Vegetation Hydrodynamics at the Blade and Canopy Scale

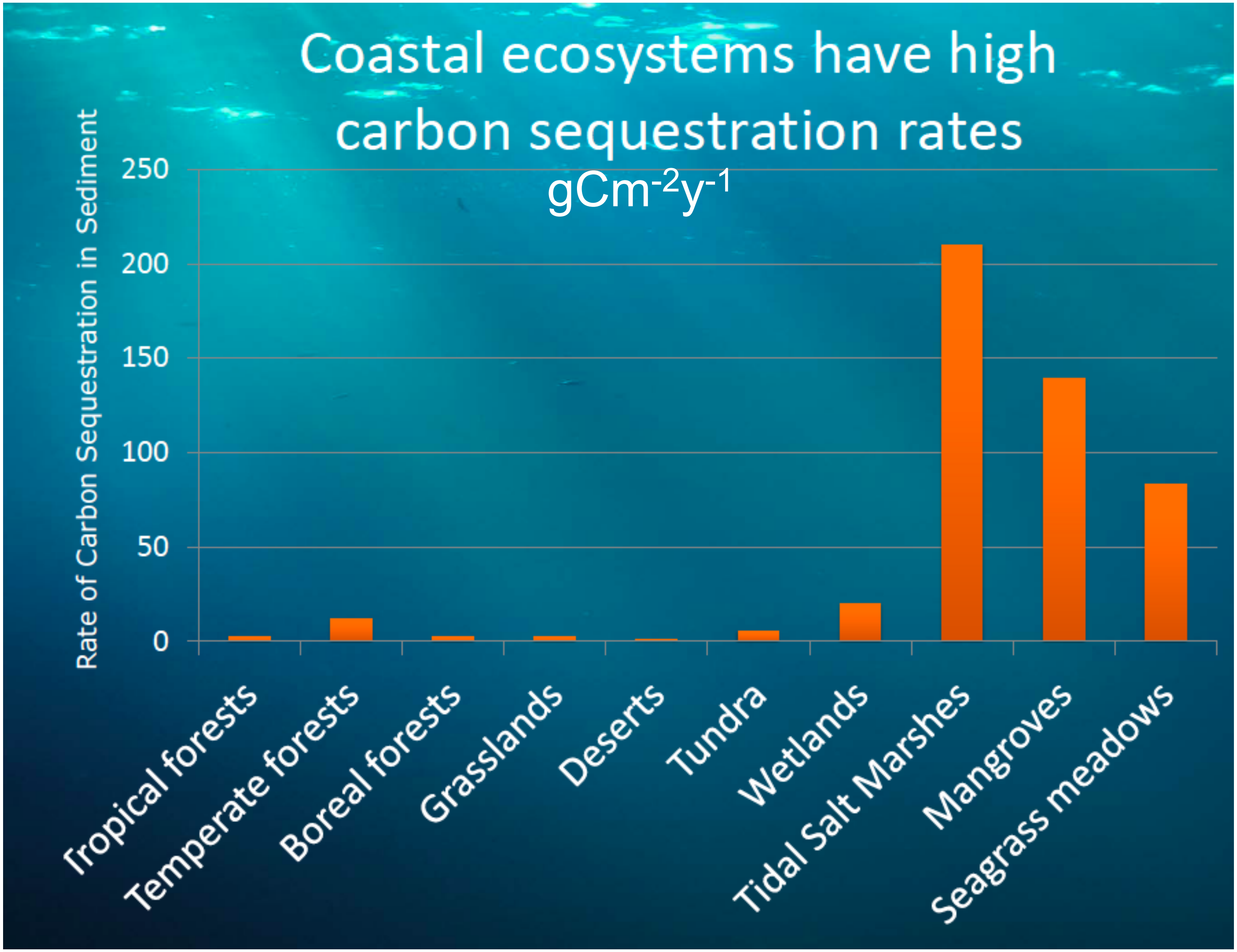
Heidi Nepf Massachusetts Institute of Technology

Coastal Protection

Mangroves and Coastal Marshes diminish storm surge and waves

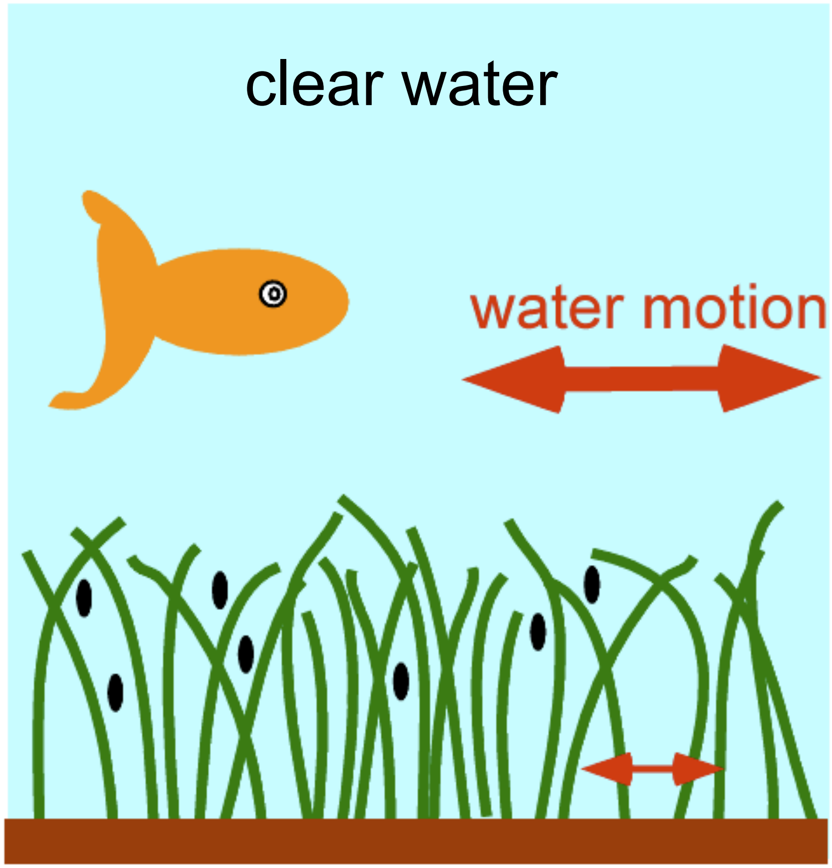
http://www.rgbstock.com

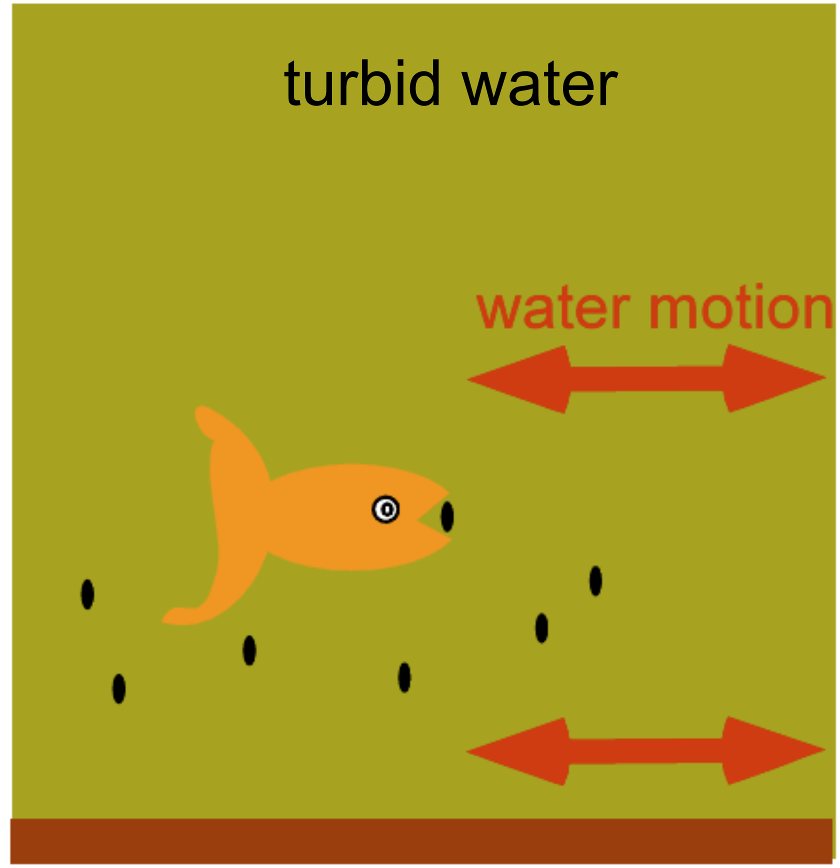
Blue Carbon Initiative



Pidgeon. 2009, 2012. Carbon Sequestration by Coastal Marine Habitats:.

Water Clarity Feedback





low re-suspension
protection of algal grazers
nutrient removal reduces algae
light climate good for growth

high re-suspension
algal grazers unprotected
high nutrient levels
algae dominates
poor light climate

Ecosystem Value

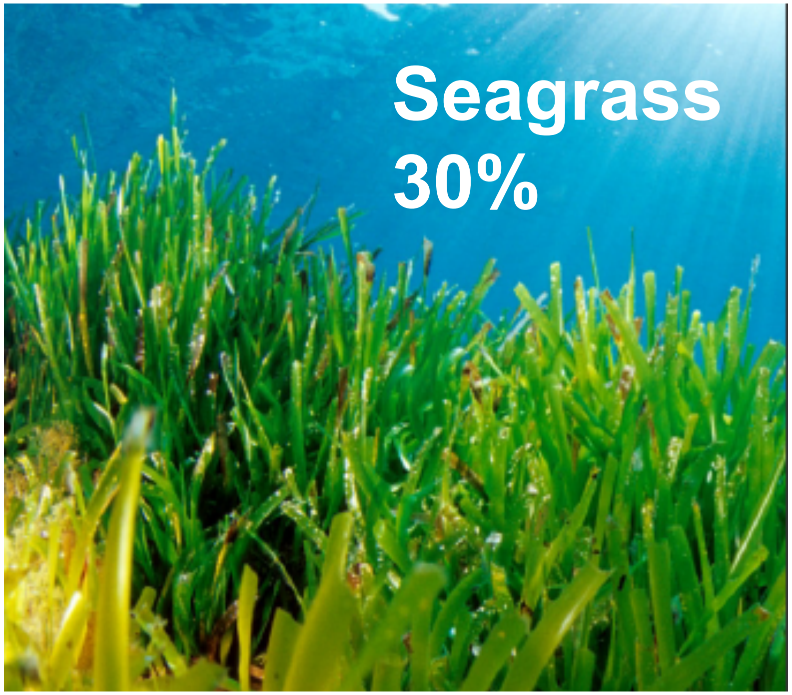
Constanza et al. 1997

coastal protection
water quality protection
nutrient cycling
flood regulation
habitat provision

Seagrass
3.8 Trillion USD

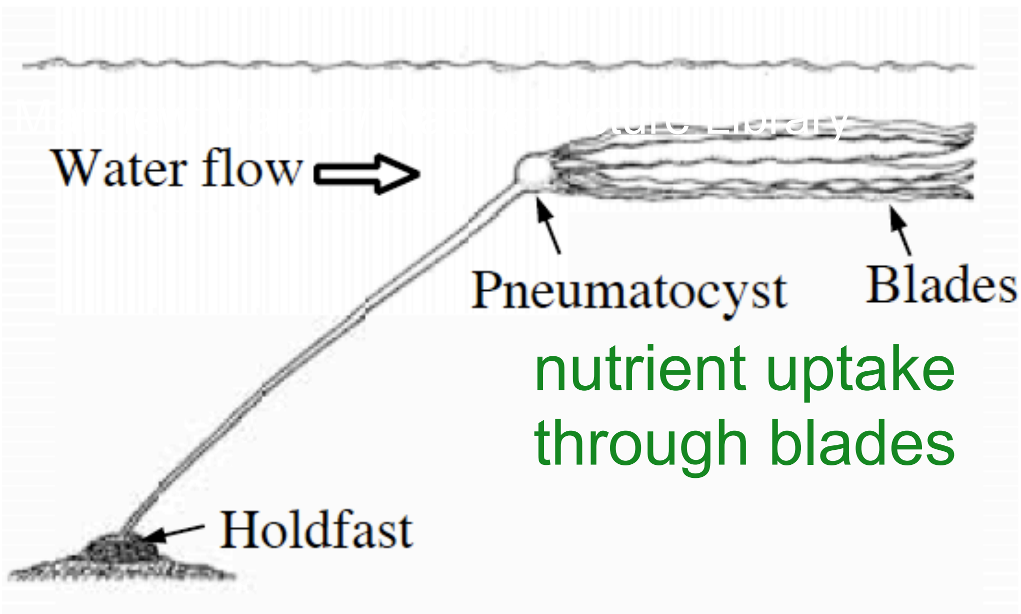
Wetlands 4.9 Trillion USD

Marsh and Mangrove
1.6 Trillion USD



Loss of vegetated habitat in the past century

Crooks et al. 2010. Pidgeon 2012



Nereocystis luetkeana
M.A.R. Koehl. J. Exp. Biol. 1999

Kelp Forest

To Wrinkle, or not to Wrinkle – that is the Question.
Phenotypic plasticity

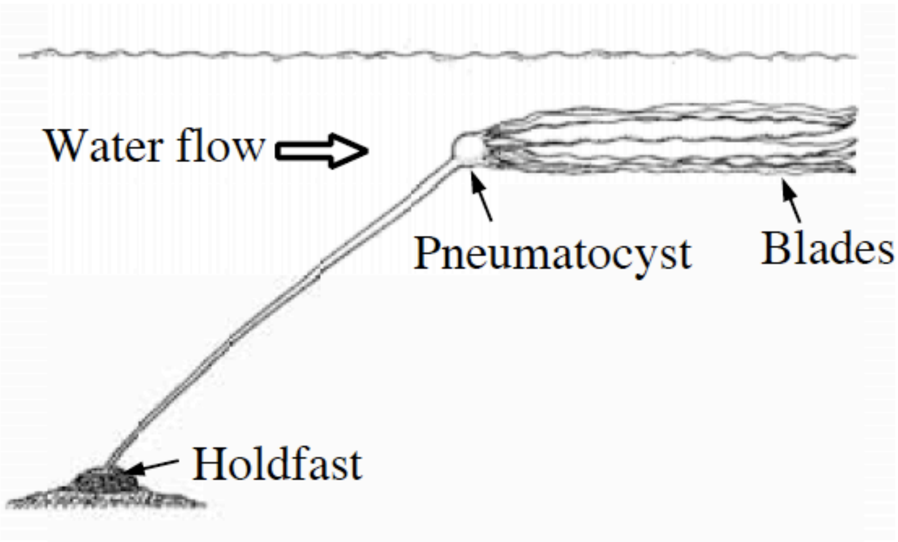
Laminaria - Sugar Kelp
Exposed Site
$U_{ave} > 10$ cm/s, $U_{max} = 1$ m/s

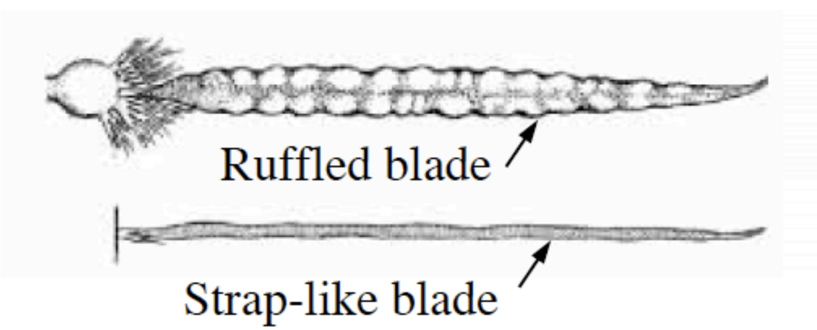
Fete de la Science
http://www.awi.de/typo3temp/pics56a3137d27.jpg

