured deposition over periods of months to years is generally much less than values predicted using the standard equilibrium equations – <u>effects of factors limiting entrainment and supply</u>



(Costas et al. 2020)



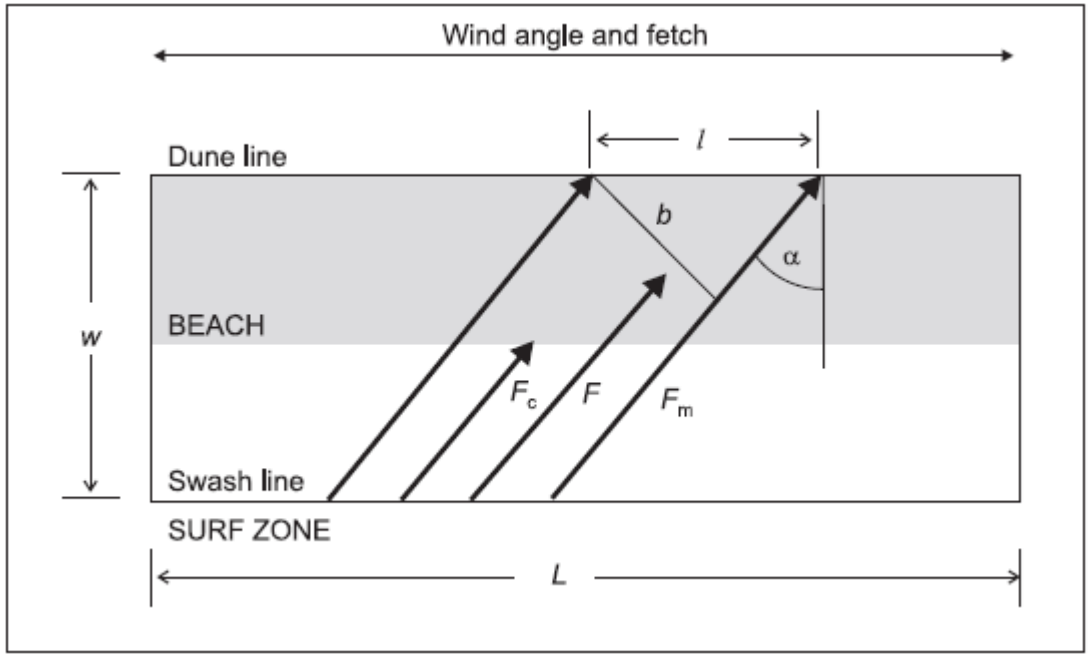
*ATB-D sand transference from the backshore to the dune
ATF-B sand transference from the beachface to the backshore
ATD movement of sand within the dune because of the lack of fixing

Dune formation

Aeolian processes – sediment transport

Equilibrium transport

- **Fetch effect**: under optimal conditions, the number of saltating particles increases exponentially to a maximum value (Bauer and Davidson-Arnott, 2003), indicative of the saturation of the sediment.
- The distance at which transport becomes saturated is known as the **Critical Fetch Distance** (F_c).



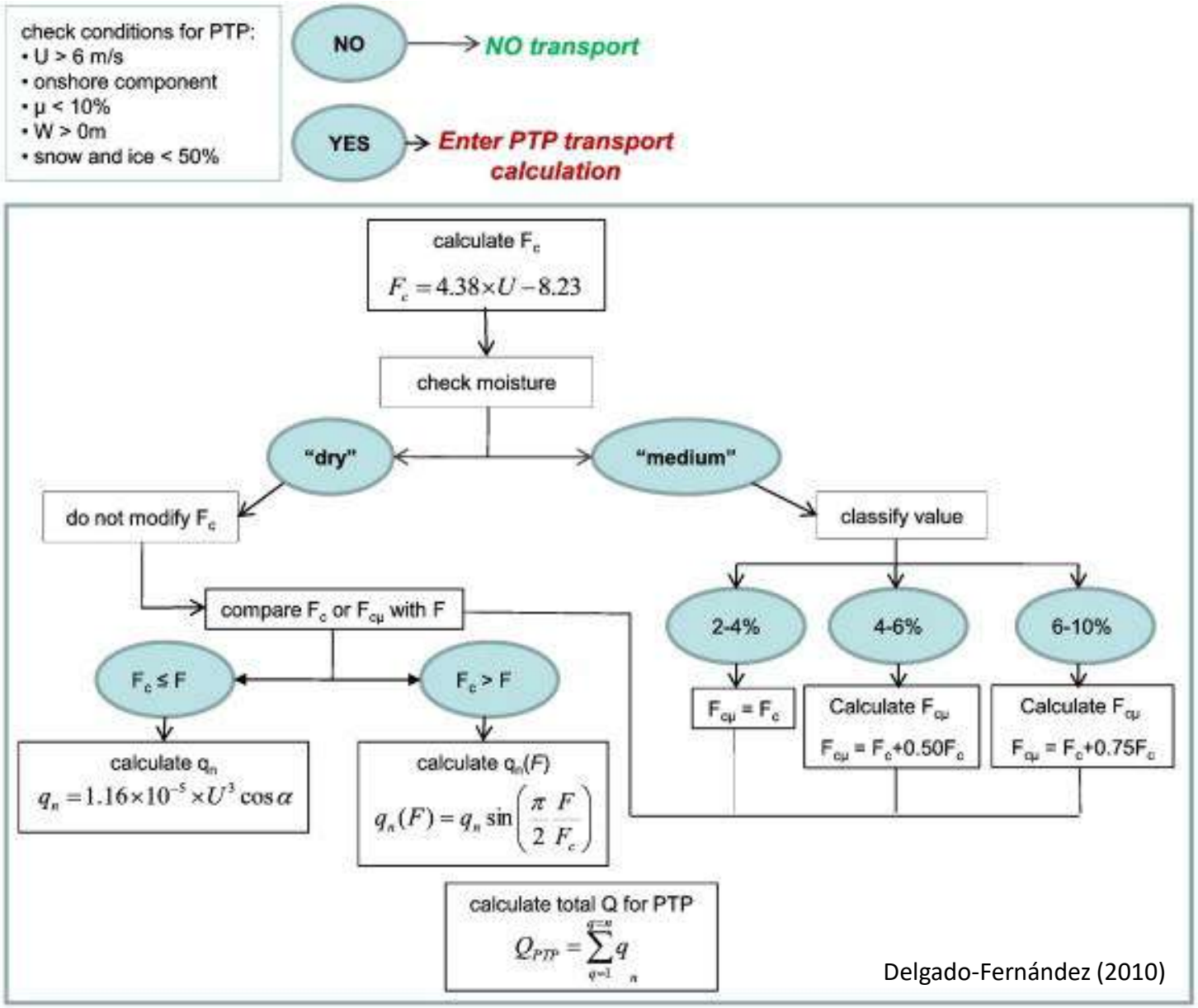
$$F_c = 4.38\,u - 8.23$$

(Davidson-Arnott and Law, 1996)

Dune formation

Aeolian processes – sediment transport

Steps and analytical procedure applied to hourly records of wind speed (U) and direction (α), fetch distance (F), critical fetch distance (Fc) and moisture (μ) for potential transport periods (PTPs)



Delgado-Fernández (2010)

Dune formation

Aeolian processes – sediment transport

- Sand is deposited as a result of a drop in wind speed due to changes in the wind flow or interaction of the wind with a topography or obstacles (e.g. vegetation).
- “Vegetation” can keep up with deposition, leading to the growth of embryo and foredunes.
- The effectiveness of vegetation controlled by the % cover but also plant height, form and flexibility (Hesp, 1989).
- The maximum depth of sediment that can be trapped on the order of 0.2-0.5 m (Davidson-Arnott, 2010).





Dune evolution

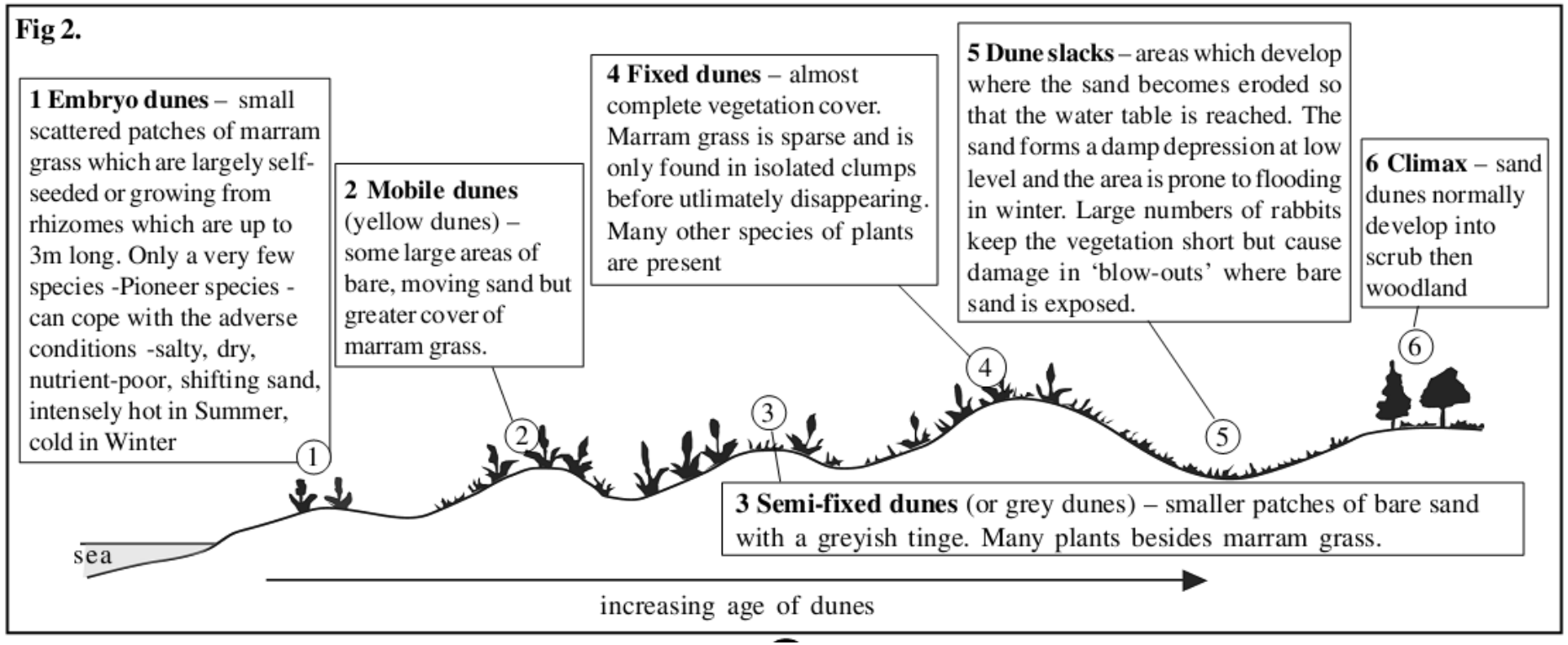
Dune evolution

Idealised dune profile – imprints of coastal dune evolution

Decreasing sediment transport

Sand dune succession

Various zones can be recognised in a set of sand dunes which may represent different stages of succession (Fig 2)



