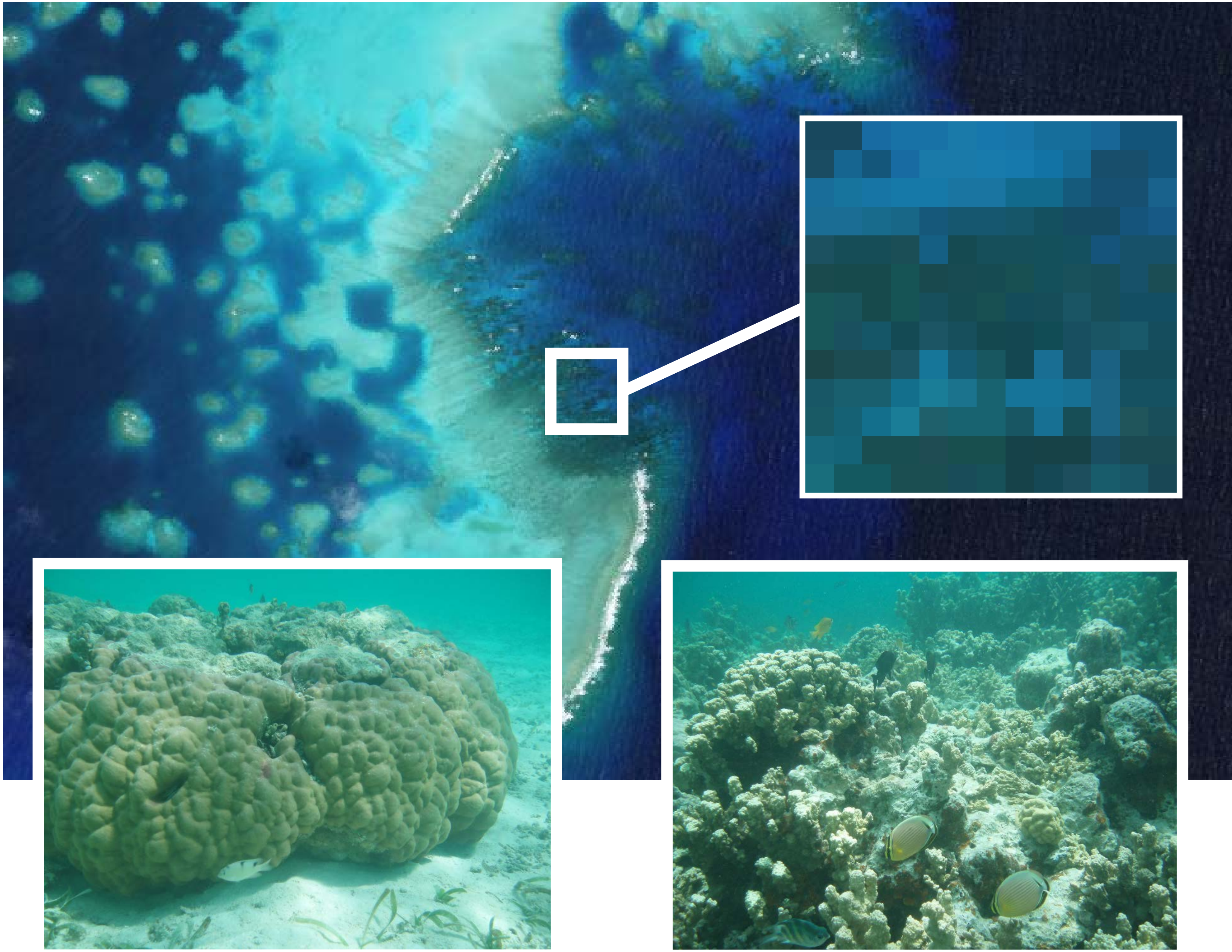
Three dimensional light environment: Coral reefs and seagrasses

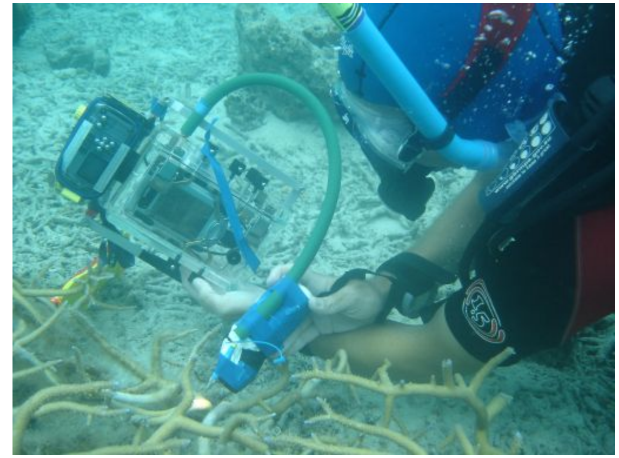
1) Three-dimensional radiative transfer modelling