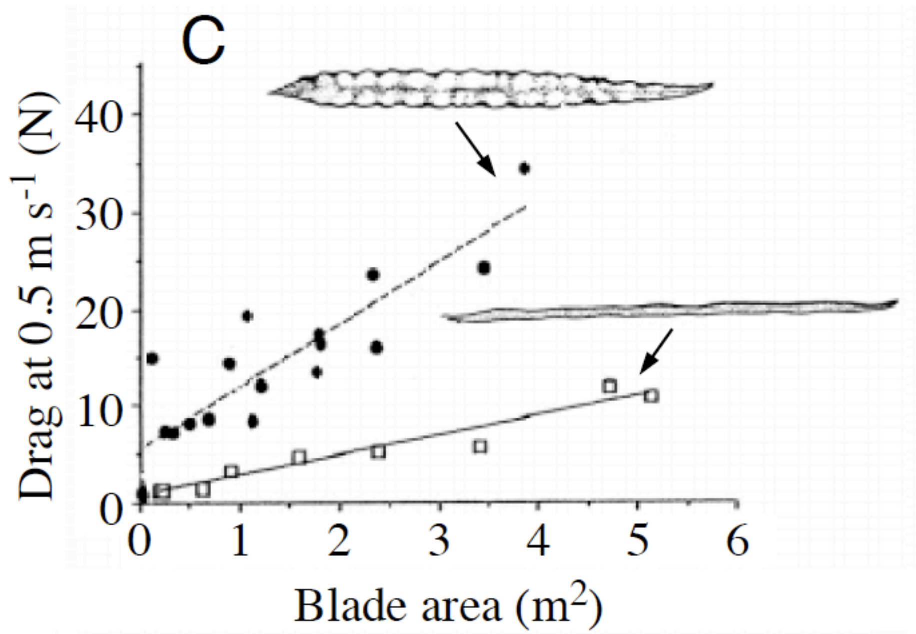
Laminaria - Sugar Kelp
Protected Site
$U_{ave} < 10$ cm/s

Alfred Wegener Institute
http://www.awi.de/typo3temp/pics/56a3137d27.jpg

Morphology Influences Drag



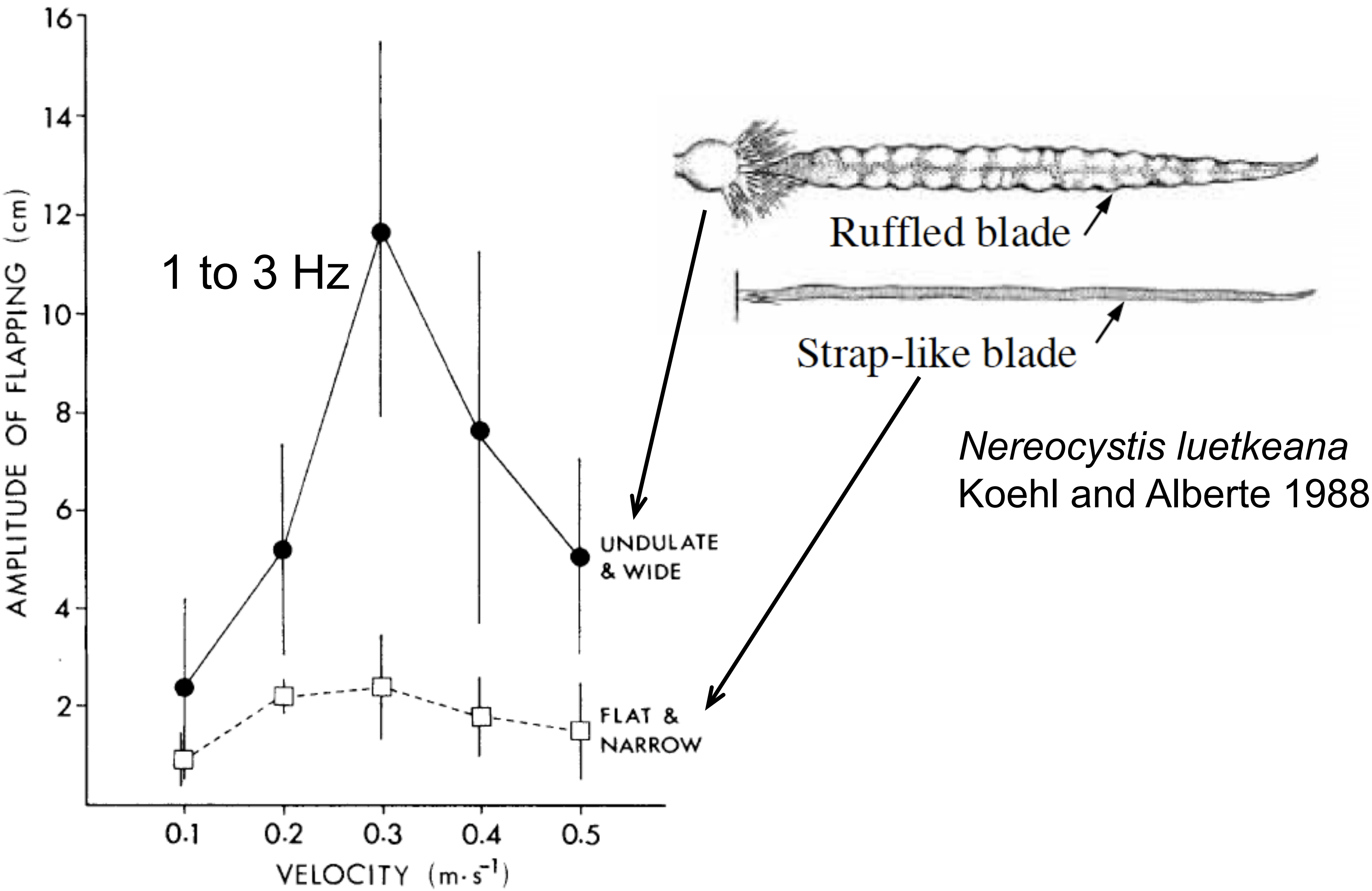




Nereocystis luetkeana

M.A.R. Koehl. J. Exp. Biol. 1999

Flapping Promoted by Ruffled Morphology



Nereocystis luetkeana
Koehl and Alberte 1988

Diffusive Boundary Layer

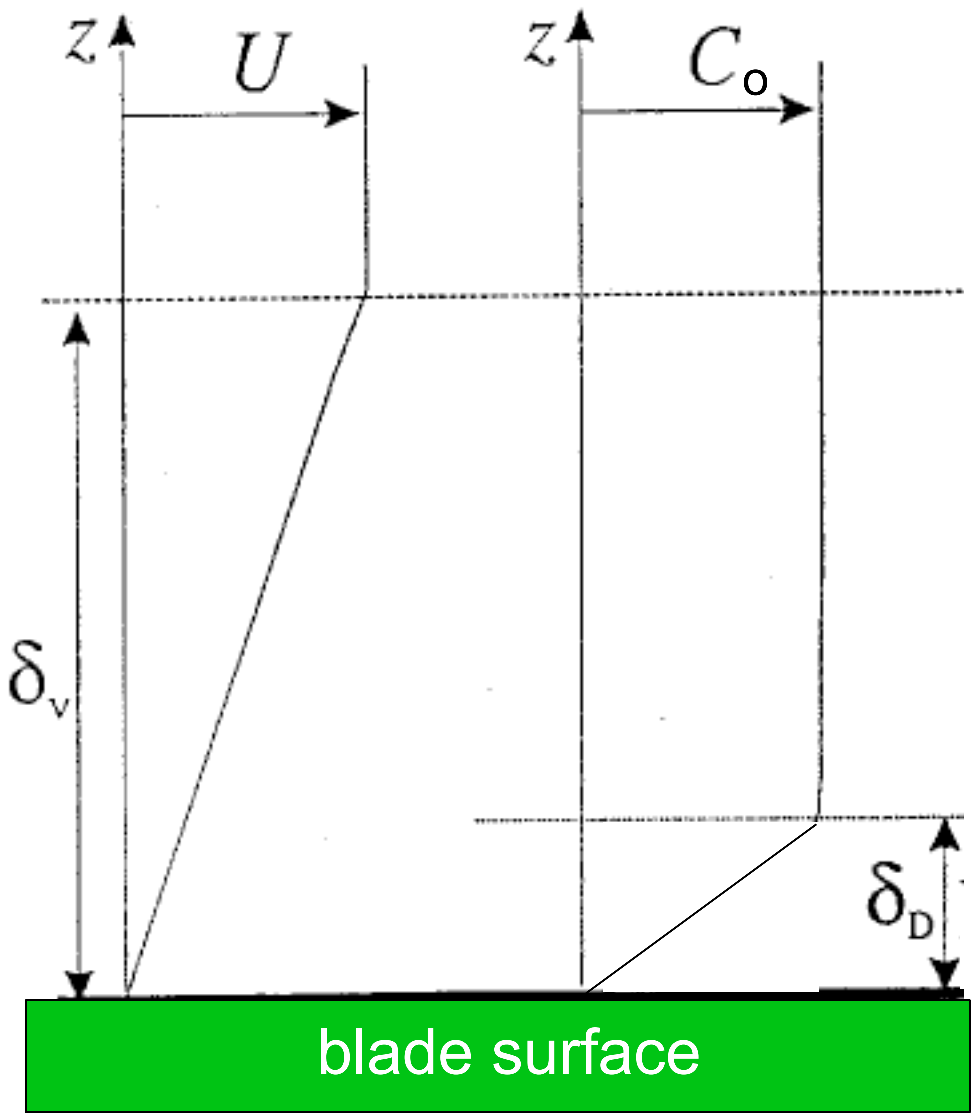


Figure modified from Stevens and Hurd 1997

viscous sub-layer

$$\delta_v = 10\nu / u_*$$

diffusive sub-layer

$$\delta_D = \delta_v \, Sc^{-1/3}$$

Schmidt number

$$Sc = \nu / D$$

in water

$$\delta_D \approx 0.1 \, \delta_v$$

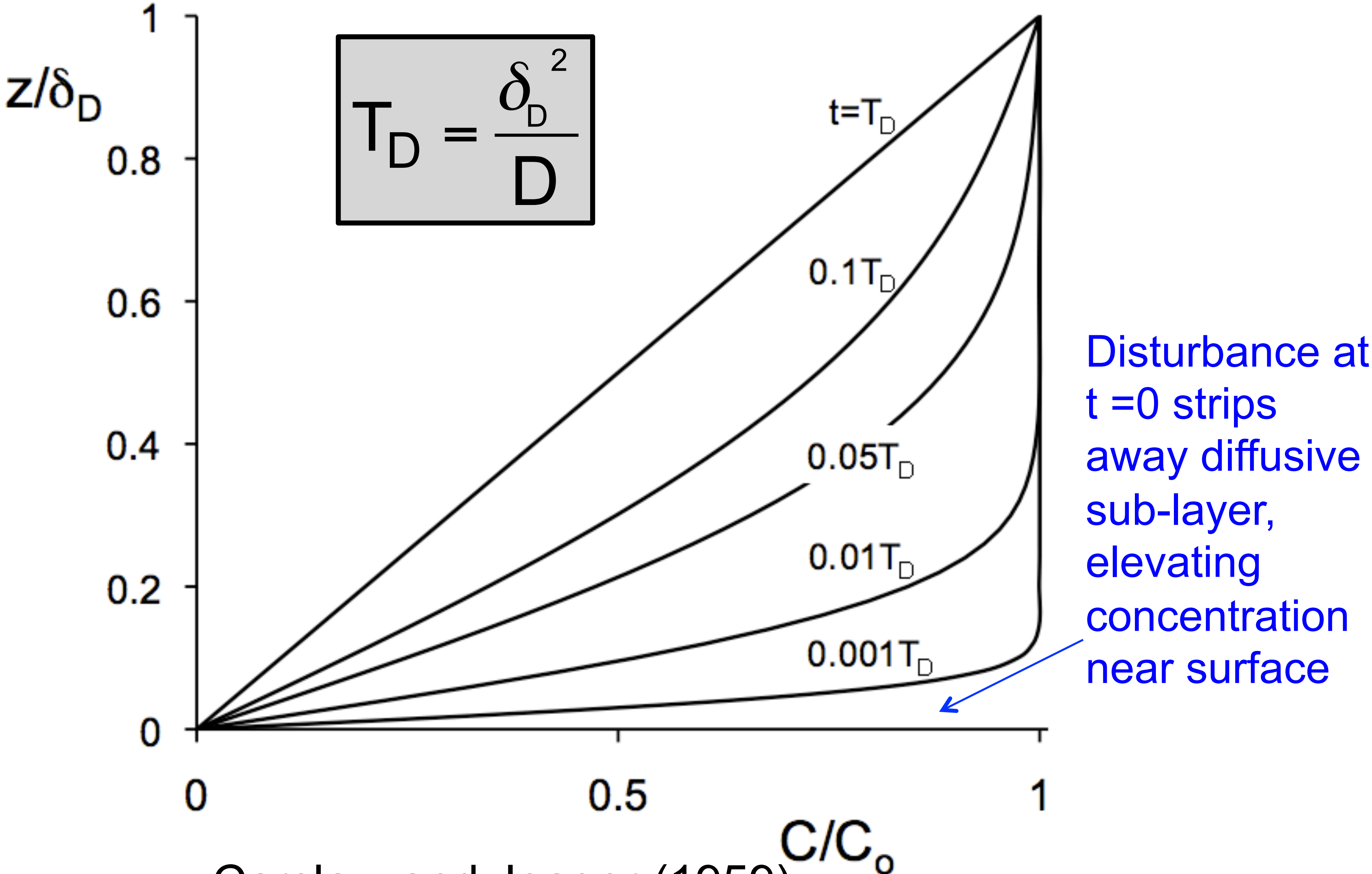
Flux per blade area

$$J_s = DC_o / \delta_D$$

static boundary layer

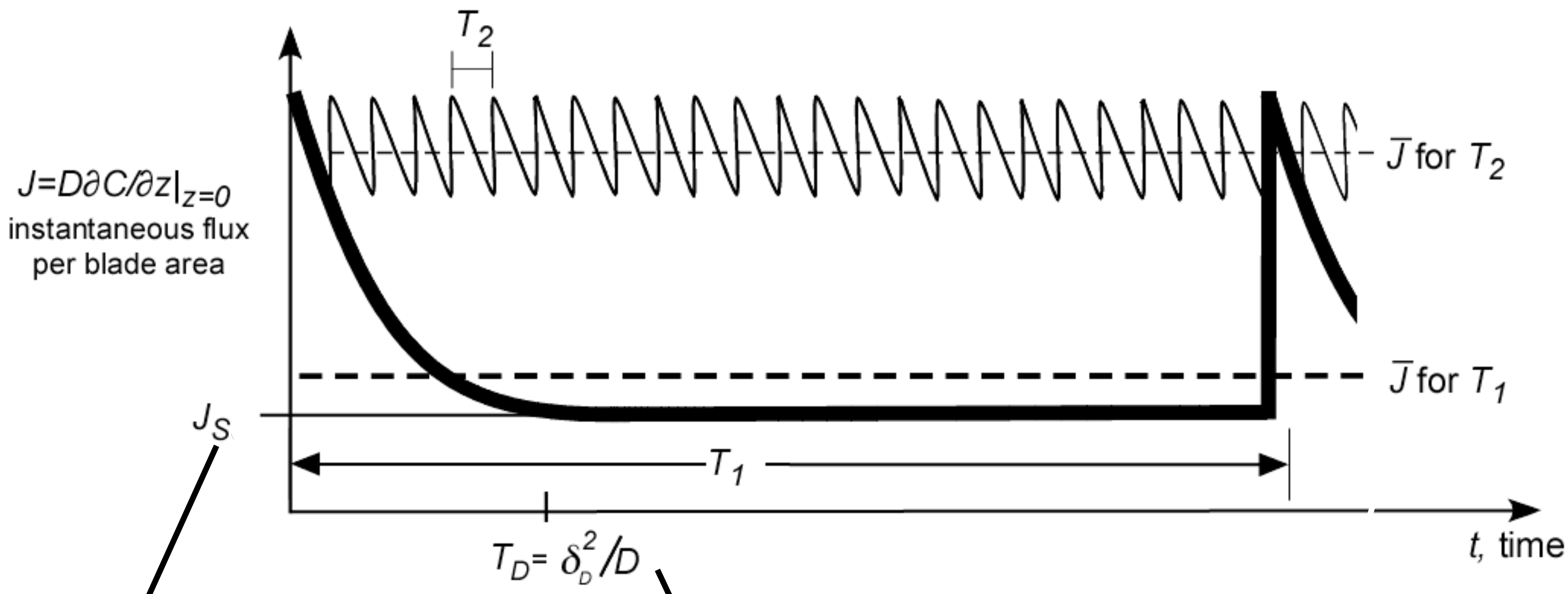
e.g. Dade 1993

Recovery of Diffusive Boundary Layer After Disturbance



Carslaw and Jeager (1959)