Dune evolution

Drivers of coastal dune evolution (> 10^1)

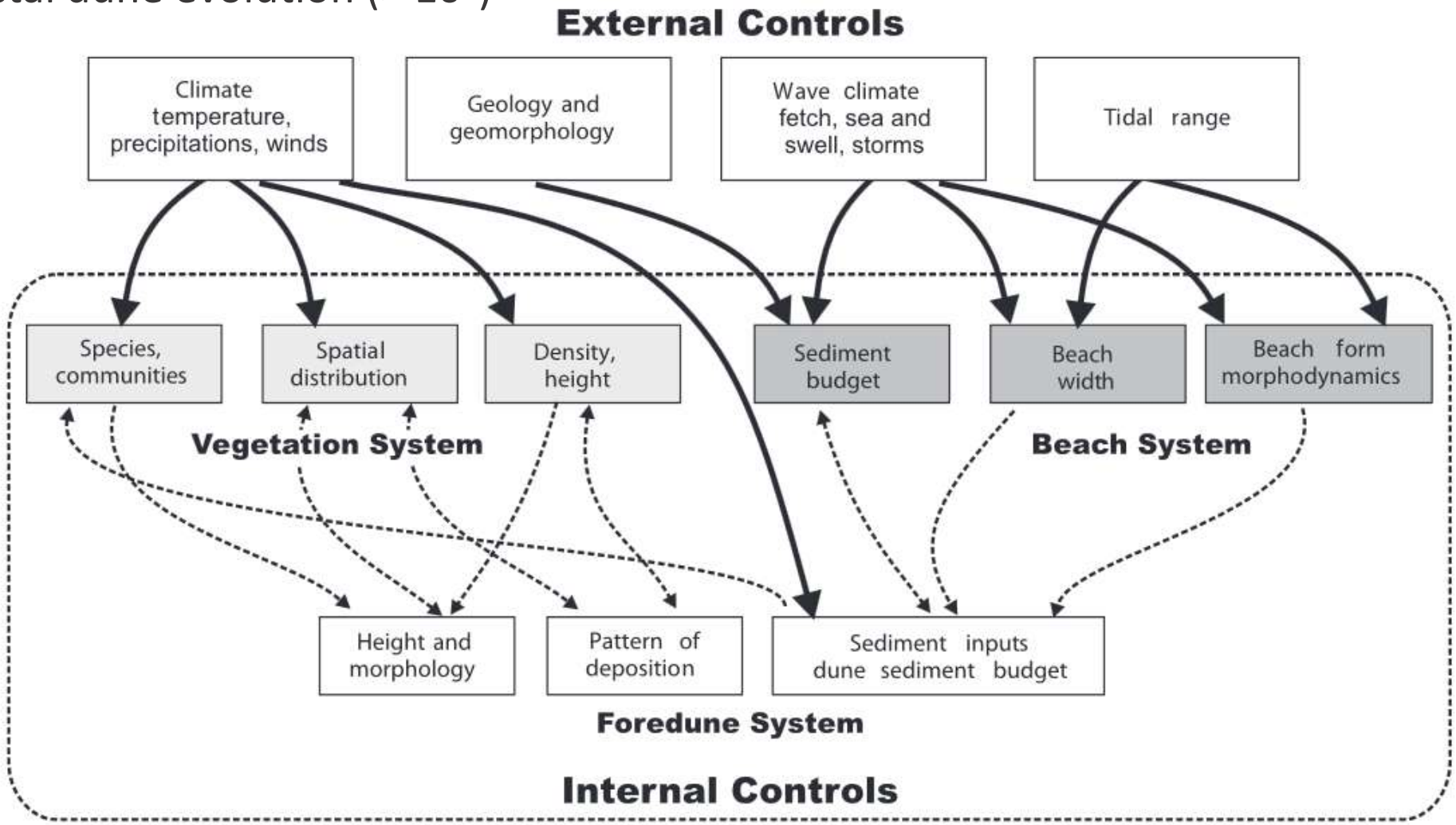


FIGURE 5.13. Internal and external controls on coastal sand dune development.

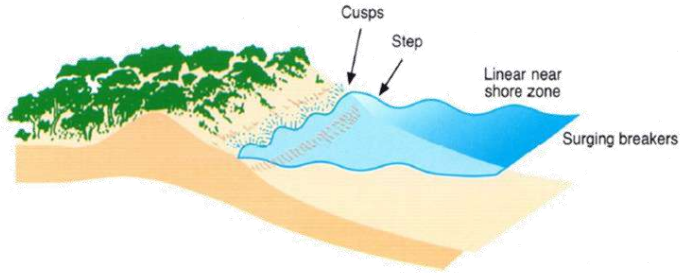
Reed et al. 2009

Dune evolution

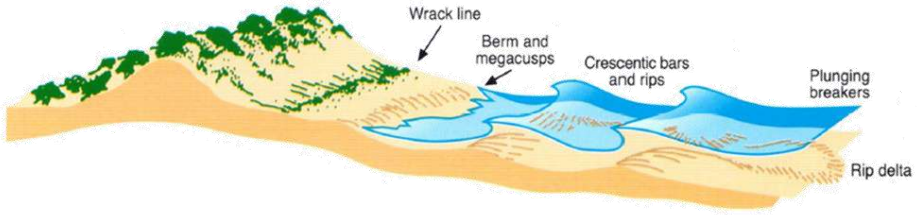
Conceptual models of dune evolution

Beach state model – shape of the beach

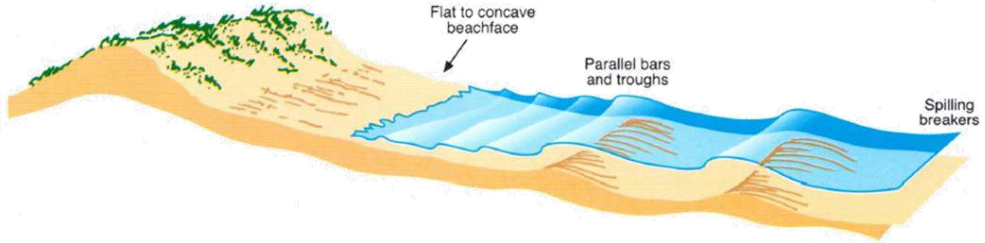
- **Beach width**
- Beach slope



reflective beaches: low potential sediment transport and few episodes of destabilisation, leading to stable foredune development and limited inland transport of sand.



intermediate beaches: types have higher probabilities of foredune destruction and the development of large-scale parabolic dunes.



dissipative beaches: high potential for aeolian sediment transport and a high frequency of foredune destabilisation by storm waves, initiate episodes of transgression

Short and Hesp (1982)