2) Relevance to remote sensing

3) Photobiology in submerged canopies

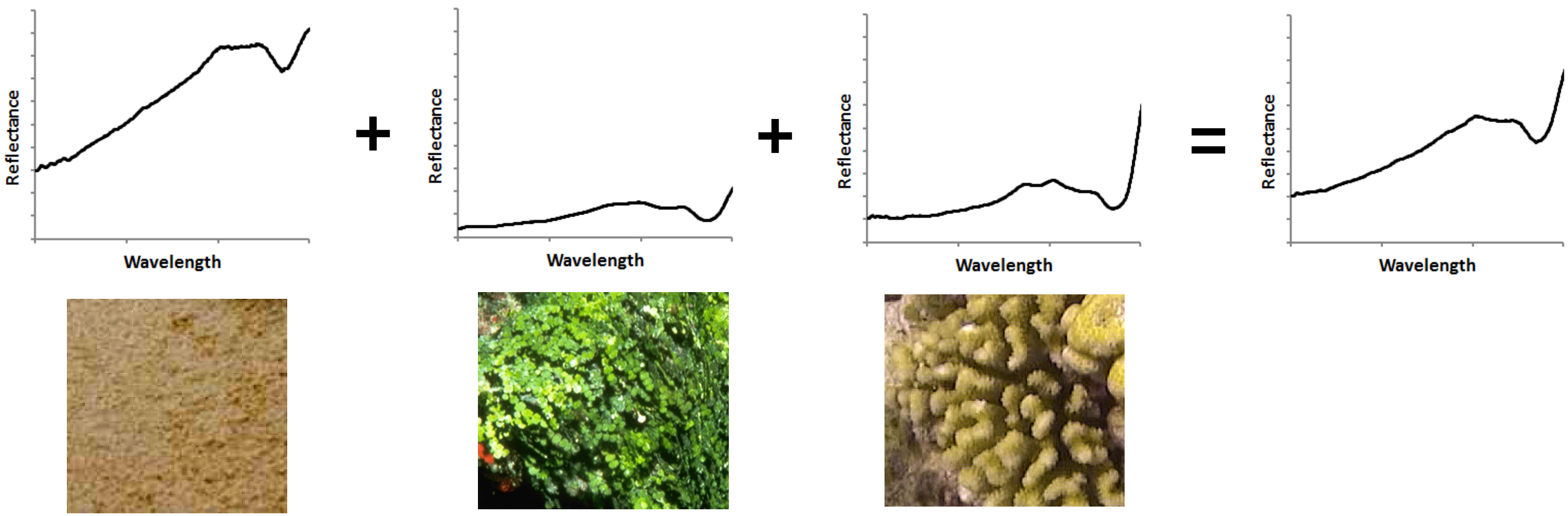


What is the bottom reflectance ?



Linear mixing

- sum individual type reflectances in proportion to their areal cover
- treat them as essentially flat patches