Instantaneous and Average Flux at the Blade Surface



$$J_s = D\frac{C_o}{\delta_D}$$

$$T_D = \frac{\delta_D^{\ 2}}{D}$$

Flux Enhancement = $f(T/T_D)$

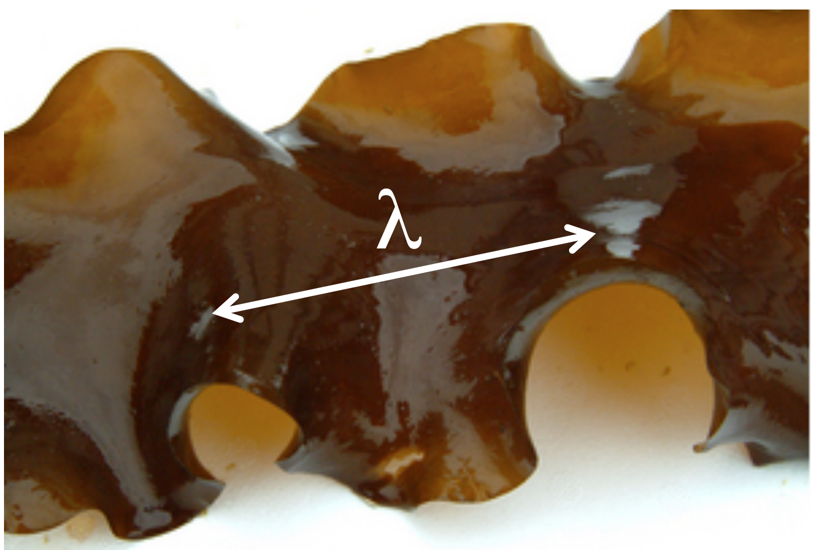
$$\frac{\bar{J}}{J_s} = 1 + 2\frac{T_D}{T}\sum_{n=1}^{\infty}\frac{1}{n^2\pi^2}\left(1 - exp\left(-n^2\pi^2\frac{T}{T_D}\right)\right)$$

Stevens and Hurd (1997)
Huang, Rominger, Nepf (2011)

Ruffles produce vortices which provoke flapping

Huang, Rominger, Nepf (2011)

$$St = \frac{f\,L}{U} = 0.19$$ Blevins, 1990



λ = 5 to 20 cm

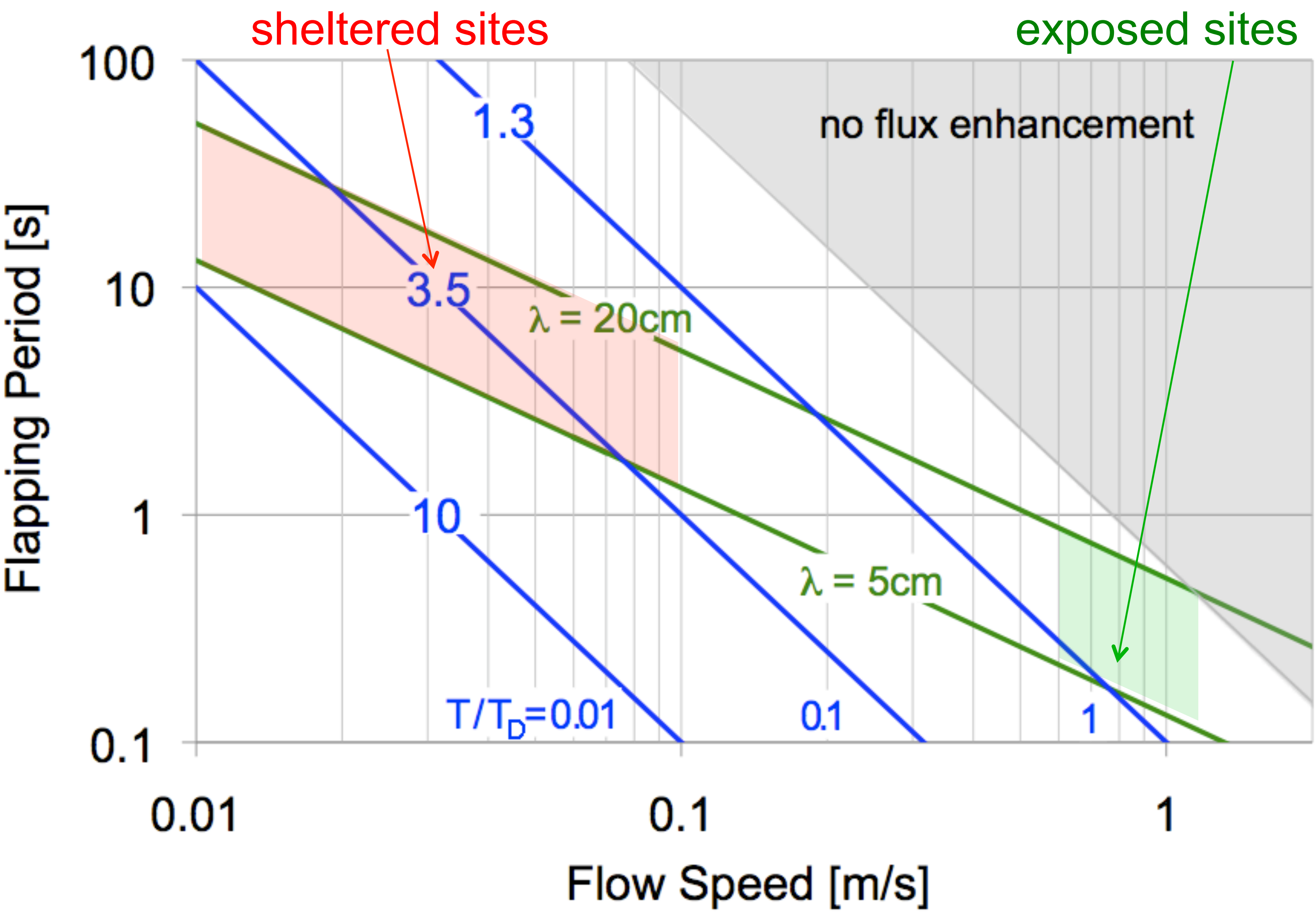
$L = \lambda/2$

$f = St\,U / L$

U = 0.3 m/s

f = 0.6 to 2.3 Hz,

Potential Impact of Blade Flapping in the Field

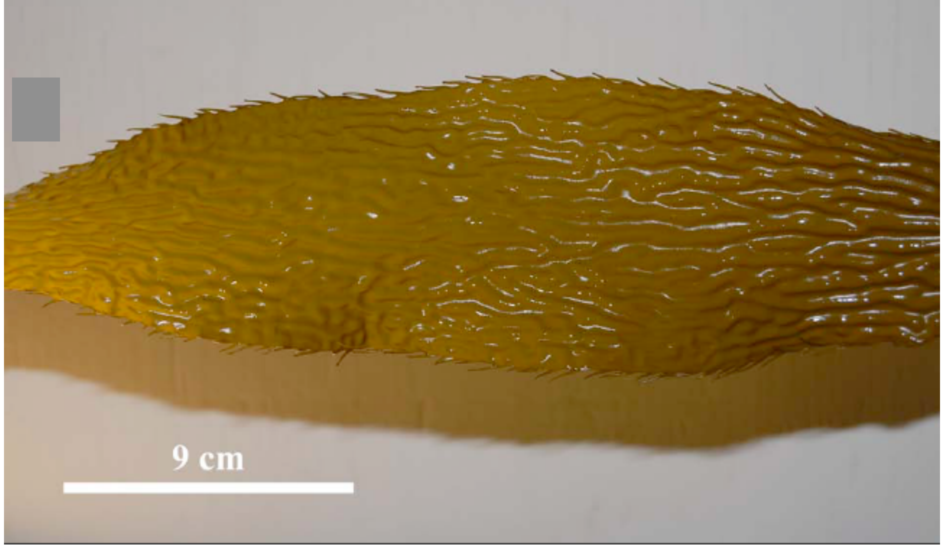


Sheltered Sites:
ruffles provide flux benefit
with little drag disbenefit.

Exposed Sites:
ruffles provide little flux benefit
with large drag disbenefit.

Michael Guiry's Seaweed Site

Another Kind of Wrinkle



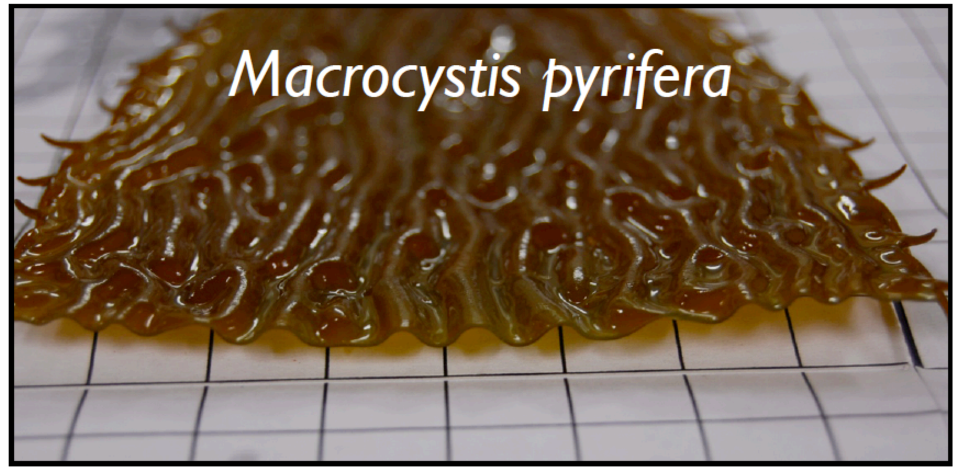
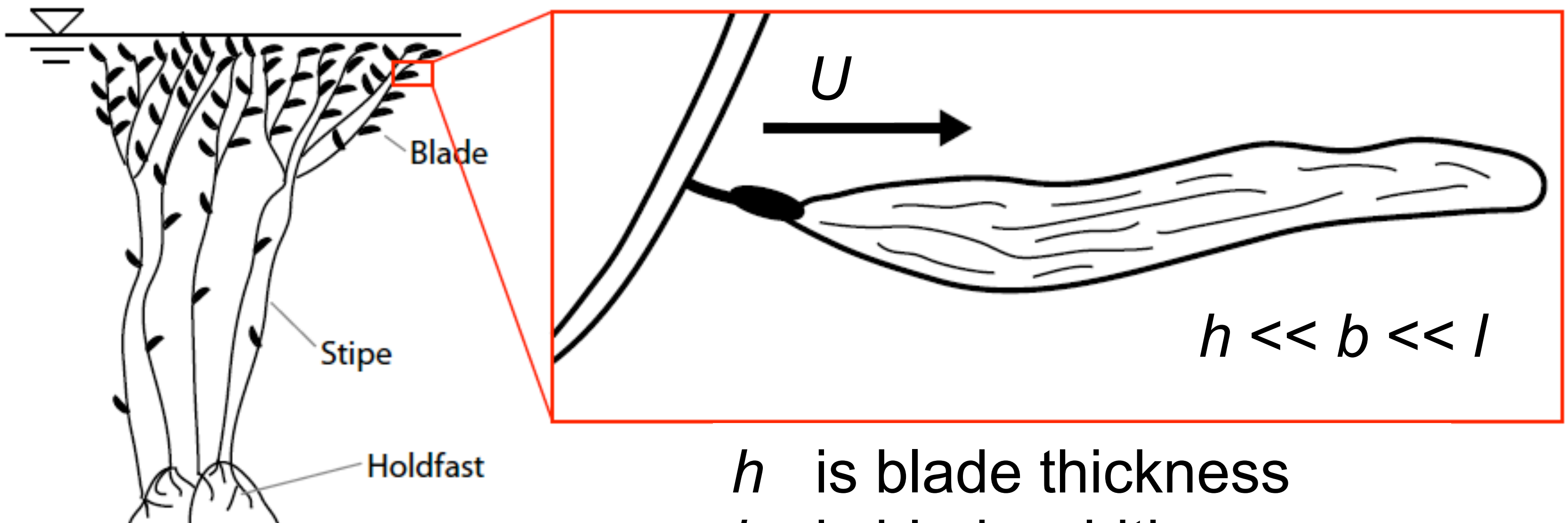


Photo: J. Rominger



h is blade thickness

b is blade width

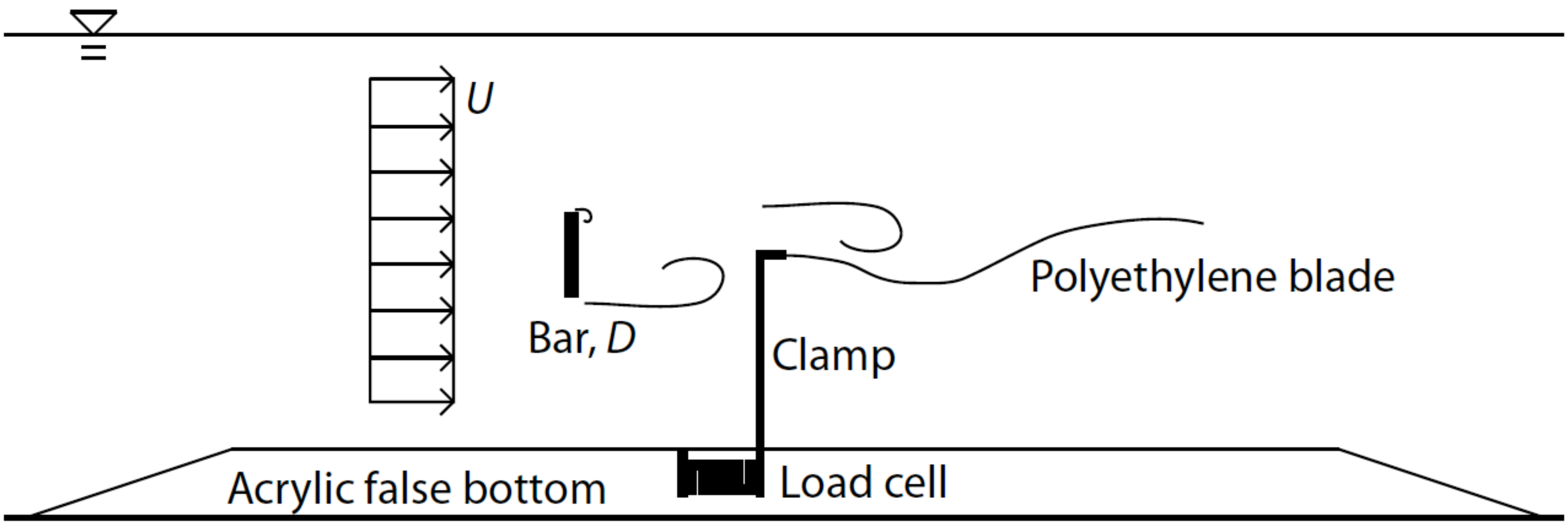
l is blade length

$$\mu = \frac{\rho h}{\rho_f l}$$

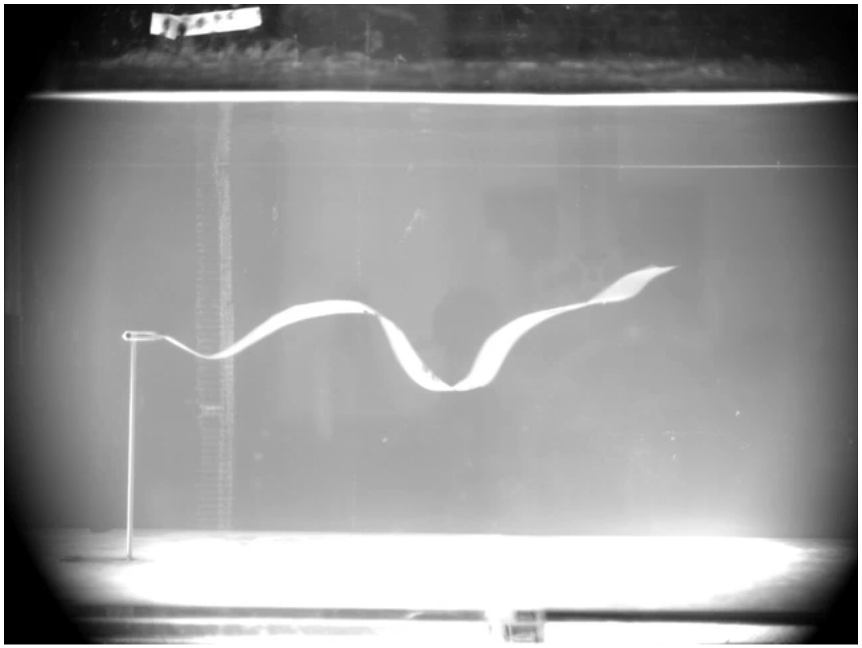
$$\eta = \frac{EI}{\rho_f b U^2 l^3} = \frac{\text{rigidity}}{\text{fluid forcing}}$$