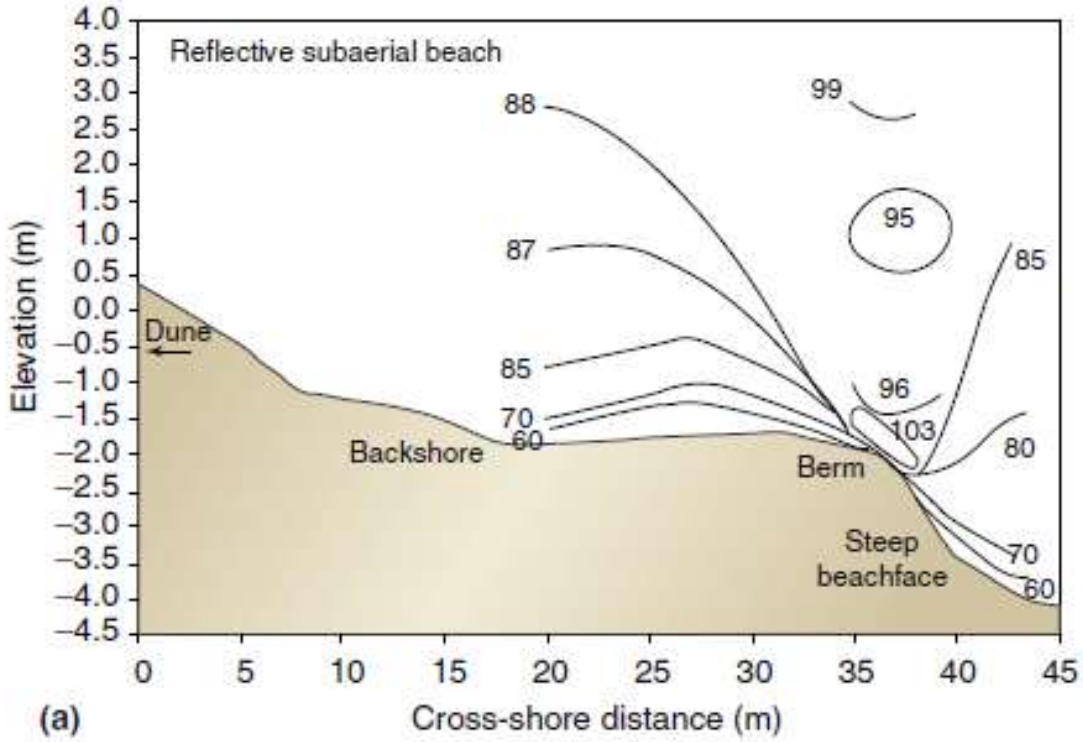
Dune evolution

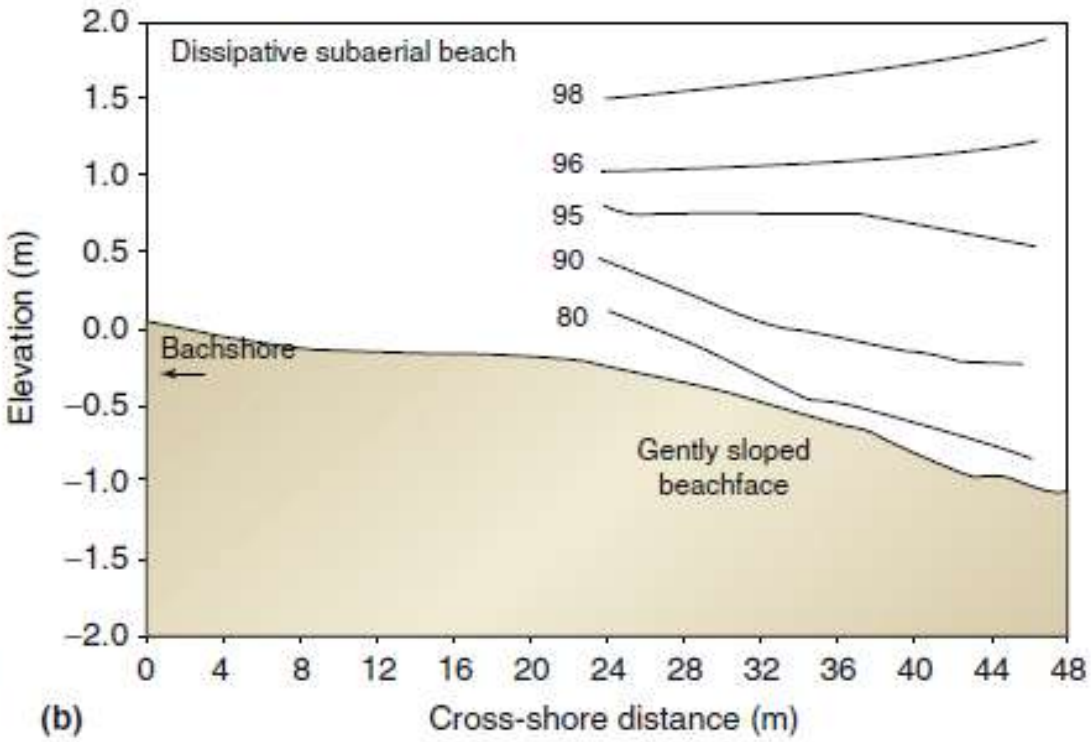
Conceptual models of dune evolution

Beach state model – shape of the beach

Beach width

Beach slope



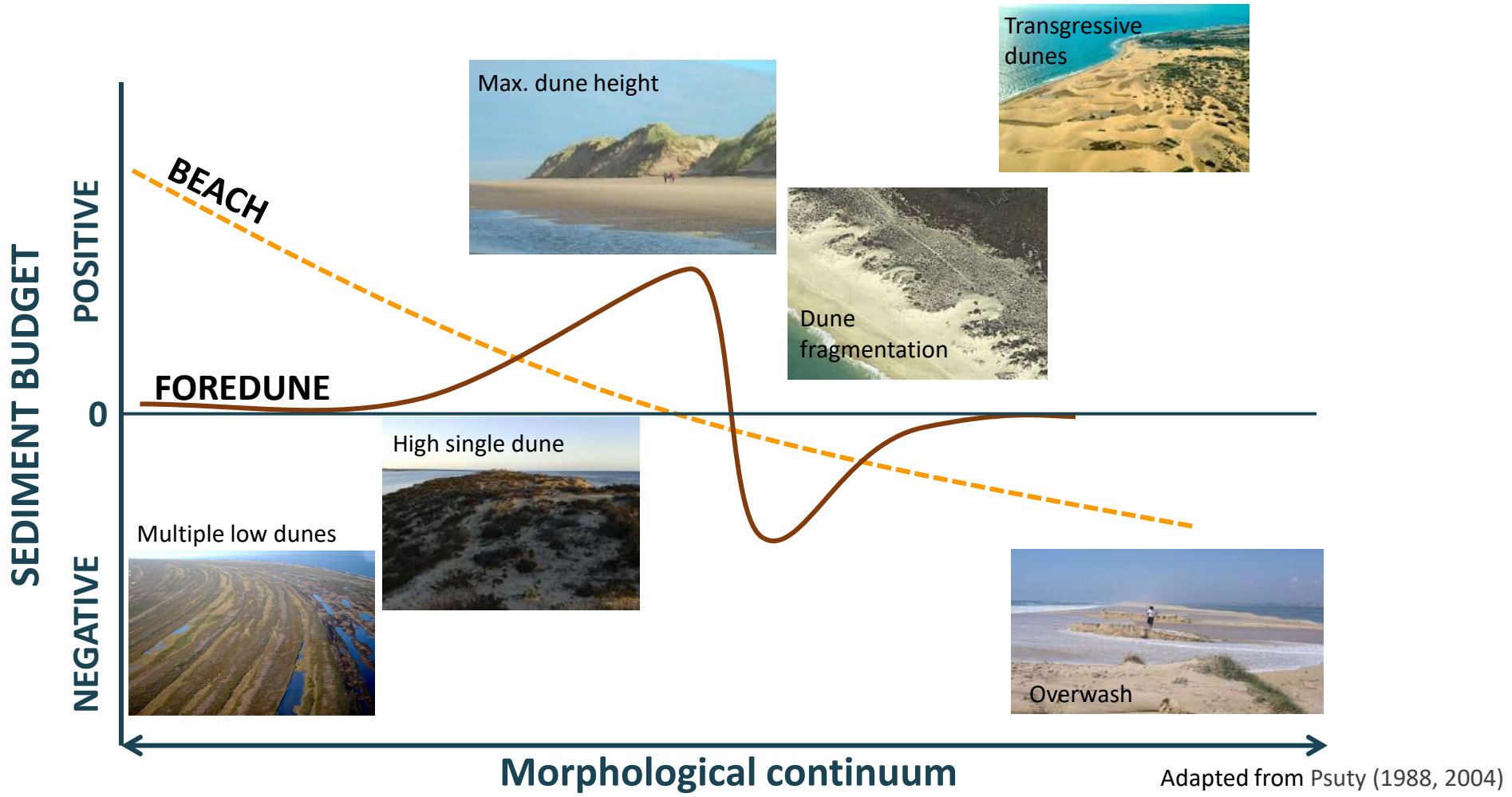


Short and Hesp (1982)

Dune evolution

Conceptual models of dune evolution

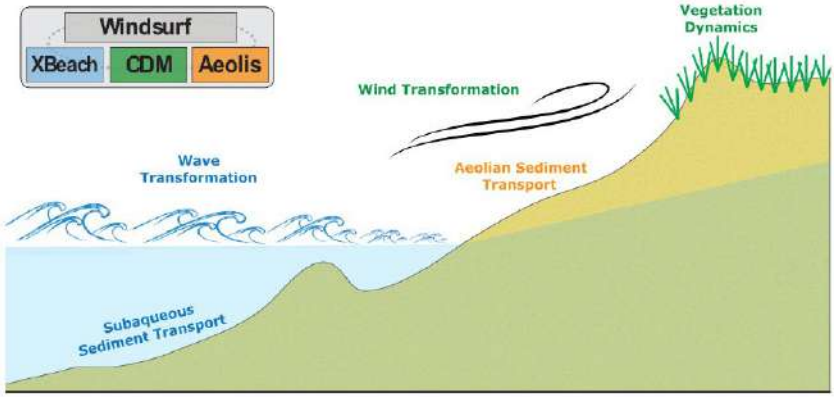
The morphological continuum – sediment budget based



Adapted from Psuty (1988, 2004)