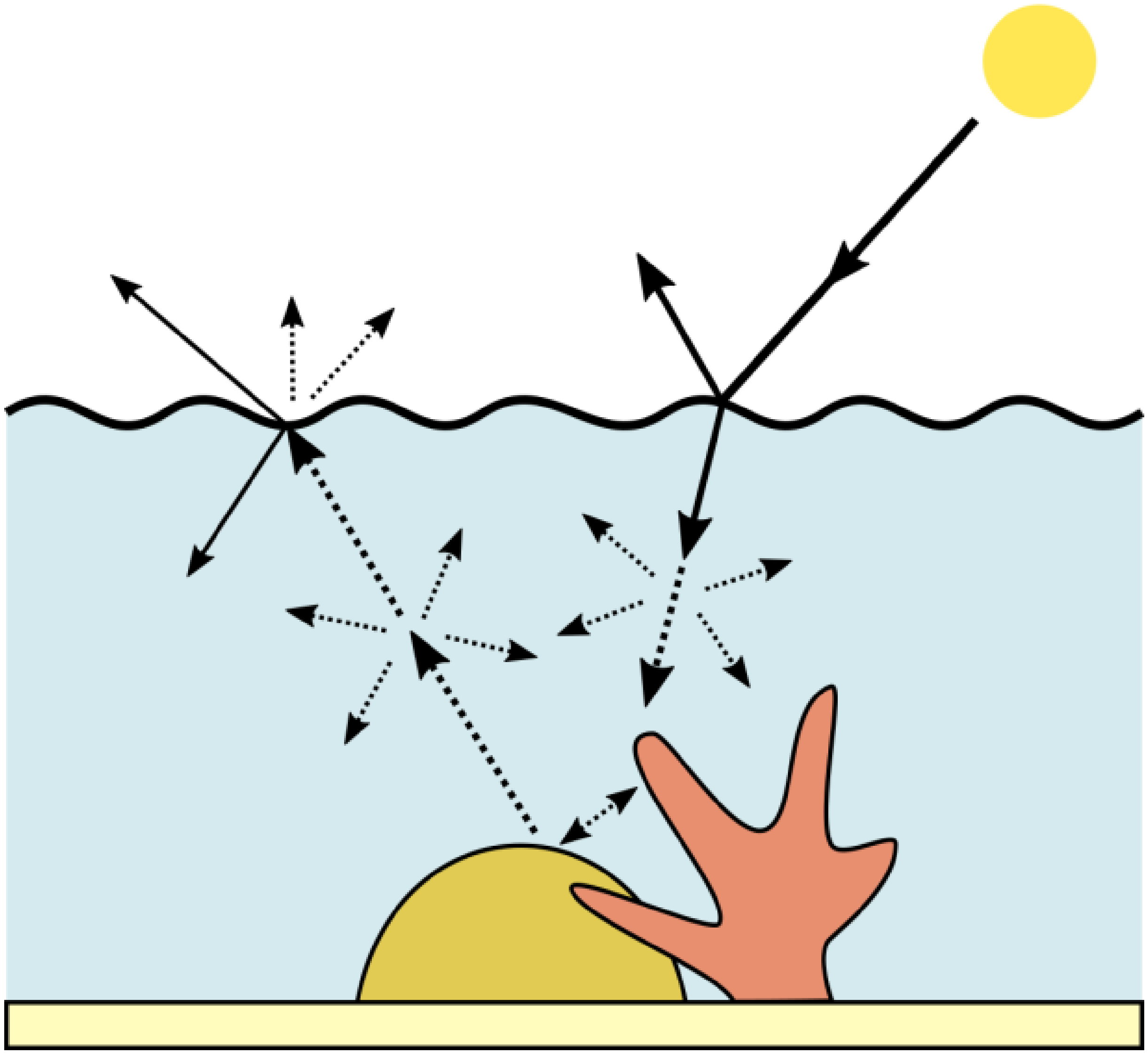


→ Works well for flat materials (Mobley & Sundman, *L&O*, 48, 329-336)

→ Misses vertical structure, shadows, etc.