$$I = \frac{bh^3}{12}$$

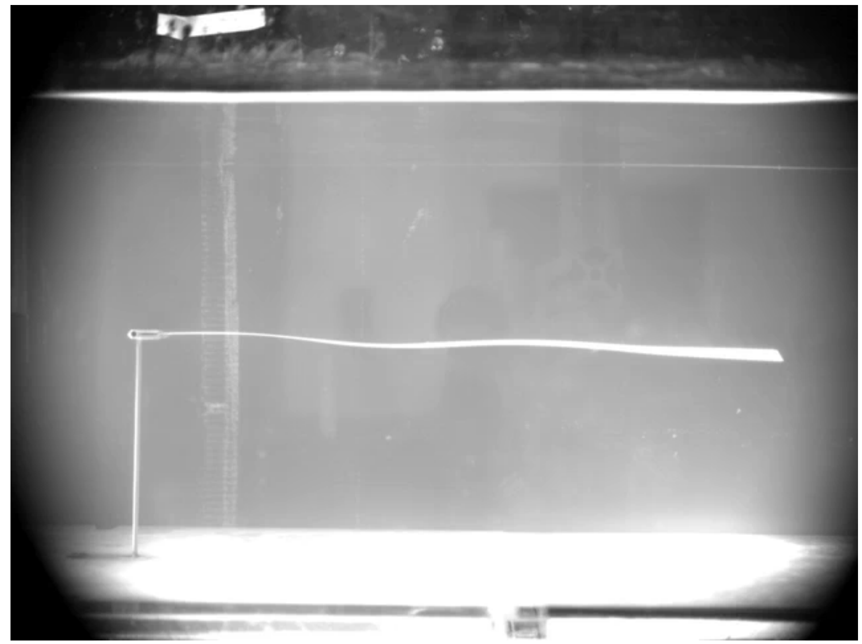
$\eta = 10^{-6}$ to 10^{-2}



50 μm blade
$\eta = 4 \times 10^{-5}$

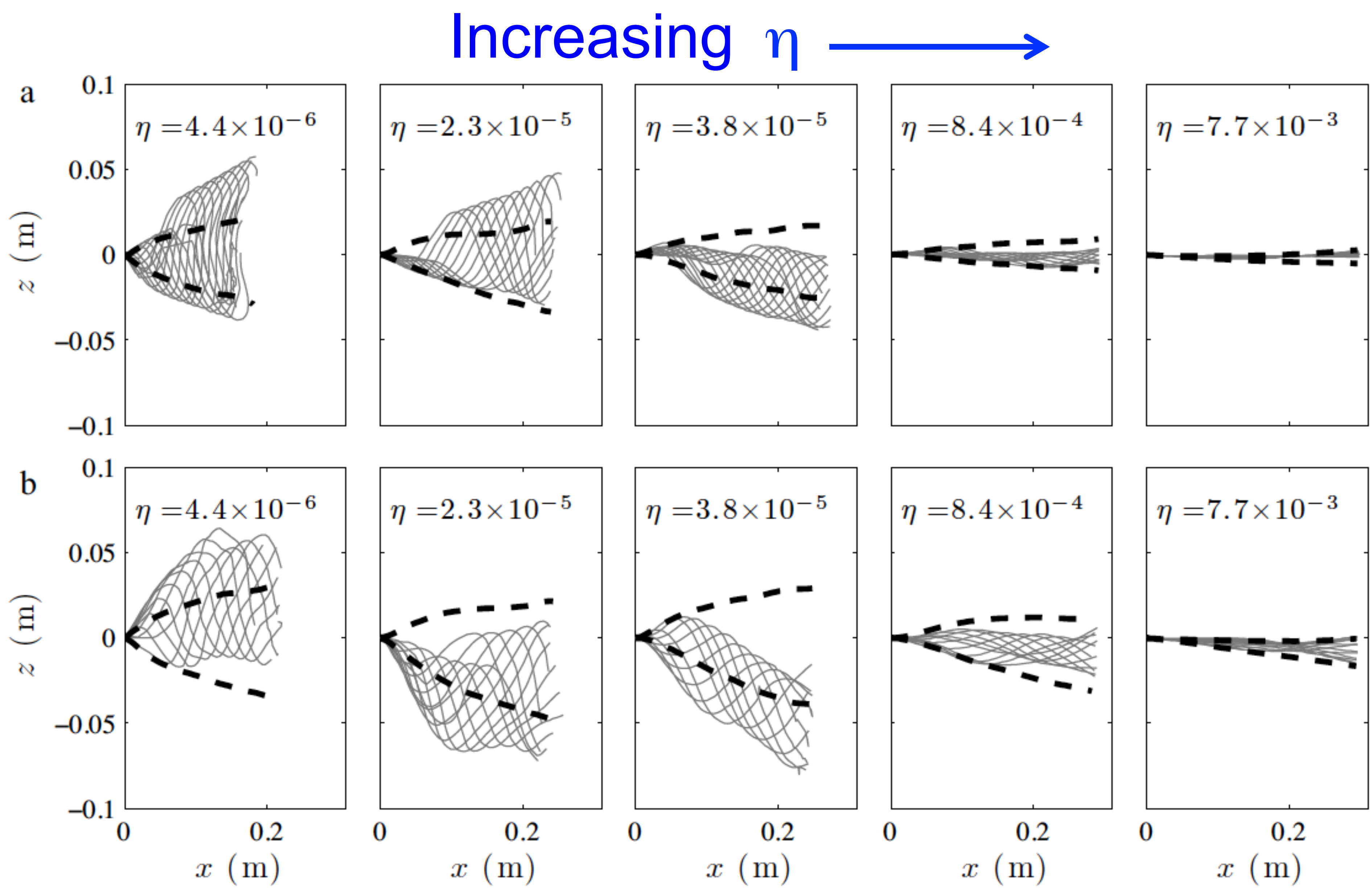


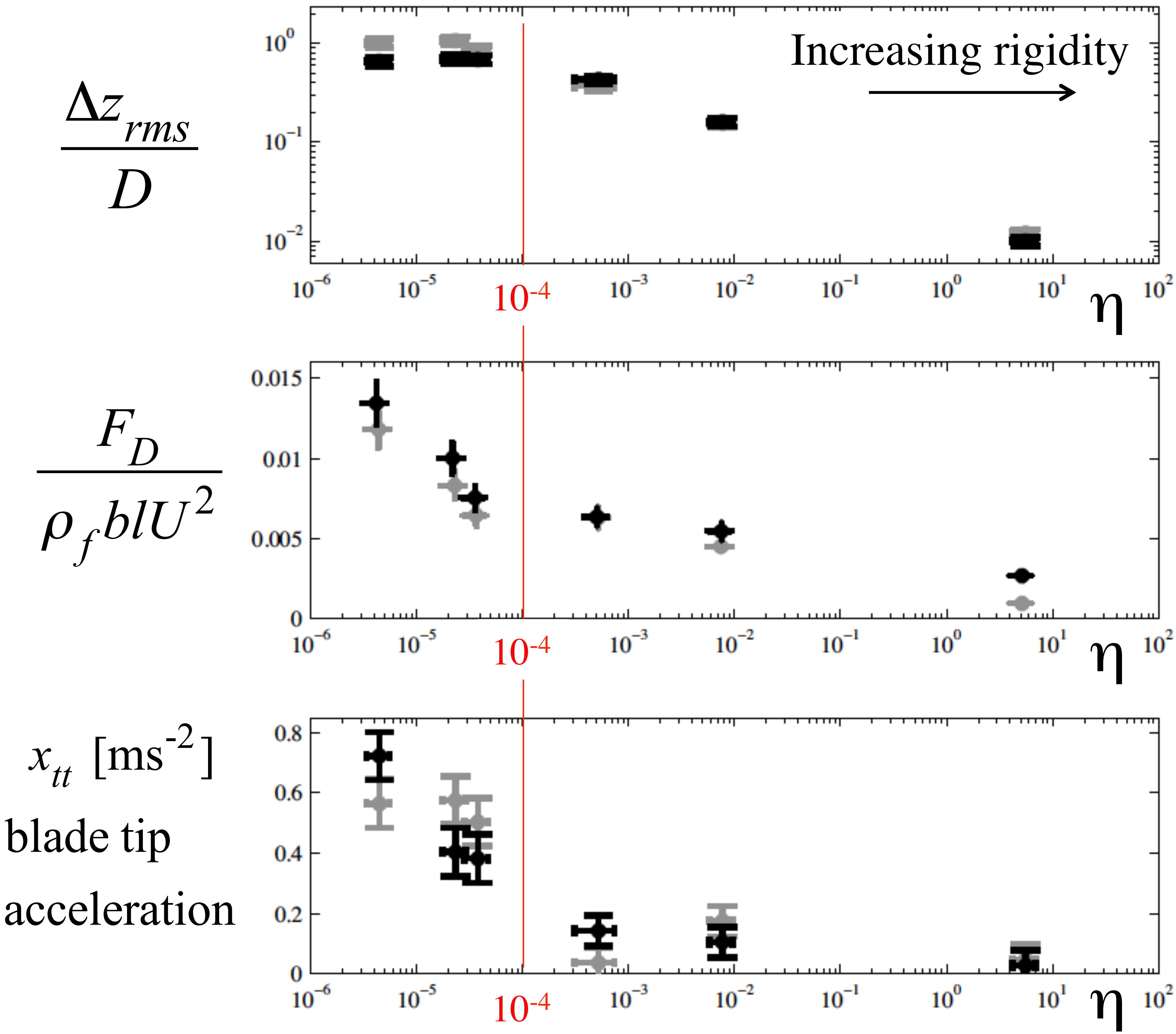
250 μm blade
$\eta = 5 \times 10^{-4}$



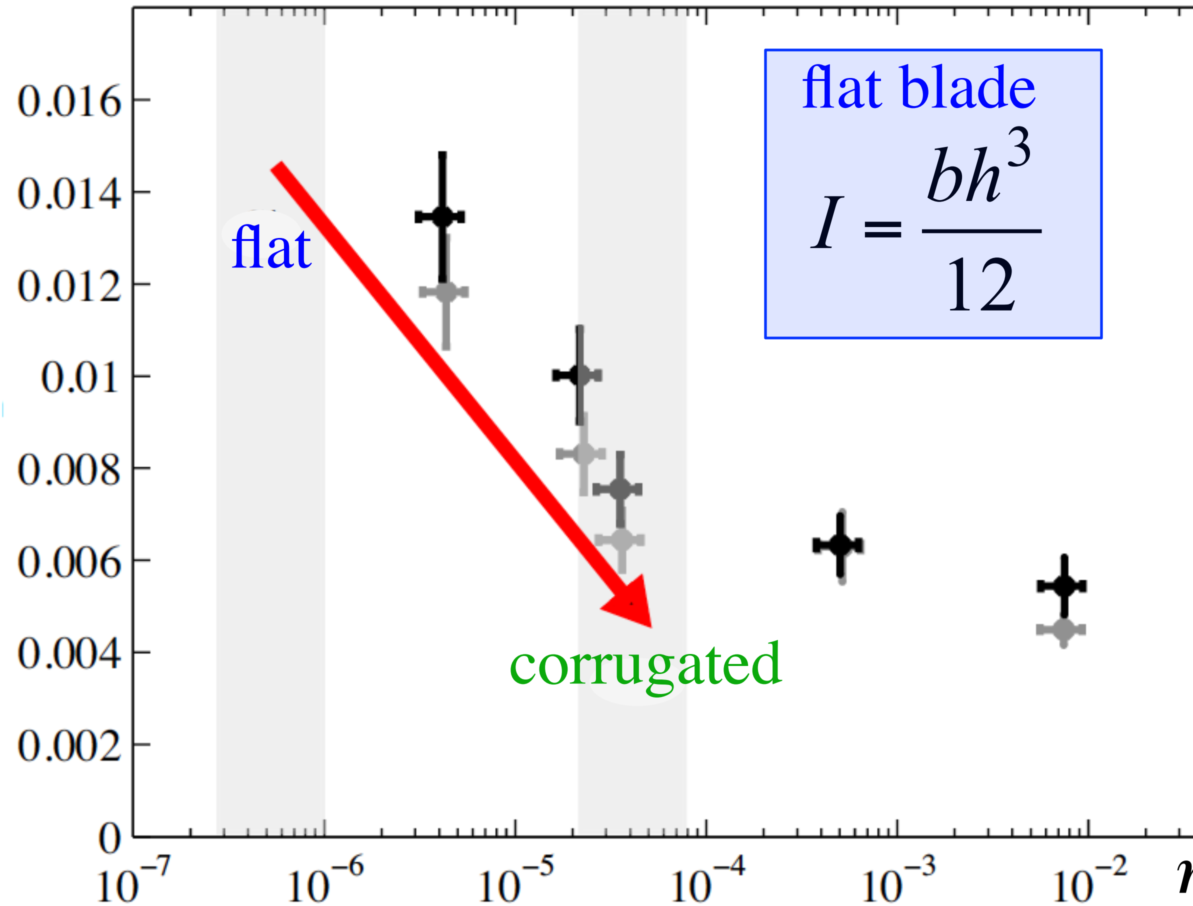
$$\frac{F_{50}}{F_{250}} = 1.8 \pm 0.2$$

Blade Motion Decreases as η Increases





Δz_rms / D
Increasing rigidity
F_D / ρ_f blU^2
x_tt [ms^-2]
blade tip
acceleration
10^-4
η



$$\frac{F_D}{\rho_f b l U^2}$$

flat blade

$$I = \frac{bh^3}{12}$$

$$\eta = \frac{EI}{\rho_f b U^2 l^3}$$

http://www.studyblue.com

corrugated blade [J. Rominger]

corrugated blade $I = \frac{ba^2 h}{2}\left(1 + \frac{\pi^2 a^2}{2\lambda^2}\right)$

corrugation amplitude (a)
corrugation wavelength (λ)

Sheltered Sites: U = 0.05 ms^{-1}
η = 9 x 10^{-5}

http://www.studyblue.com

Exposed Sites: U = 0.5 ms^{-1}
η = 7 x 10^{-5}

In regions with high velocity, corrugations provide low-cost stiffness.