Dune evolution

Simulating dune evolution – numerical models



- Beach-dune interaction Models

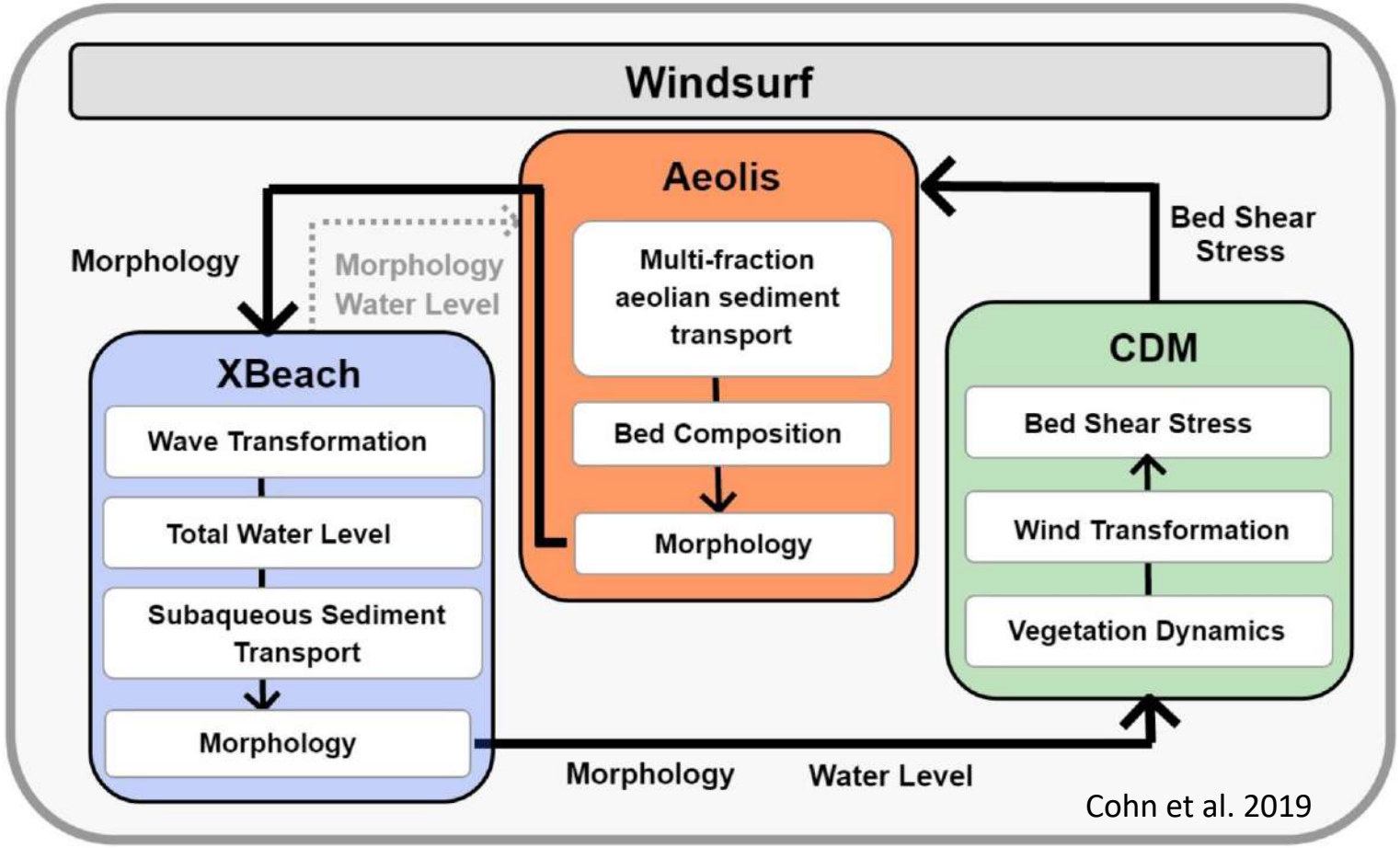
Process-based models

- **The Windsurf model**
- Composite model that connects three different model cores for simulating integrated nearshore and aeolian sediment transport.
  I. XBeach - Nearshore hydrodynamics (http://www.xbeach.org)
  II. AeoLiS - Supply-limited aeolian sediment transport (https://github.com/openearth/aeolis-python)
  III. Coastal Dune Model (CDM) - Aeolian sediment transport and wind shear accounting for morphological feedback and vegetation (http://csdms.colorado.edu/wiki/Model:Coastal_Dune_Model, https://github.com/csdms-contrib/Coastal-Dune-Model)
- Simulates 2DH nearshore and aeolian sediment transport as a result of short waves, infragravity waves, tides and currents, and wind.

Dune evolution

Simulating dune evolution – numerical models

- Beach-dune interaction Models



Cohn et al. 2019

Dune evolution

Simulating dune evolution – num. models

- Beach-dune interaction Models

Duna-XBeach coupled process-based model

Processes included:

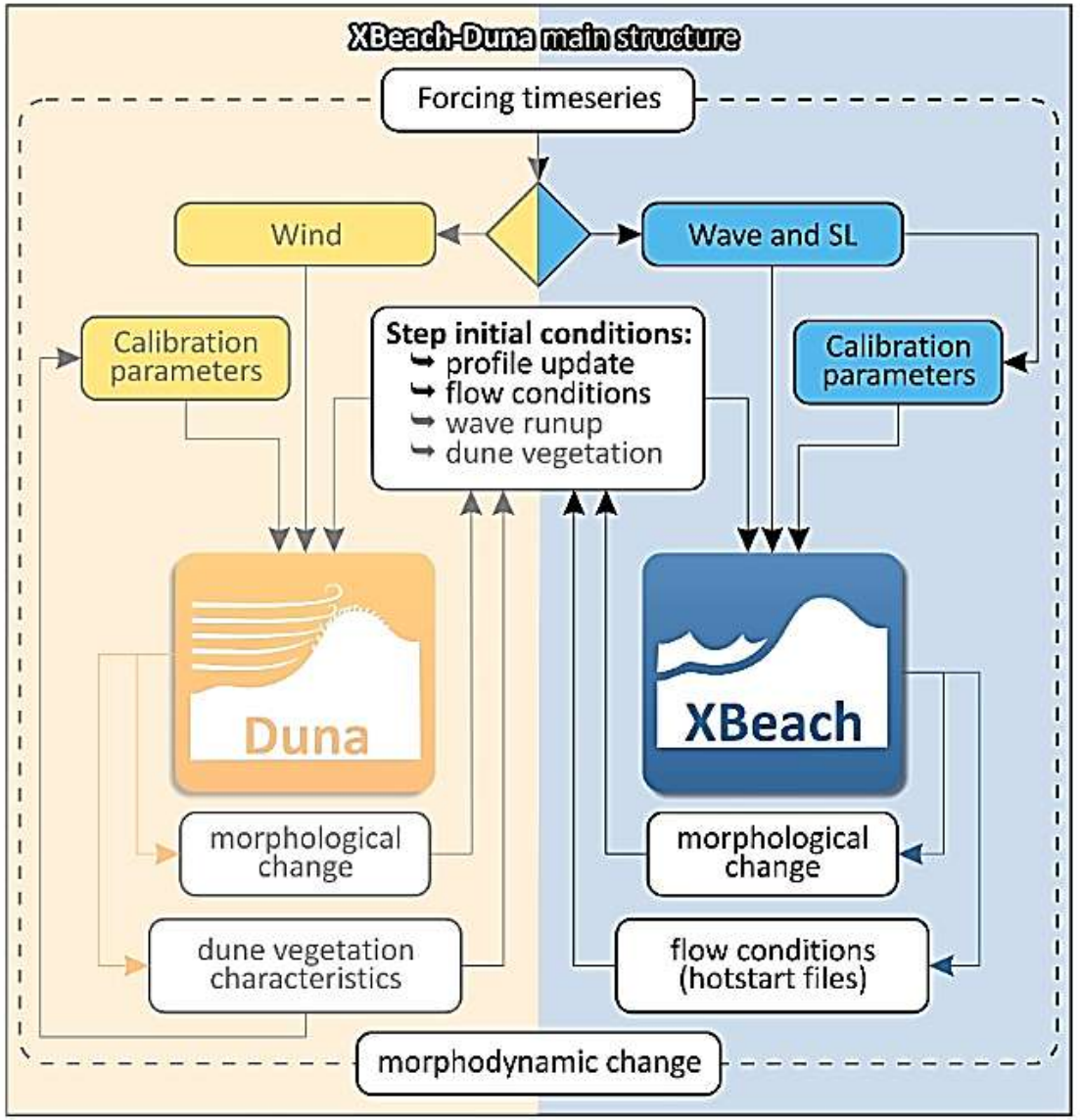
Storm erosion by waves and wave moderate conditions

Aeolian transport and vegetation growth

Models included:

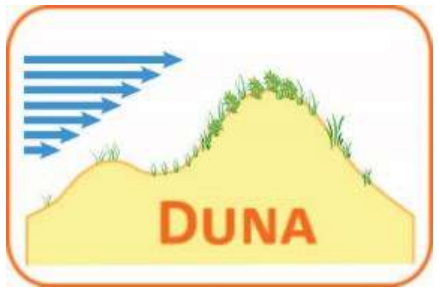
1D XBeach instationary or stationary

1D Duna model



Roelvink and Costas, 2019

Dune evolution



Process-based morphodynamic model componentes:

- wind flow model (Kroy et al. 2002),
- sediment transport (Bagnold, 1936 and Sauermann et al., 2001)
- vegetation growth approach
- effect of factors limiting sediment transport (e.g., grain size, vegetation, slope and moisture, fetch distance)

Process-based morphodynamic models applied at medium to long scale integrate short scale processes, providing the actual linkage between scales … and may also help us understand patterns not yet fully demonstrated through numerical experiments