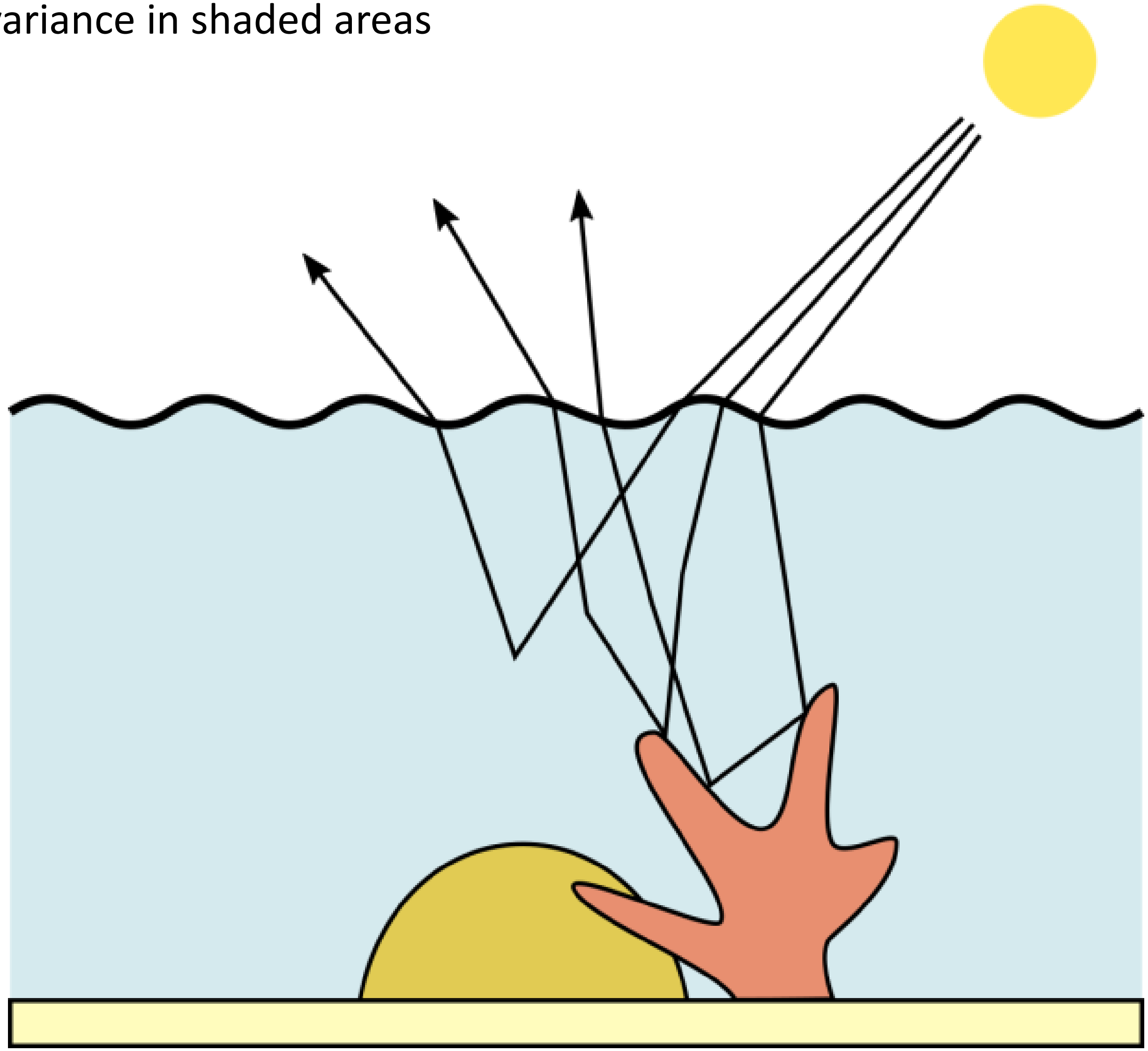
→ No information about light environment within the canopy, photobiology.