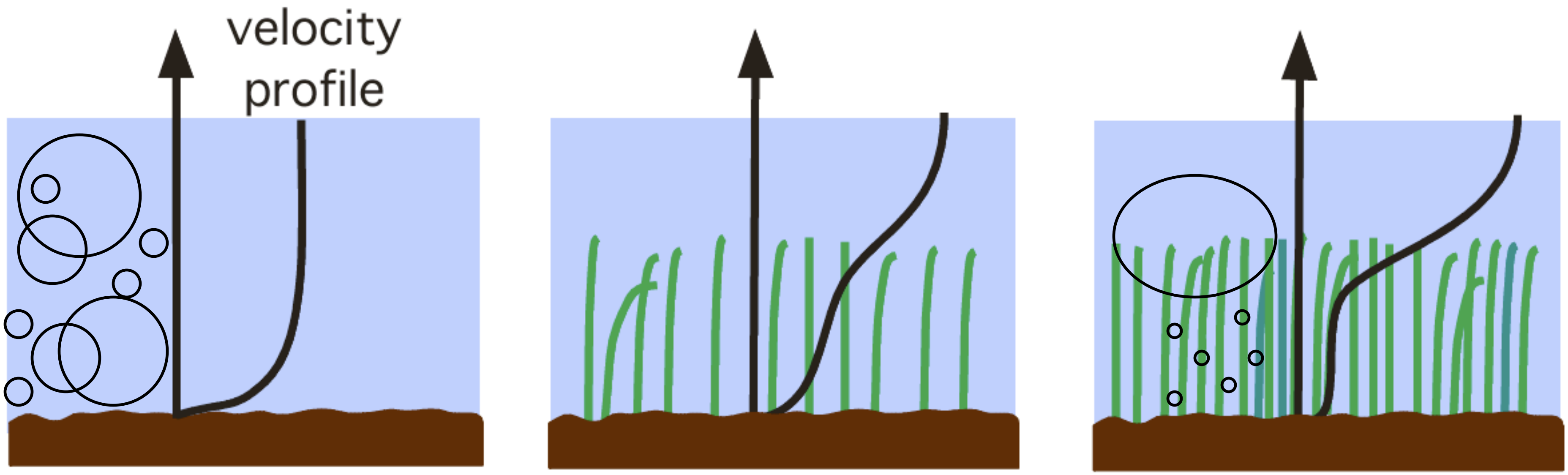
J. Rominger

Blades may tune $$\eta = \frac{EI}{\rho_f b U^2 l^3}$$

to achieve an optimum trade off between flux and drag

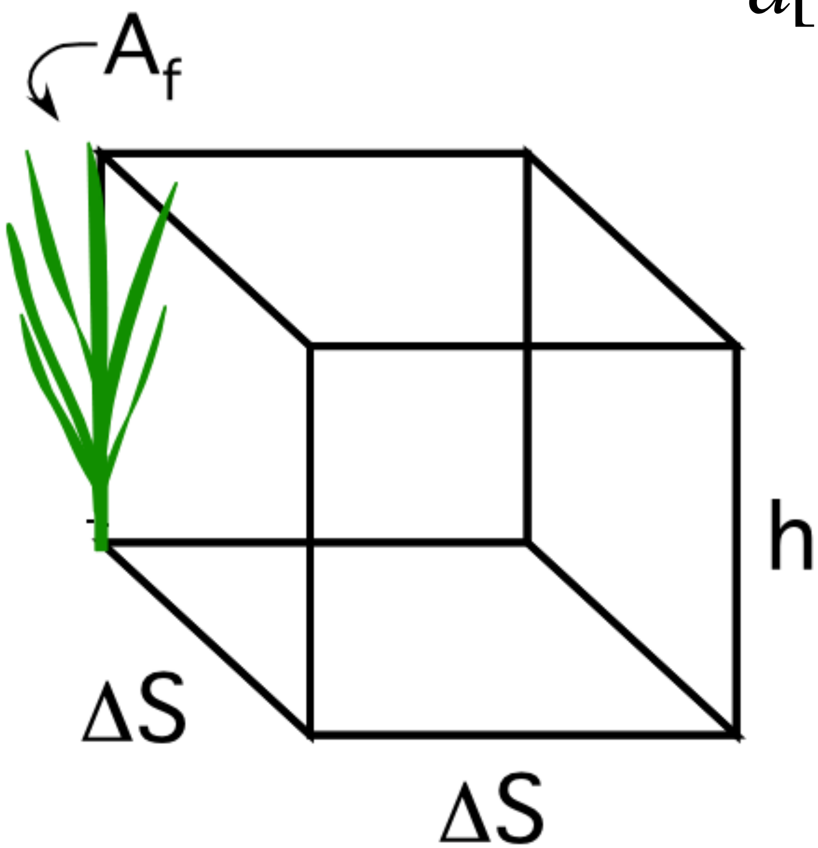
Canopy Scale:

vegetation changes the mean flow and the turbulence



Canopy Definitions

$$a[L^{-1}] = \frac{A_f}{\Delta S^2 h} = \frac{\text{frontal area}}{\text{volume}}$$

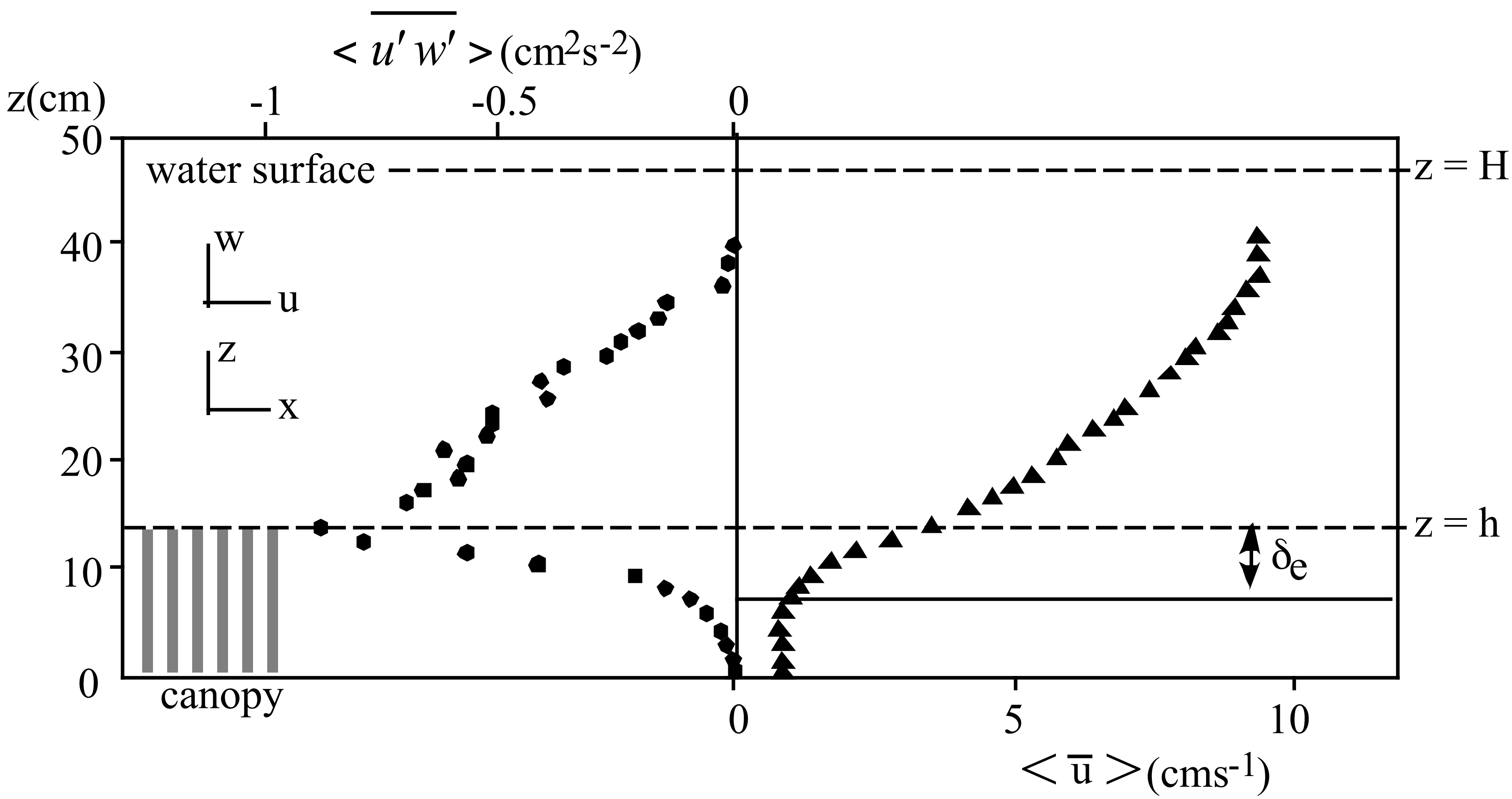


dimensionless meadow density
a.k.a. roughness density

$$ah = \frac{\text{frontal area}}{\text{bed area}}$$

$$\frac{\text{Drag}}{\text{Volume}} = \frac{1}{2}\rho C_D\, a\, u^2$$

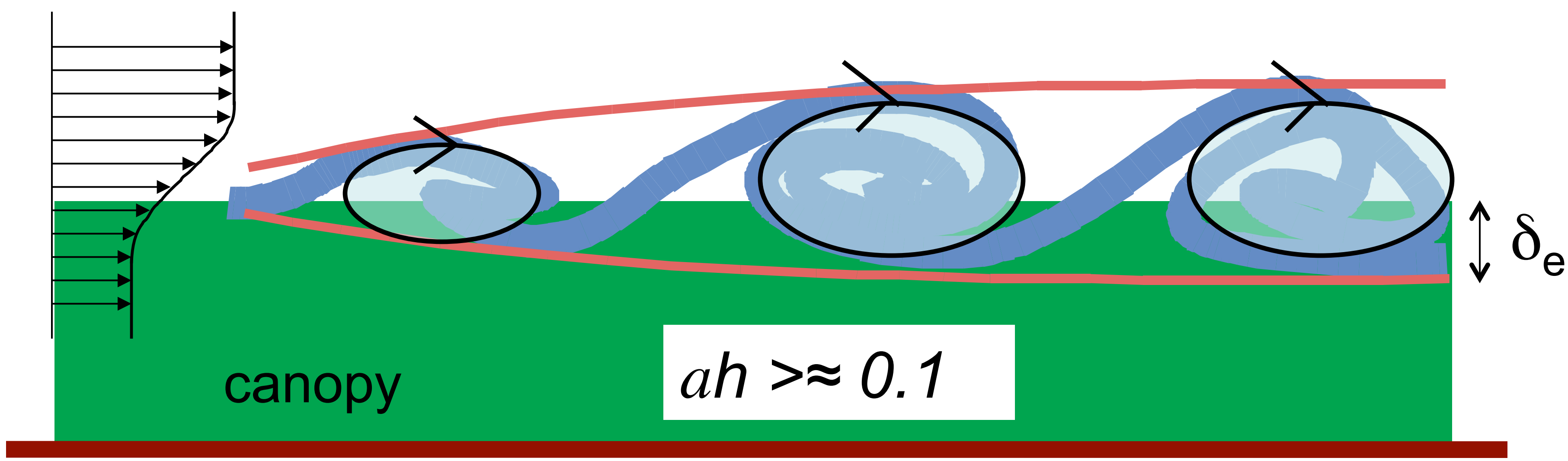
Changes in Mean and Turbulent Fluid Motion



data from Ghisalberti 2005

Mixing Layer Analogy

Raupach, Finnigan, and Brunet 1996



Strong, coherent vortices form above the canopy

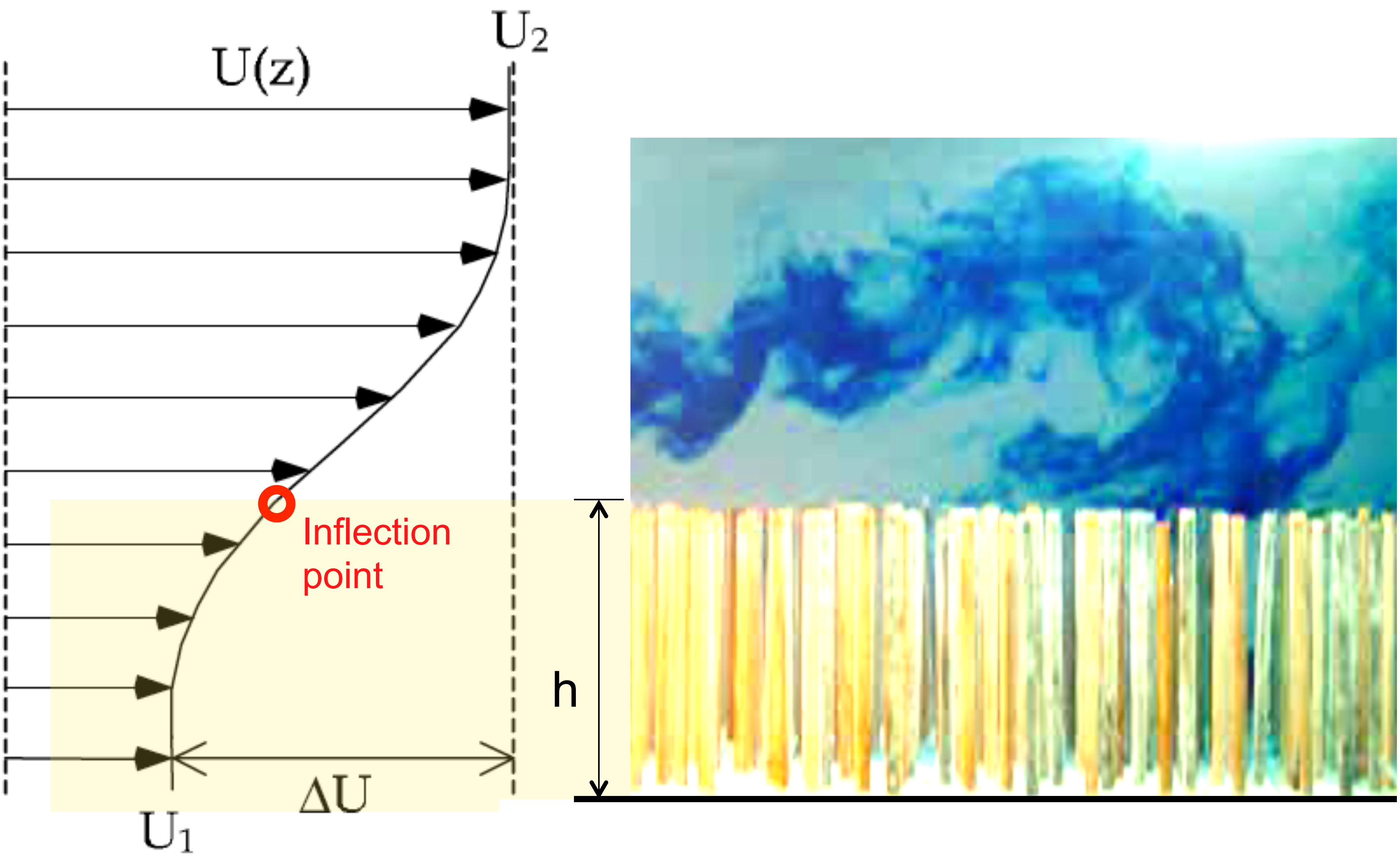
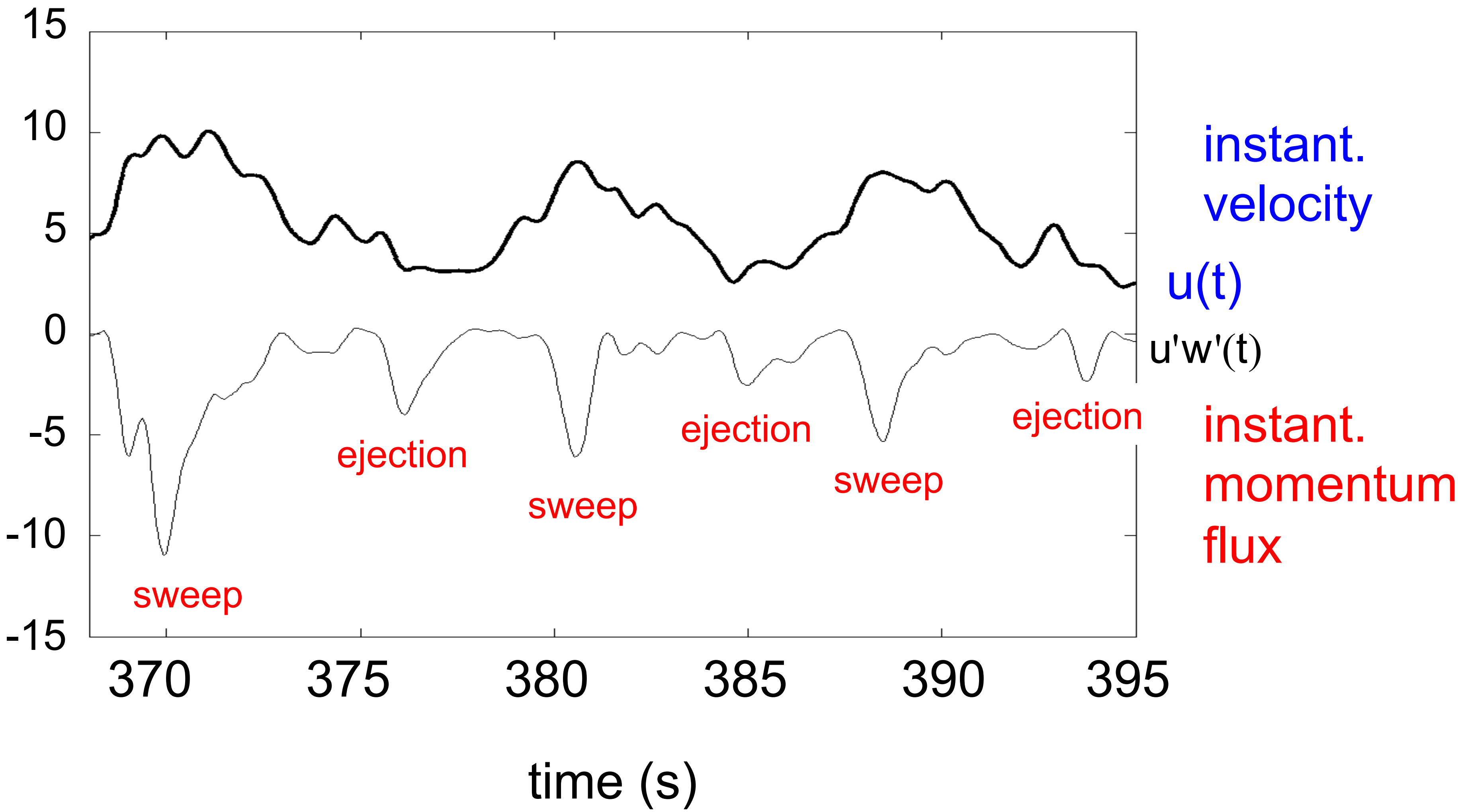