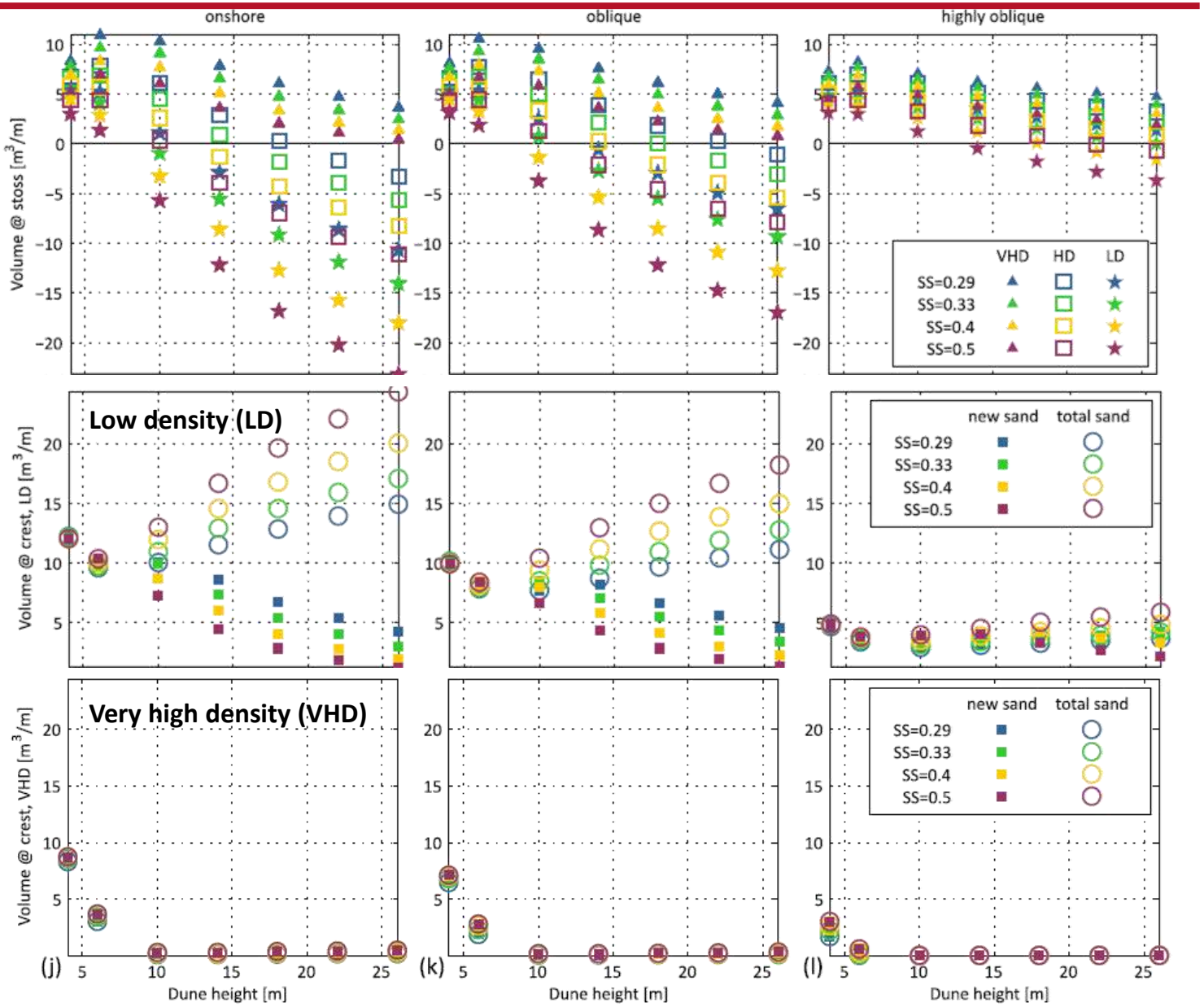
Dune evolution

Volume change – numerical experiments:

- What is the contribution of sand toward the crest?
- What is the contribution of the beach to the growth of the crest?

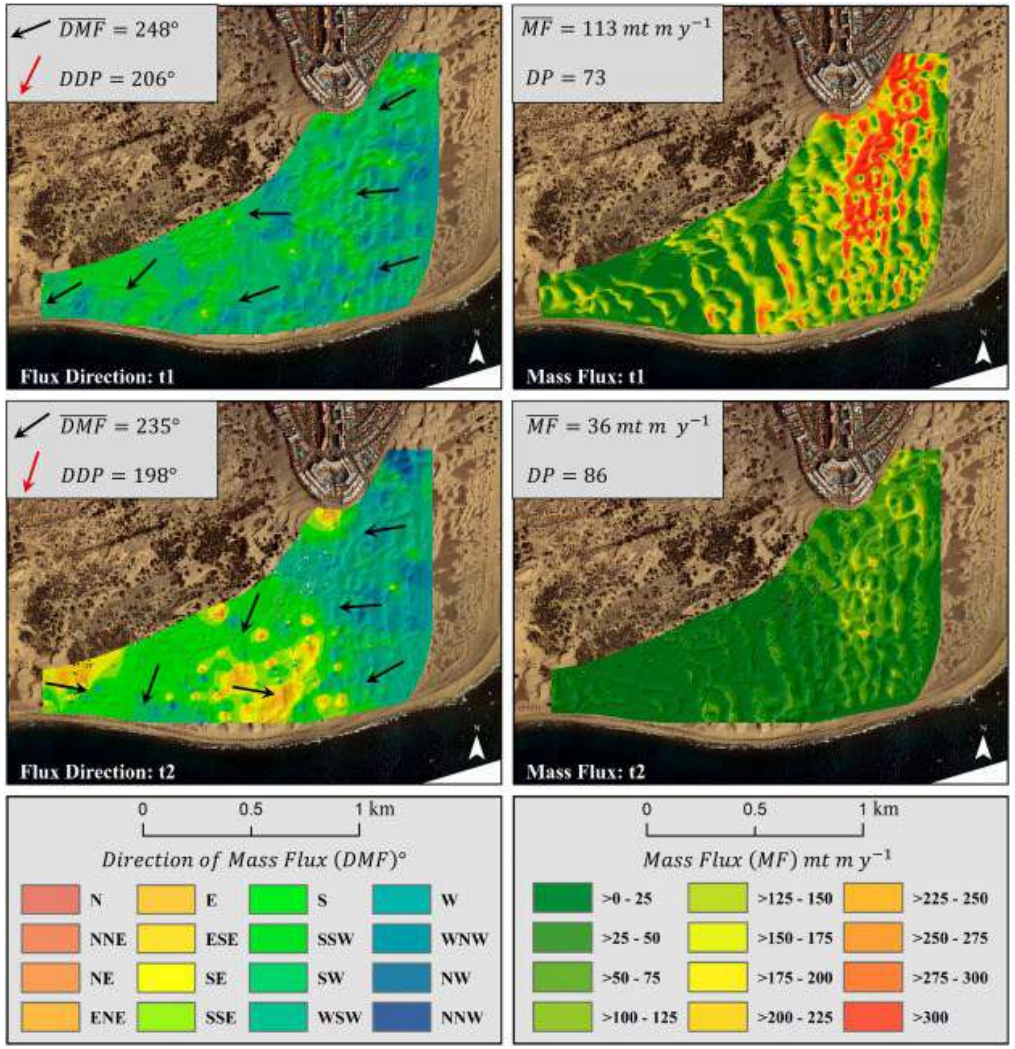
Effect of vegetation

- Increased density helps fixing the stoss (accumulation), preventing stoss cannibalisation
- The volume of sand reaching the dune sourced by the beach
- Most sand is retained within the stoss, the crest only gains new sand from the beach in case of low dunes

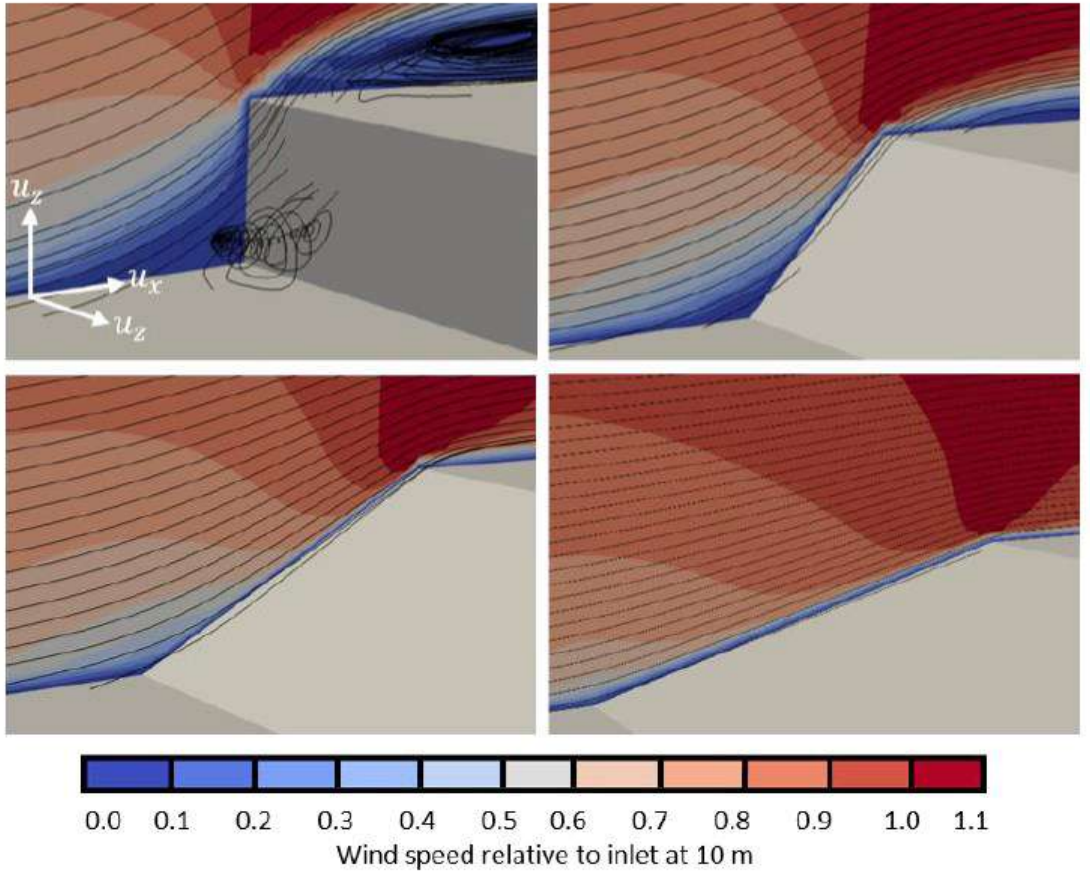


Dune evolution

Computational fluid dynamics (CFD)