Modelling and the 3-dimensional light environment



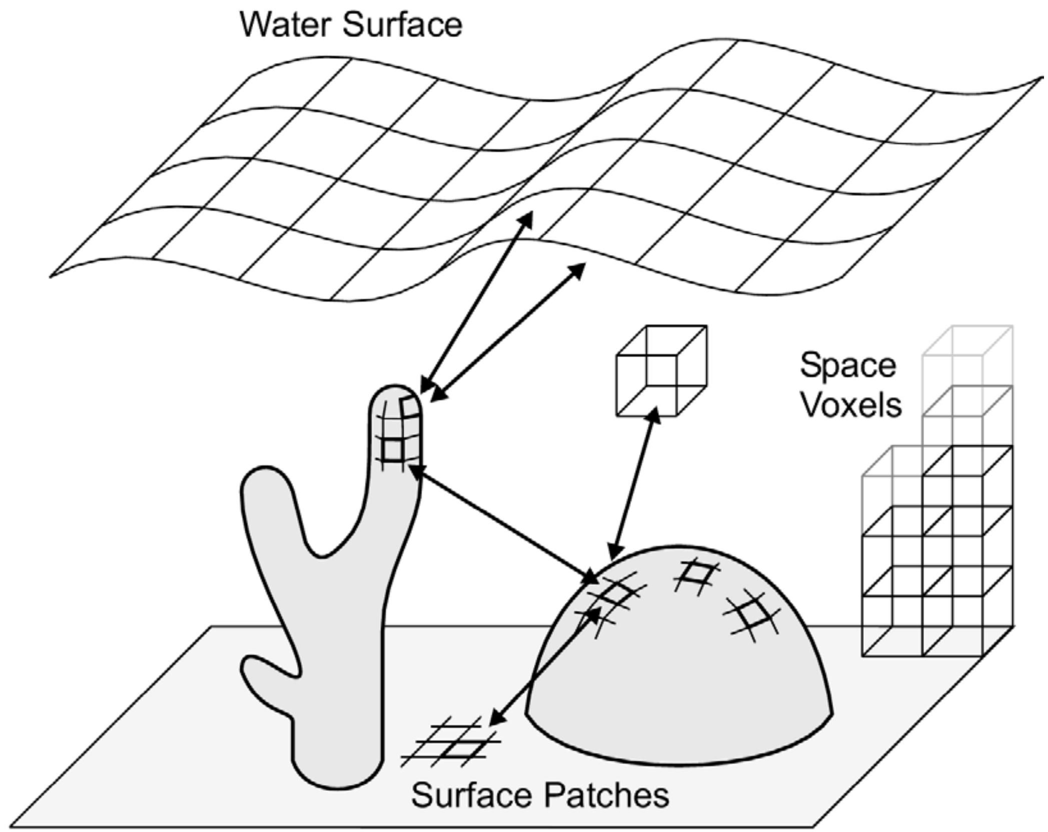
Monte-Carlo Modelling

- slow for complex structures
- high variance in shaded areas



Global Illumination Method

$L(x, y, z, \theta, \phi, \lambda)$



Discretise spatially as well as directionally

$\rightarrow$ surfaces are composed of patches

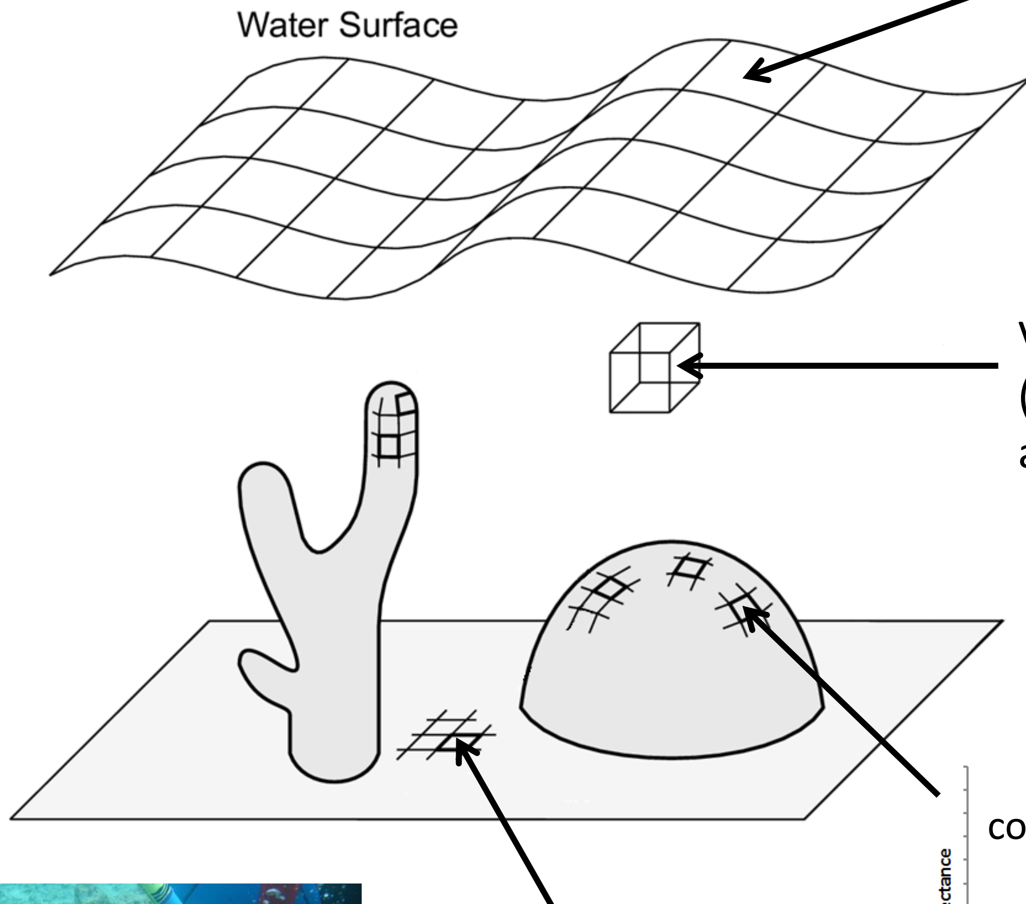
$\rightarrow$ volumes are composed of cubes (voxels)