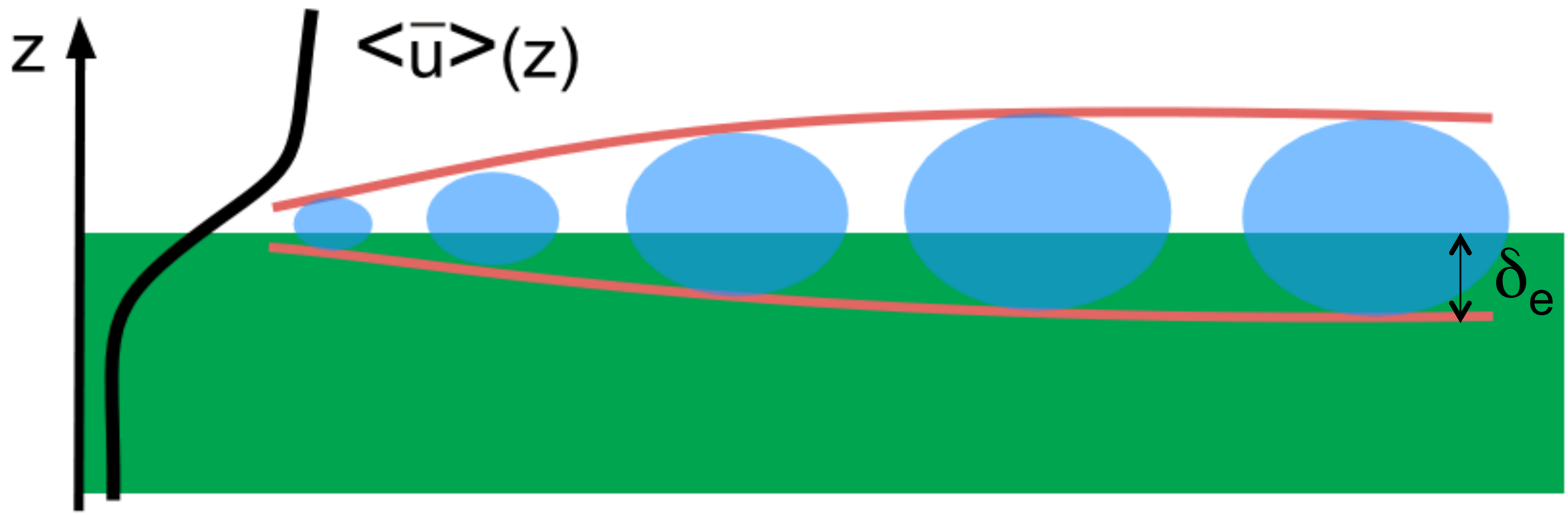
Image by Marco Ghisalberti

Shear-Layer Vortices Dominate Momentum Transport



Ghisalberti and Nepf 2002

Kinetic Energy (k_s) Balance



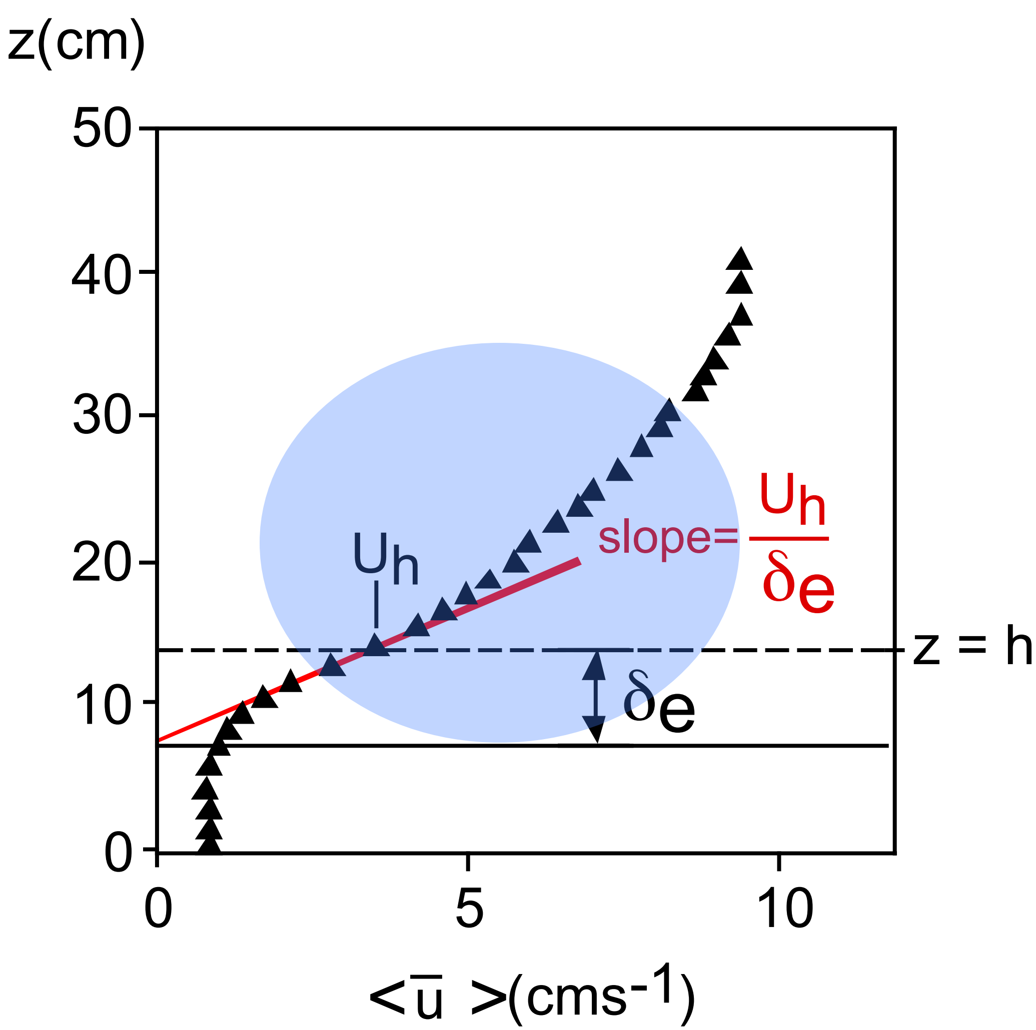
$$\frac{D}{Dt}\left\langle \overline{k_s} \right\rangle = -\left\langle \overline{u'w'} \right\rangle \frac{\partial \langle \overline{u} \rangle}{\partial z} - \frac{1}{2} C_D a \langle \overline{u} \rangle \left(2\left\langle \overline{u'^2} \right\rangle + \left\langle \overline{v'^2} \right\rangle + \left\langle \overline{w'^2} \right\rangle \right)$$

production dissipation by canopy

$$\frac{\langle \overline{u} \rangle C_D a}{\partial \langle \overline{u} \rangle / \partial z} = -\frac{2\left\langle \overline{u'w'} \right\rangle}{2\left\langle \overline{u'^2} \right\rangle + \left\langle \overline{v'^2} \right\rangle + \left\langle \overline{w'^2} \right\rangle} = 0.23 \pm 0.06$$

Nepf et al. 2007

Length-Scale of Vortex Penetration



$$0.23 \pm 0.06 = \frac{\langle \overline{u} \rangle C_D a}{\partial \langle \overline{u} \rangle / \partial z}$$

$$\left.\frac{\partial \langle \overline{u} \rangle}{\partial z}\right|_{z=h} \approx \frac{U_h}{\delta_e}$$