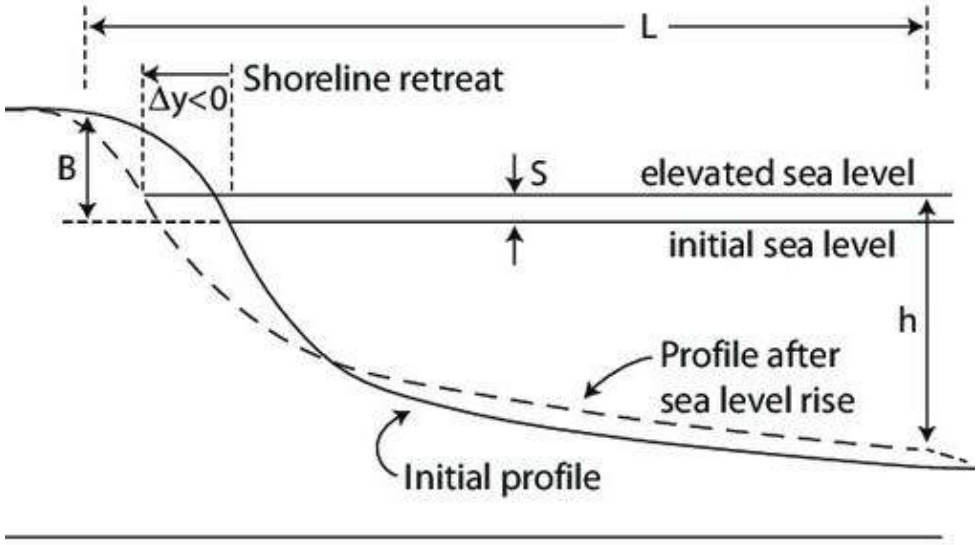
Smith et al. 2021



Hesp et al. 2021

Dune evolution

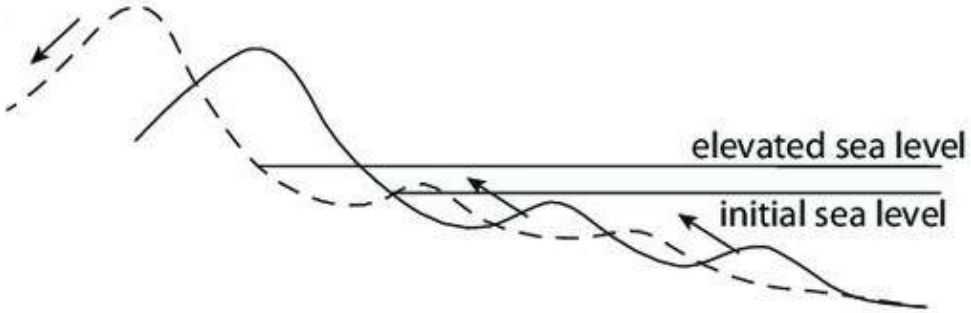
Coastal dunes in a context of sea-level rise



Bruun Rule (Bruun, 1962)

$$\Delta y = \frac{SL}{h + B}$$

Morphological changes (i.e. exchange of sediment between the upper and lower beach) related to processes to maintain an equilibrium profile



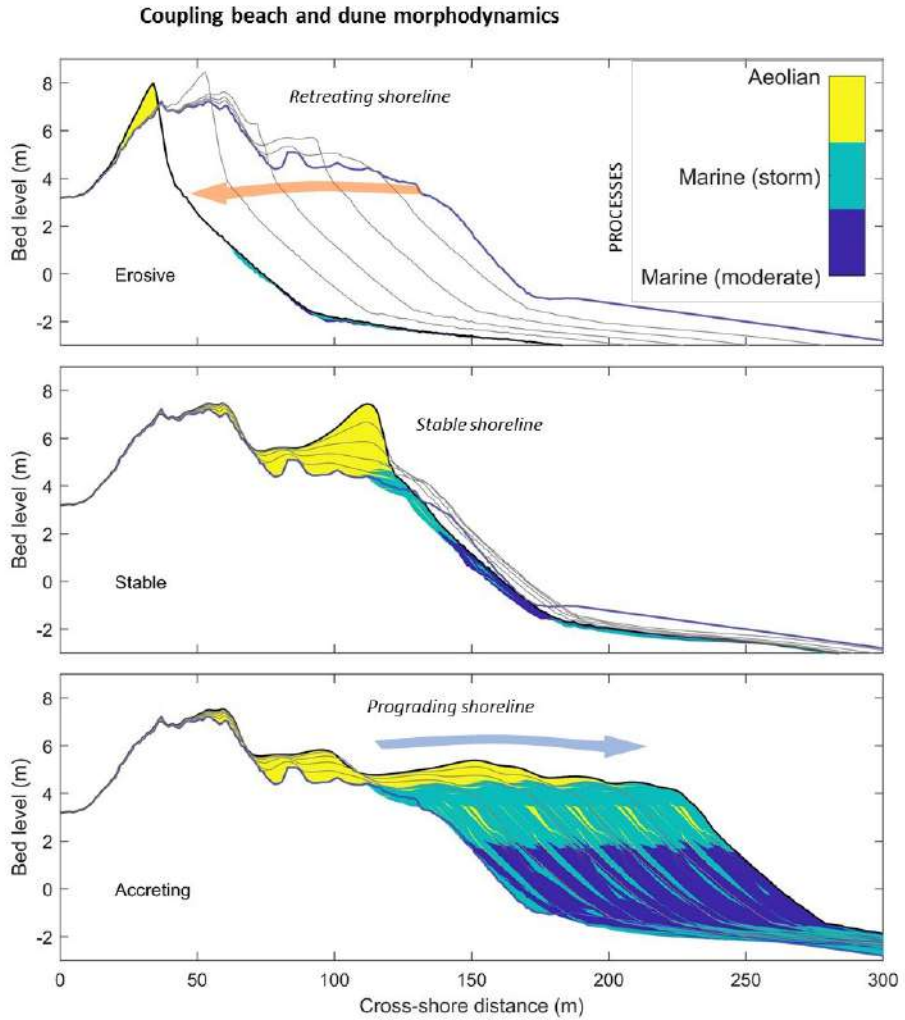
Robin Rule (Davidson-Arnott, 2005, Davidson-Arnott & Bauer, 2021)

$$R_t = T\,\frac{1}{tan\beta}\,\Delta S$$

Landward transgression of dune toe, colloquially referred as ‘‘Robin’s Rule” embodies the landward transgression of the entire profile

Dune evolution

Coastal dunes in a context of sea-level rise



Roelvink and Costas, 2019

Conceptual models, observations and process-based morphogynamic approaches suggest that sandy coasts with sediment budget deficits will retreat while those coasts with excess sediment will progradate or advance seaward.

While retreating, there are high chances, as seen in previous slides, that sediment is transferred inland.

A new problem may arise while coasts try to adapt and migrate inland to accommodate rising sea levels.