$$\delta_e = \frac{0.23 \pm 0.06}{C_D a}$$

$$\frac{\delta_e}{h} = \frac{0.23 \pm 0.06}{C_D a h}$$

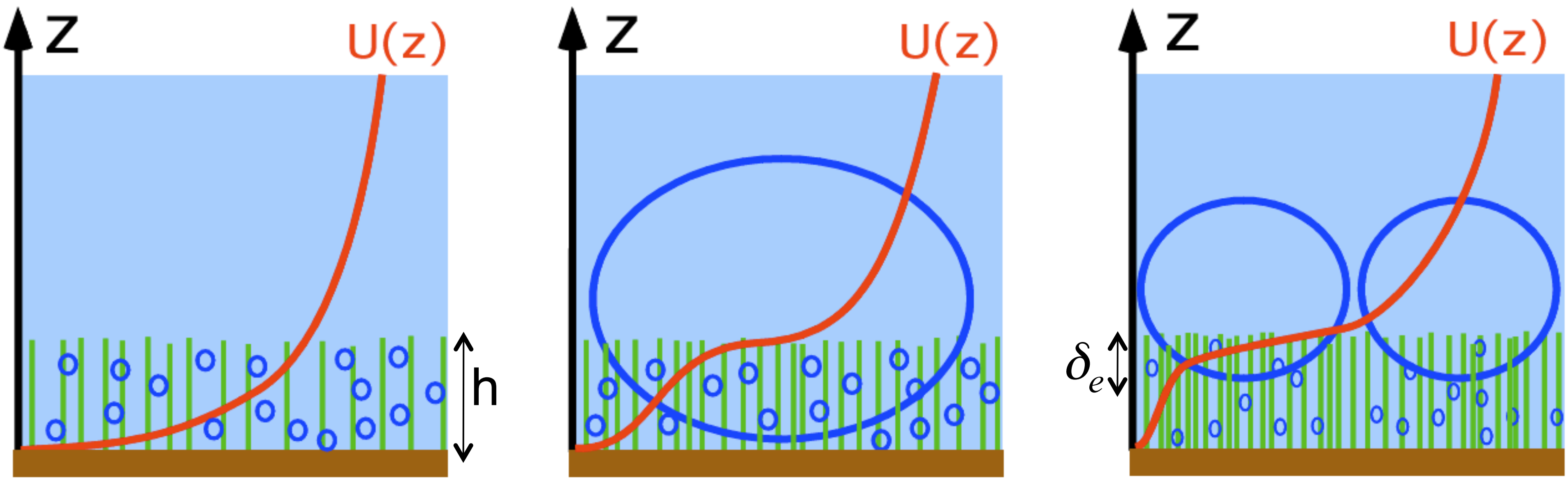
Dense and Sparse Flow Behavior

bed drag > vegetation drag

bed drag < vegetation drag

sparse

dense



$C_D a h < 0.04$

$C_D a h = 0.1$

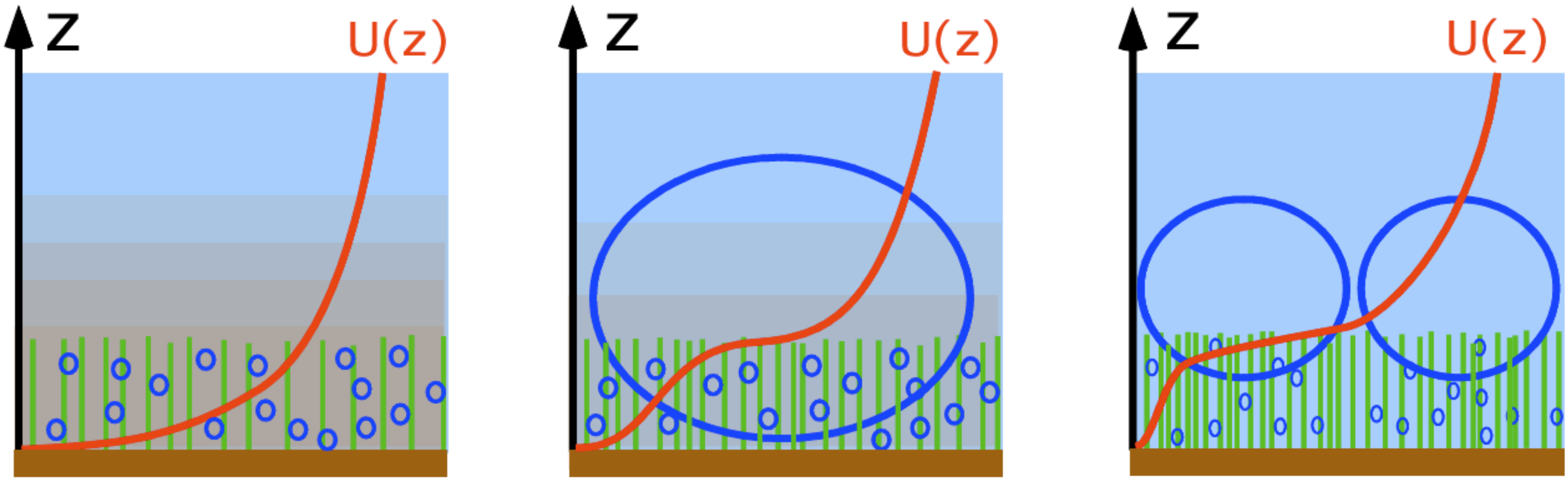
$\delta_e/h = 1$

$C_D a h > 0.23$

$\delta_e/h < 1$

Implications for Resuspension

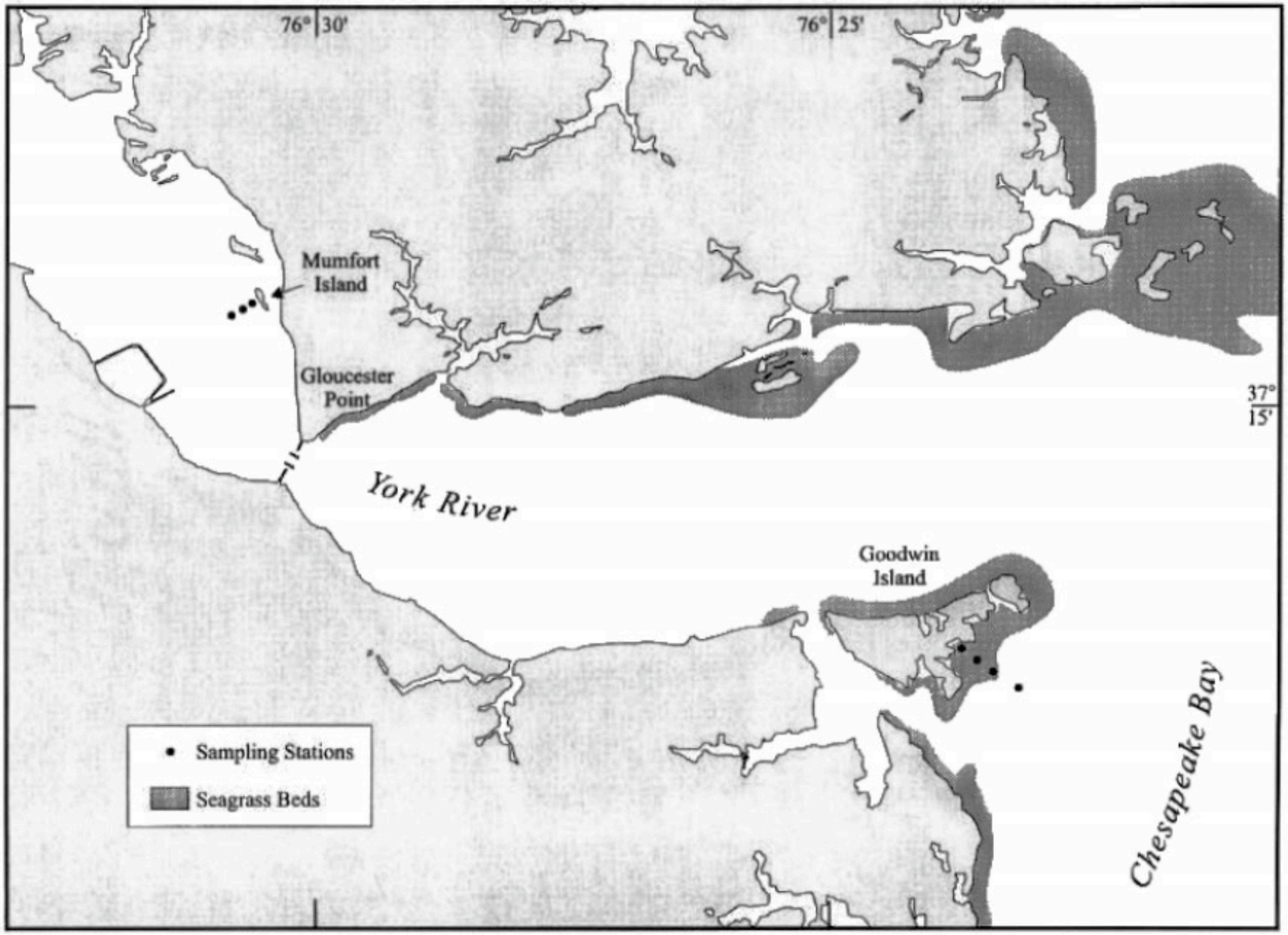
$ah \approx < 0.04$ $ah \approx 0.1$ $ah > 0.23$



high re-suspension
poor light climate

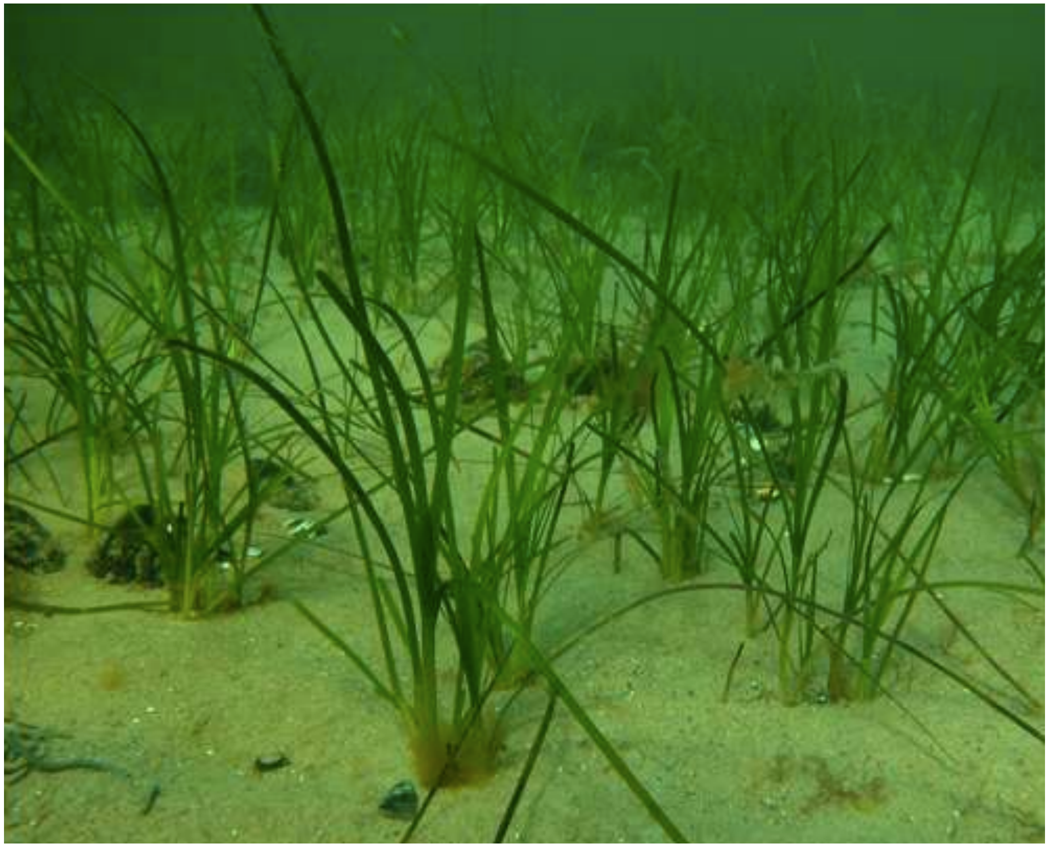
low re-suspension
good light climate

Ken Moore (2004) J. Coastal Res.



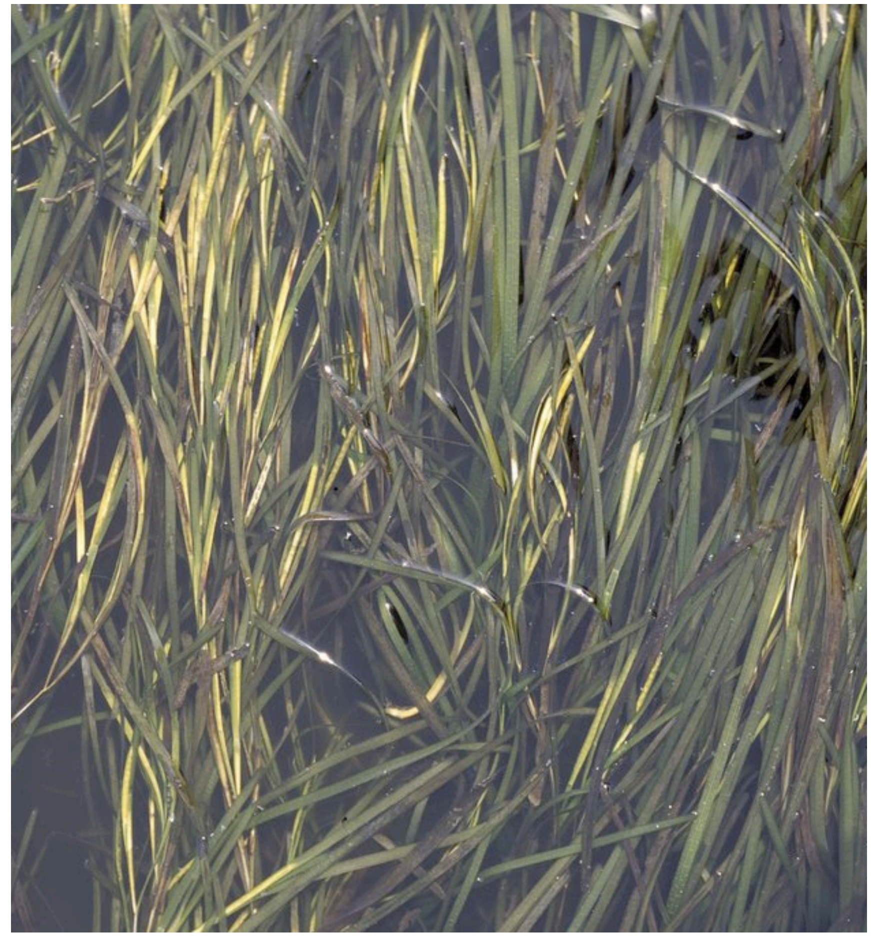
Zostera marina density changes over the growing season

sparse



http://guiamarina.com/gallery/main.php

dense



http://picasaweb.google.com/arehn76/ZostRacEs#5090358687742550738

Ken Moore (2004) J. Coastal Res.

BANDTÅNG, ZOSTERA MARINA L.

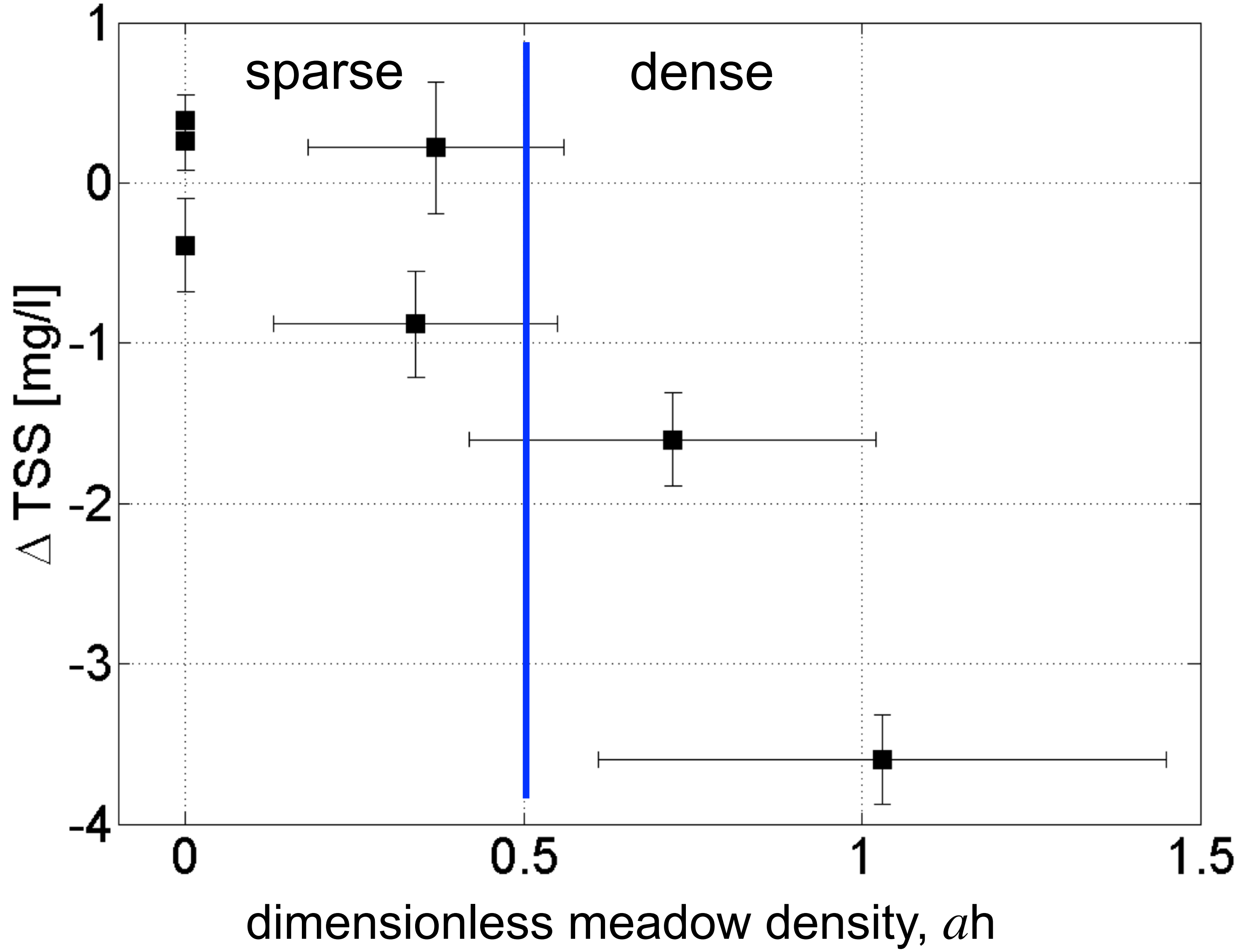
http://commons.wikimedia.org/wiki/Image:Zostera_marina_nf_clean.jpg

$$\frac{biomass}{m^2} = \rho tah$$

$$t = 0.3\ mm$$

$$\rho = 760\ kgm^3$$

ΔTSS: difference in total suspended solids (TSS) between vegetated and unvegetated sites

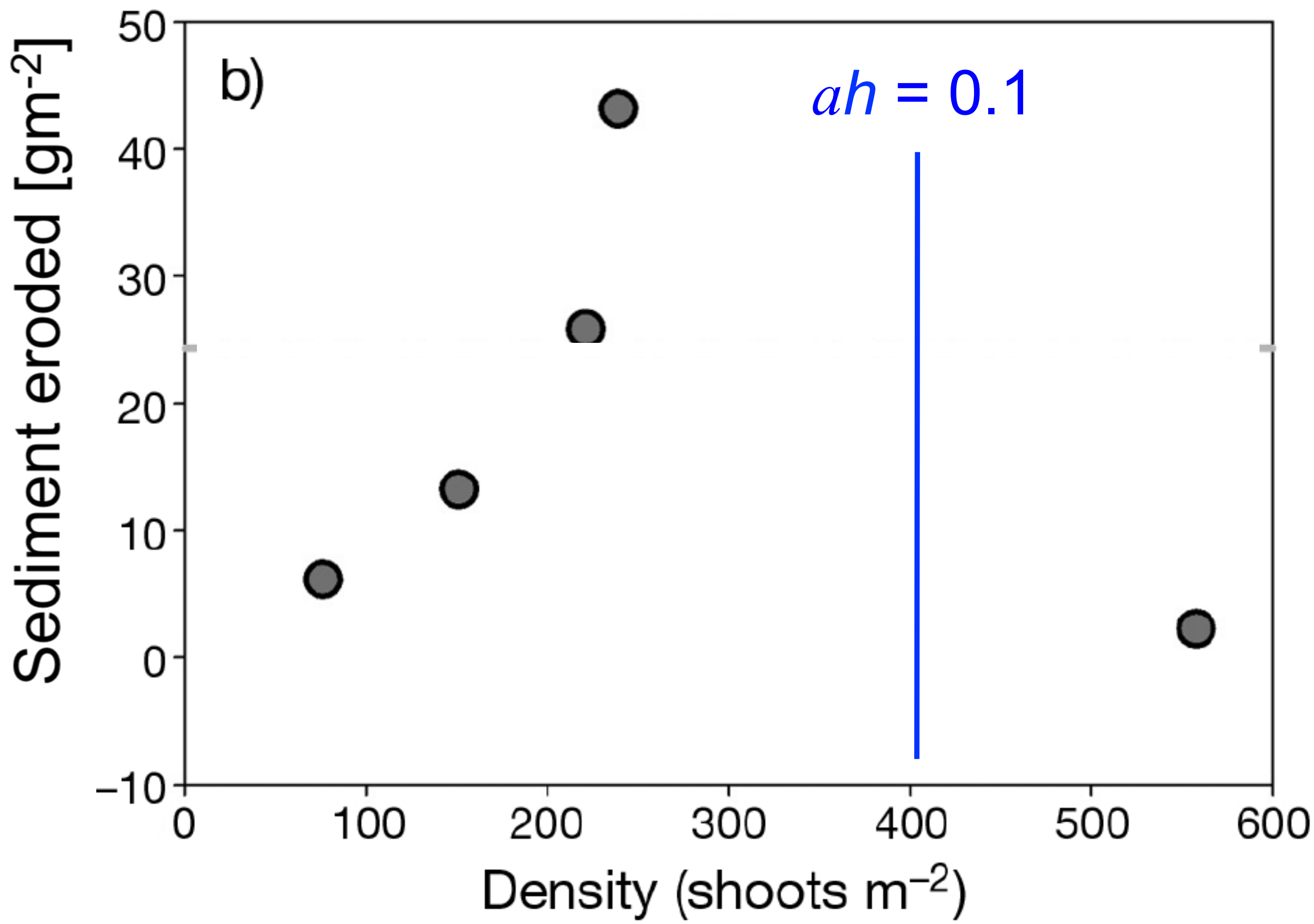


Moore
2004
JCR

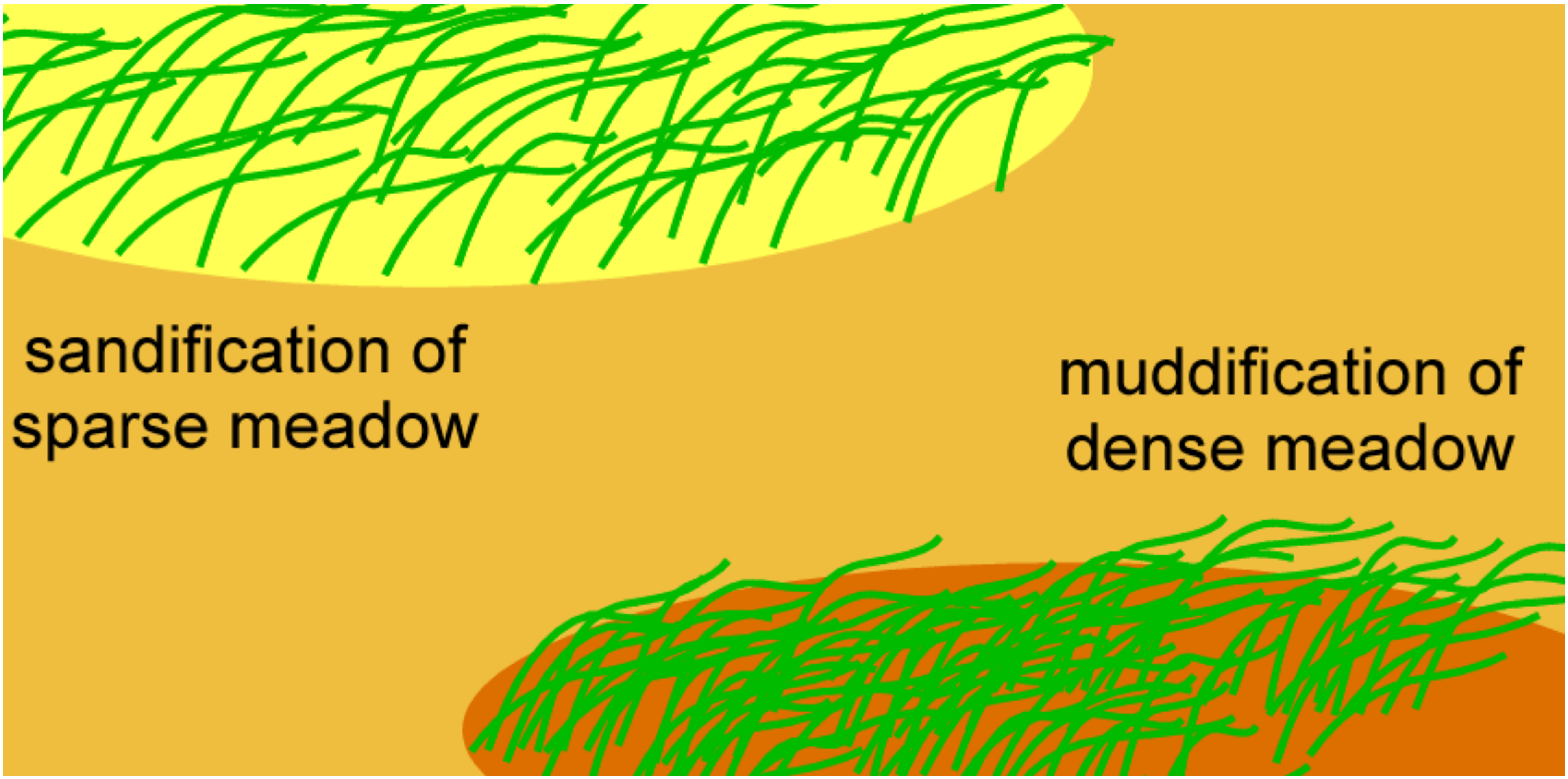
Lawson, McGlathery, Wiberg: MEPS 2012

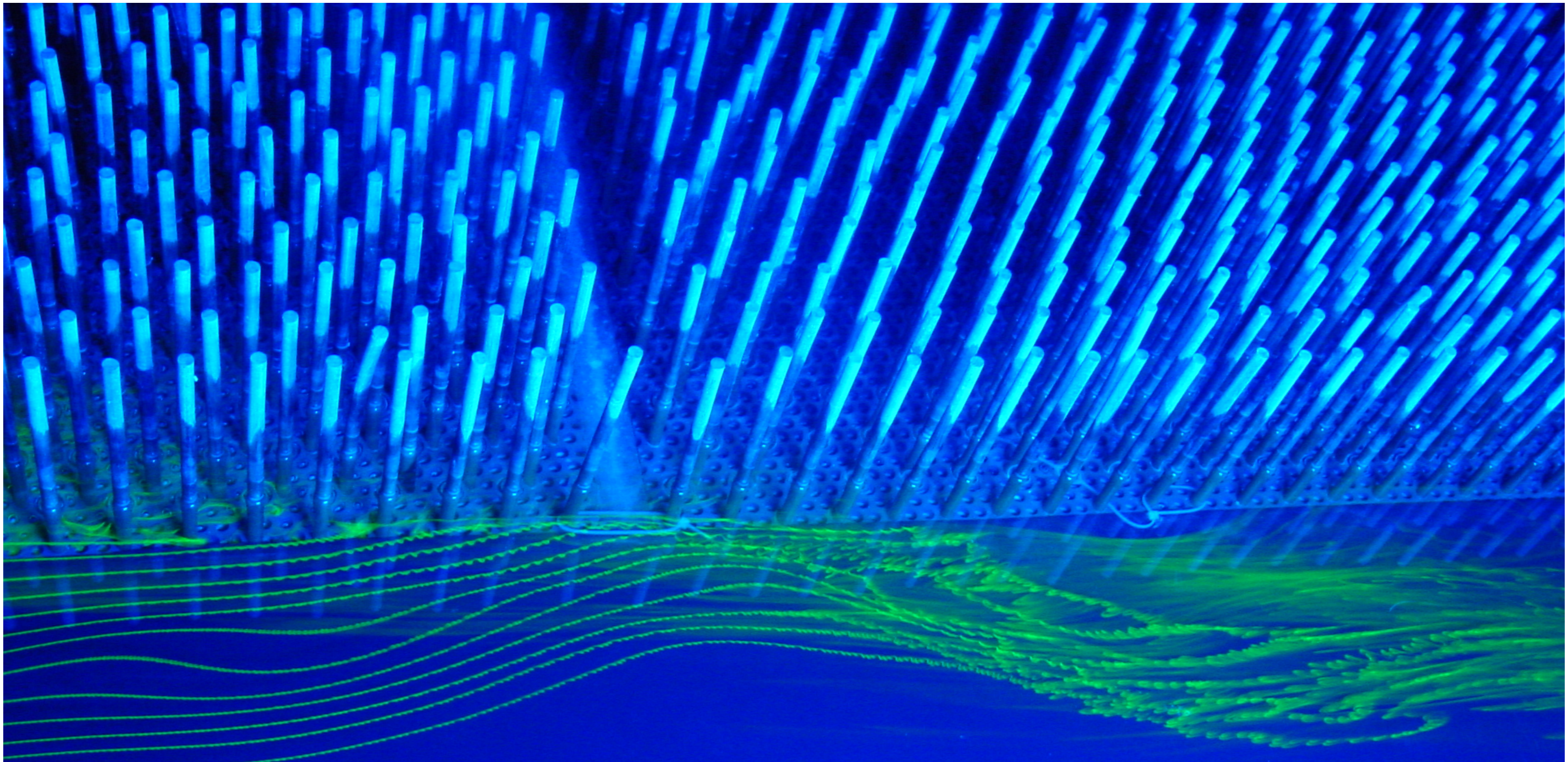
mesocosm study in circular flume

Zostera marina: d = 3 mm, h = 8 cm



Van Katwijk et al 2010 observed differences in sediment texture within patches of different stem density





Thank you for your attention

Thanks to NSF

Thanks to Ivy Huang, Jeff Rominger, and Mitul Luhar

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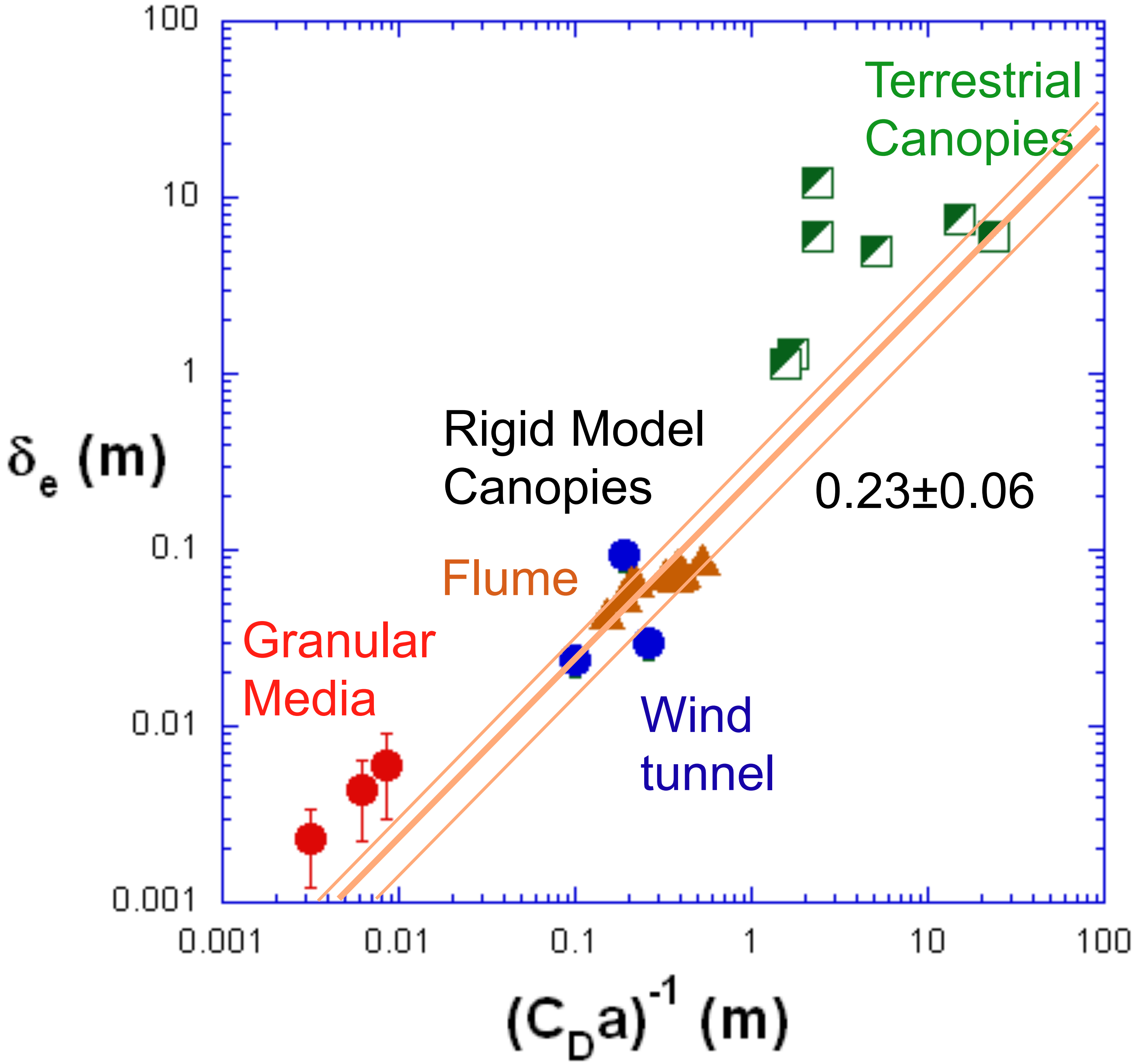
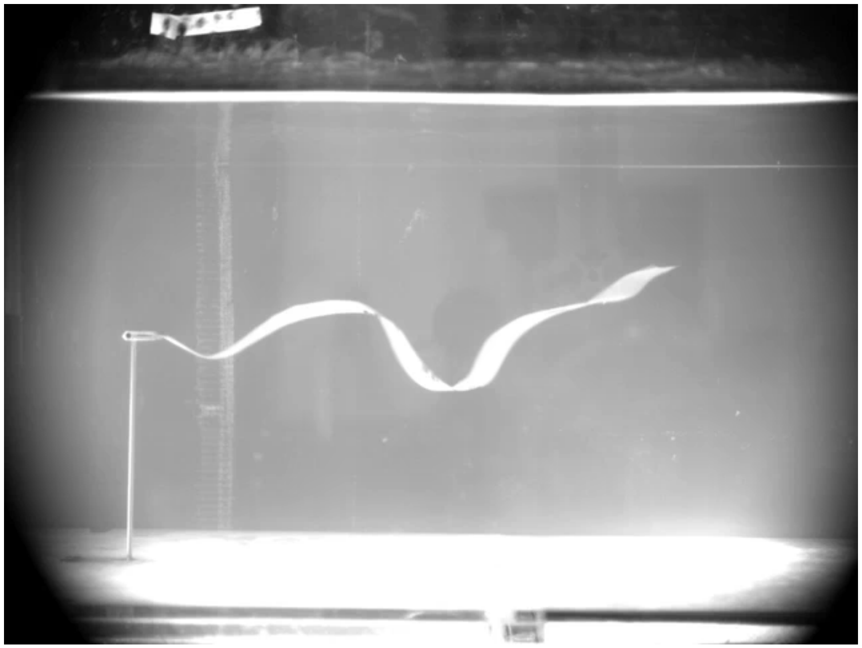
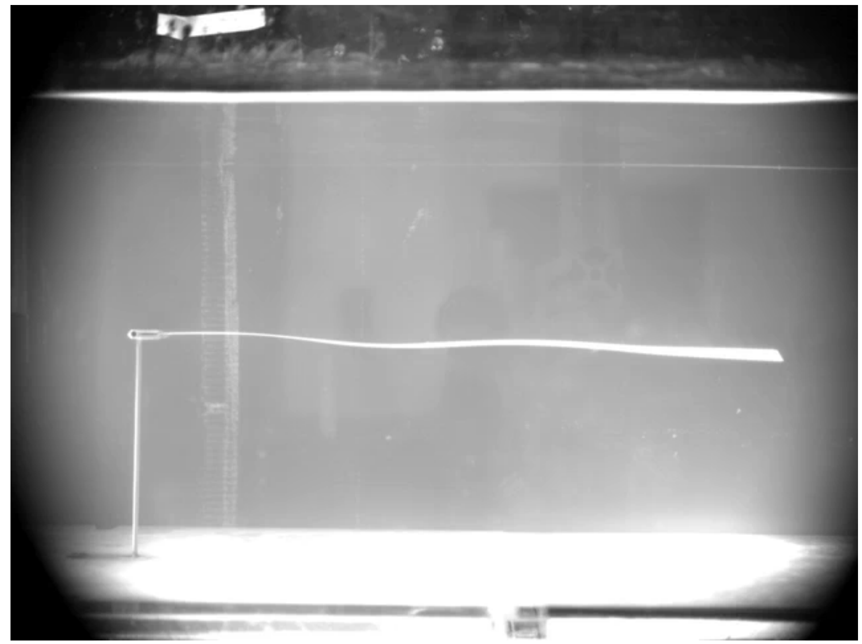


from Ghisalberti 2007

50 μm blade
$\eta = 4 \times 10^{-5}$



250 μm blade
$\eta = 5 \times 10^{-4}$



$$\frac{Flux_{50}}{Flux_{250}} = 2.0 \pm 0.6 \qquad \frac{F_{50}}{F_{250}} = 1.8 \pm 0.2$$