Dune evolution

Coastal dunes and beaches in a context of sea-level rise

The problem of the accomodation space



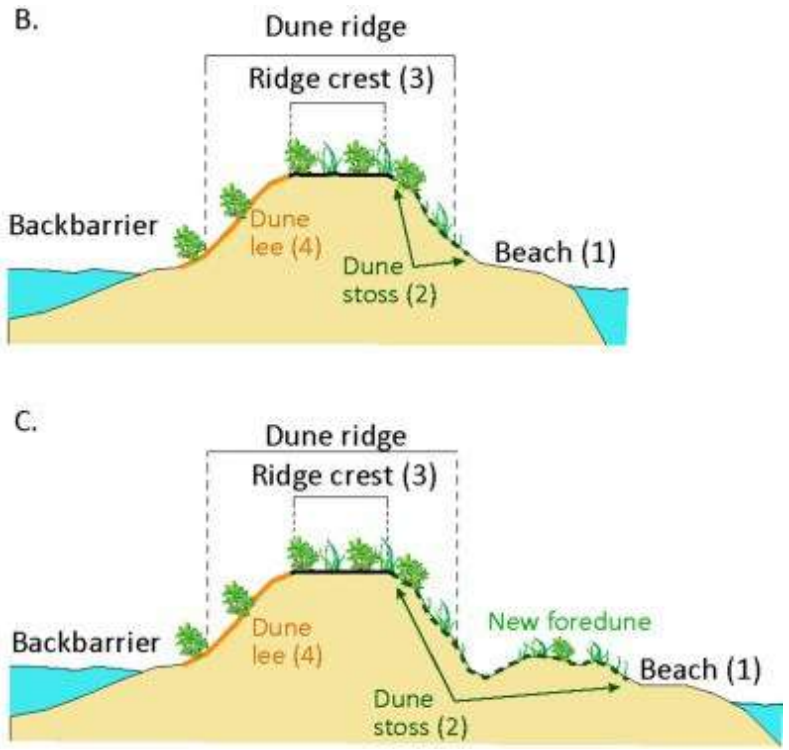


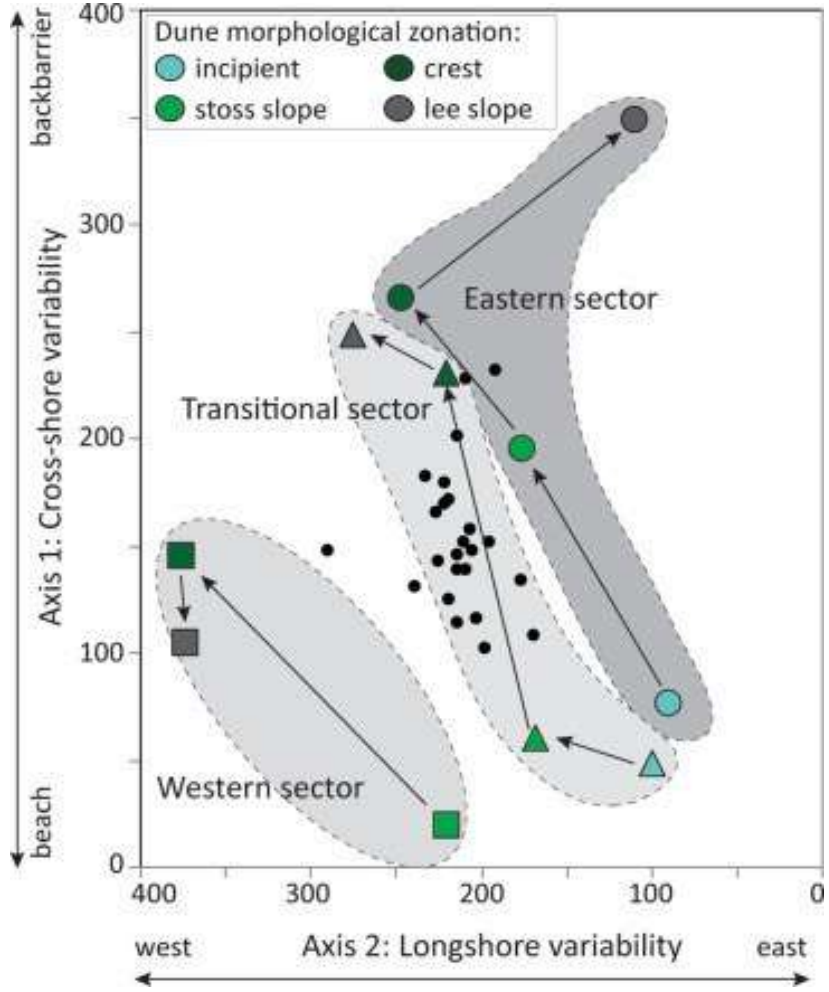
Dune evolution

Coastal dunes and beaches in a context of sea-level rise

Coastal squeeze

‘The term coastal squeeze describes the process where rising sea levels and other factors such as increased storminess ***push the coastal habitats landward***. At the same time in areas where land claim or coastal defences has created a static, *artificial margin* between land and sea or where the land rises relative to the coastal plain, ***habitats become squeezed into a narrowing zone***.’ Doody (2013)





Costas et al., 2023

Human interference

Human interference

Impacts and uses

- Sand mining
- Groundwater
- Grazing









Human interference

Impacts and uses

❖ Forest plantation





- Common practice to fix migrating or transgressive coastal dunes to prevent negative impacts to agriculture and coastal populations.
- Pine trees were planted at many locations along EU to stop the dunes.

Human interference

Impacts and uses

❖ Artificial dune fixation





L'IMBRIGLIAMENTO DELLA DUNA MOBILE, INDISPENSABILE PER LA SUA FISSAZIONE, VIENE SCRUPOLOSAMENTE ESEGUITO
CON LARGO IMPIEGO DI MANODOPERA E DI MATERIALE.» E' NECESSARIO ESEGUIRE FIN DALL'INIZIO LE OPERE A REGOL
D'ARTE ANZICHE' DOVER IN SEGUITO SPENDERE SOMME MAGGIORI PER LA MANUTENZIONE STRAORDINARIA ED IL RIFACI-
MENTO DEI TRATTI CHE IL VENTO IMPETUOSO RICONDUCEREBBE ALTRIMENTI BEN PRESTO NELLE CONDIZIONI PRIMITIVE.»

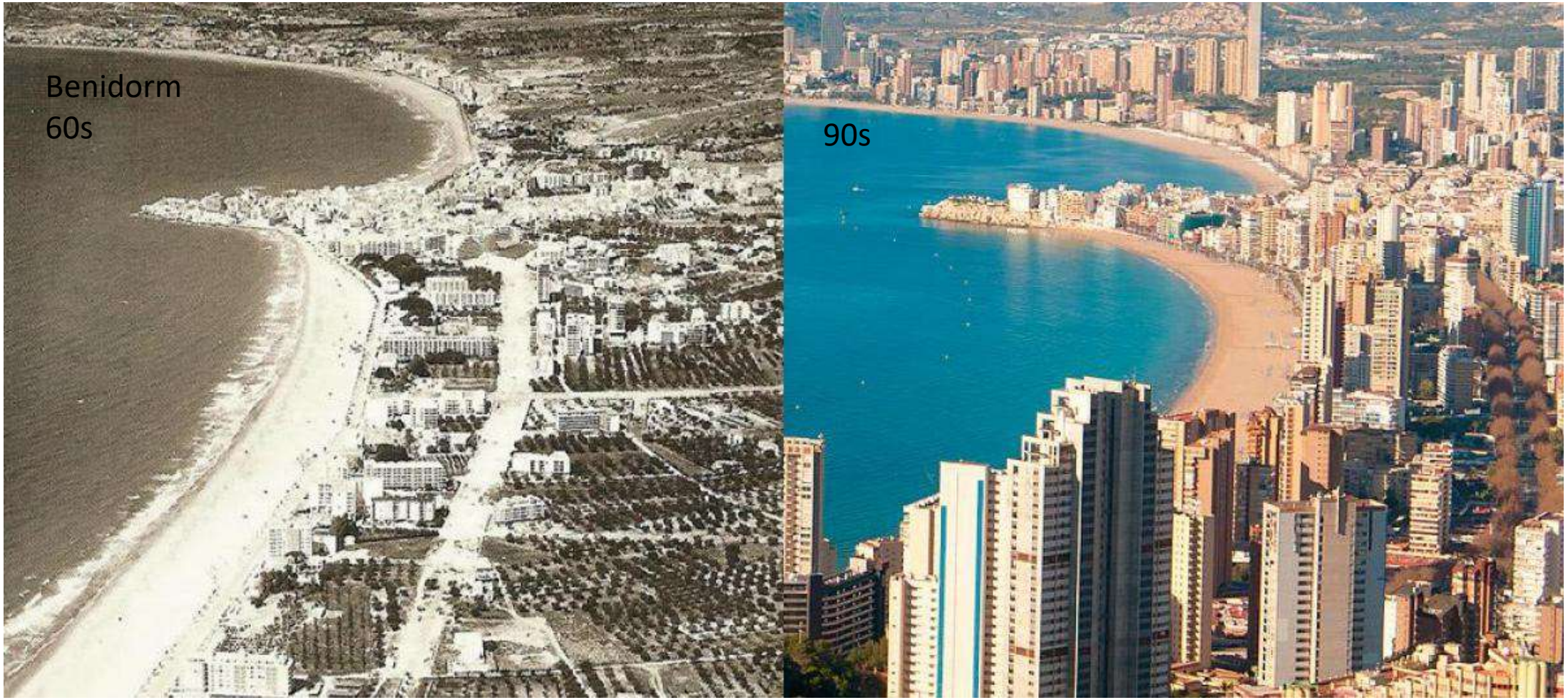
Common practice to fix migrating or transgressive coastal dunes to prevent negative impacts to agriculture and coastal populations.

e.g. Italy (Sardinia, 1952)

Human interference

Impacts and uses

- Land reclamation and Urbanisation



Human interference

Impacts and uses

- Coastal management

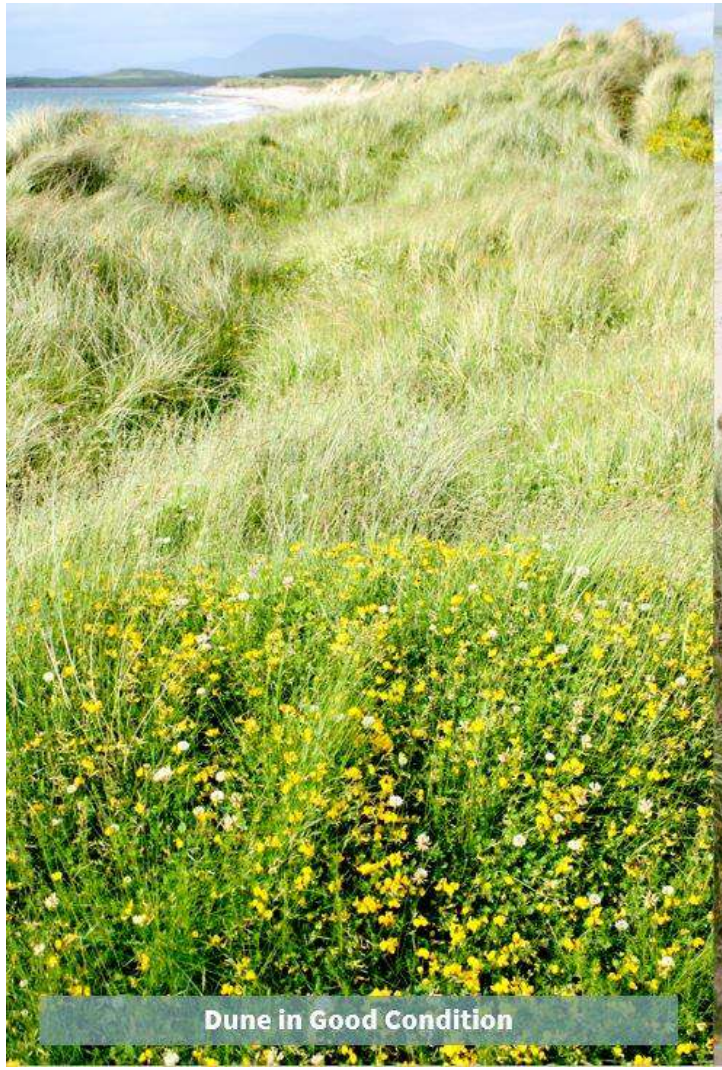




Human interference

Impacts and uses

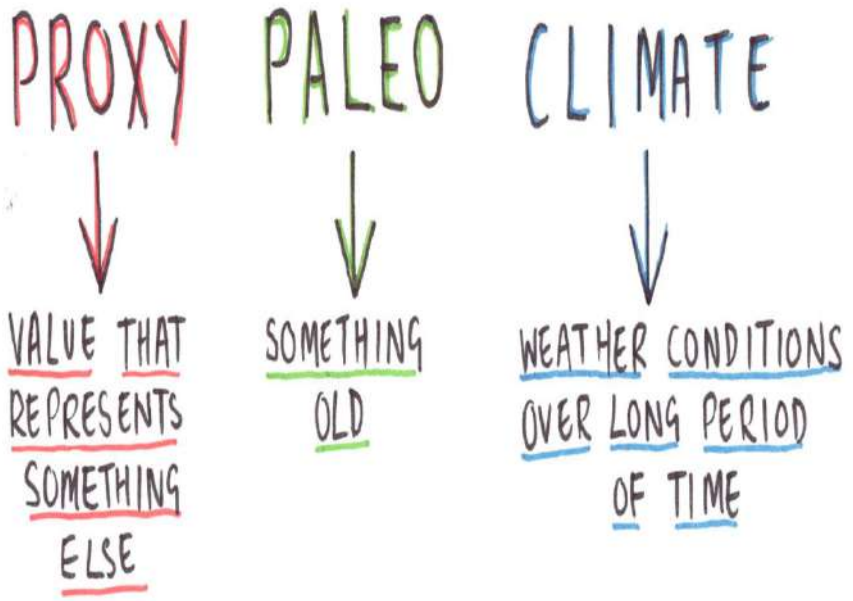
❖ Trampling







Aeolian activity as indicator



Coastal Dunes

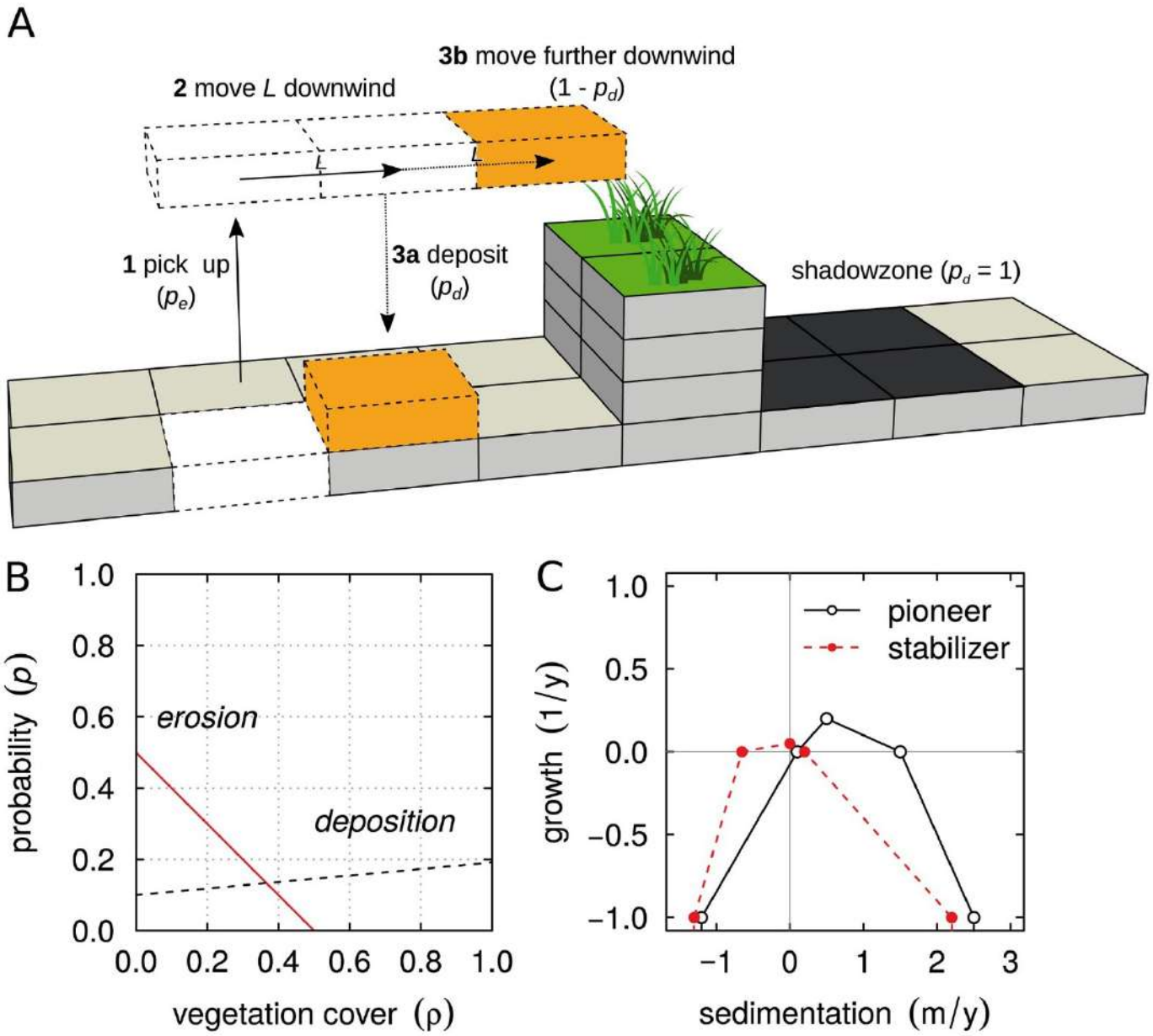
Susana Costas
Research assistant at CIMA,
Center for Marine and Environmental Research
University of Algarve, Faro, Portugal

Dune evolution

Rule-based cellular models

DUBEVEG

- Based on Werner 1995
- Interactions between wind and vegetation on aeolian transport
- The model consists of three modules: an aeolian transport module, a marine processes module, and a vegetation module.



Dune evolution

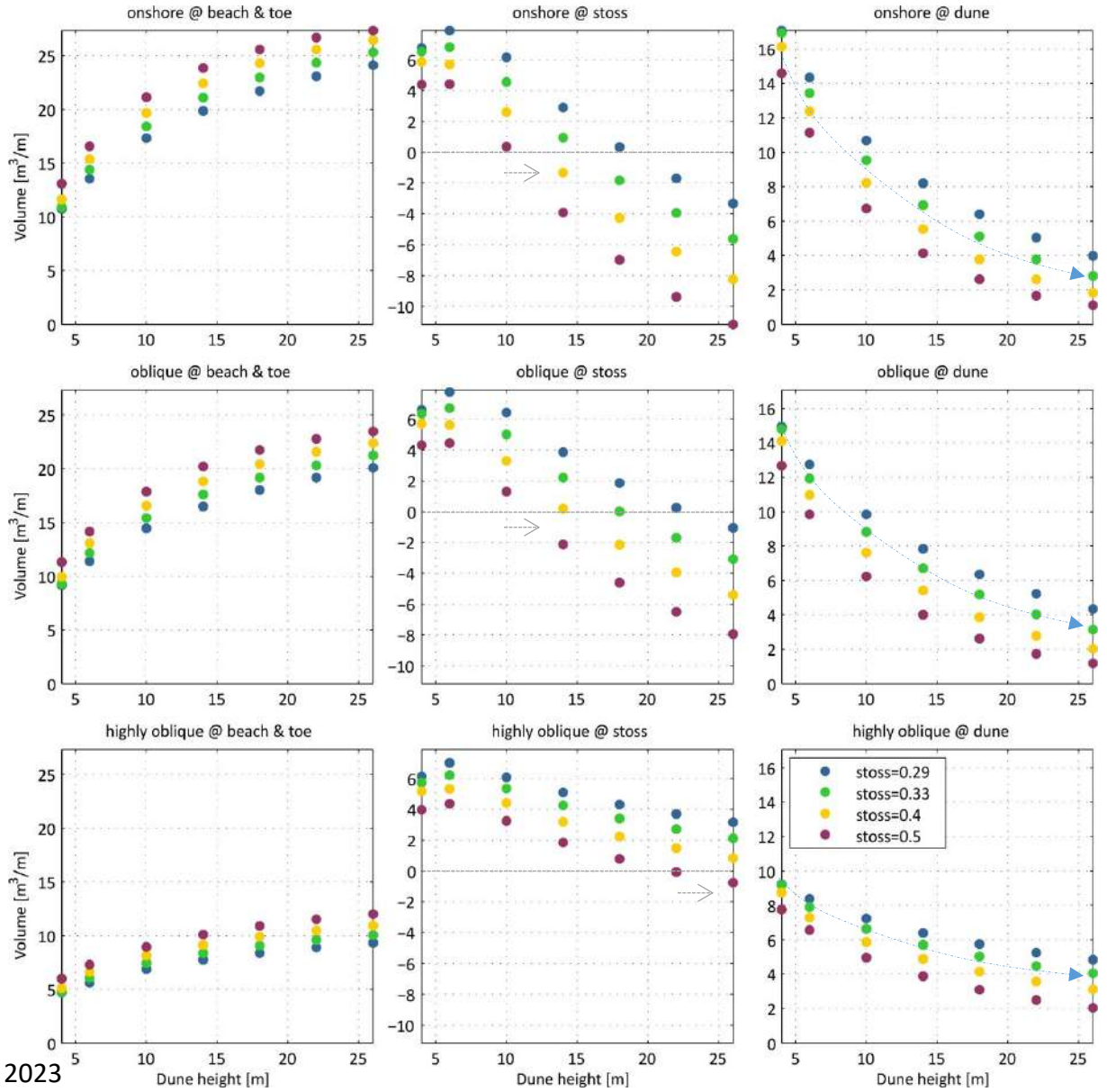
Volume change – numerical experiments:

Influence of dune morphology to sediment accumulation non-limited supply conditions (non-limited fetch)

- Wind direction bins: onshore (0-15), oblique (15-45), highly oblique (45-75)
- Dune height range [4 to 26 m]
- Stoss slope range [0.28 to 0.5]

<u>Dune stoss and crest (dune):</u>

- Reduction in accumulation with height (logarithmic), slope (linear) and angle
- All morphologies recorded positive net changes (sediment accretion)
- For onshore and oblique winds the stoss is "cannibalised" for heights above 10m (*vegetation cover and wind regime)
- Stoss mostly accreting for highly oblique winds



Kombiadou et al., 2023