$*$ **Every element potentially receives light from every other element**

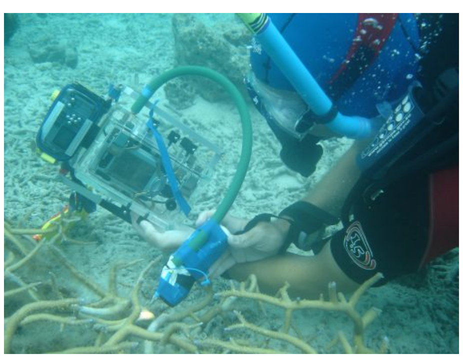
$*$ **Iterative solution**

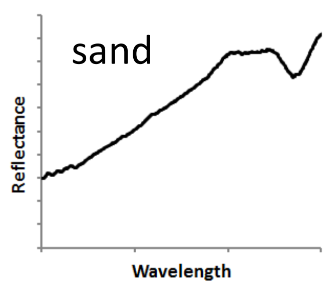
Material Properties

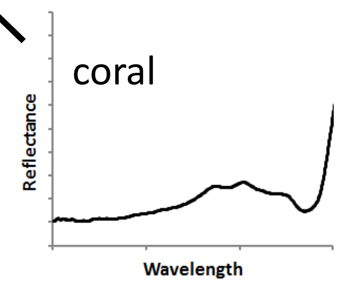
Water surface patches reflect and transmit directionally according to Fresnel equations



Volume Scattering Function (VSF)
(scattering × phase function)
and absorption

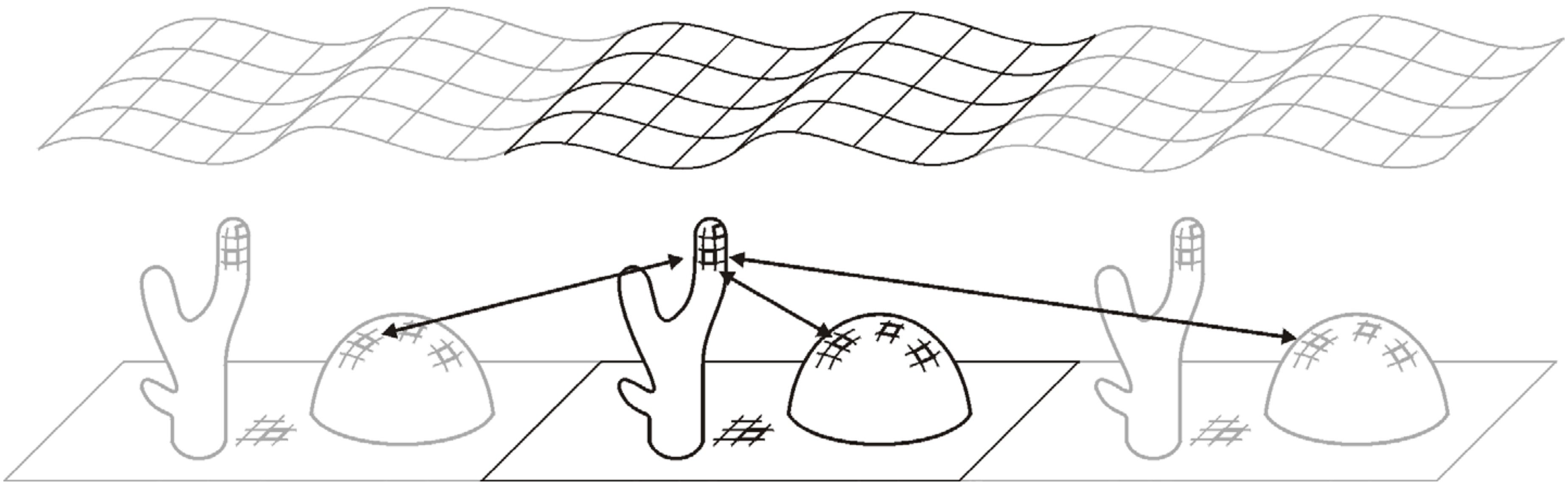




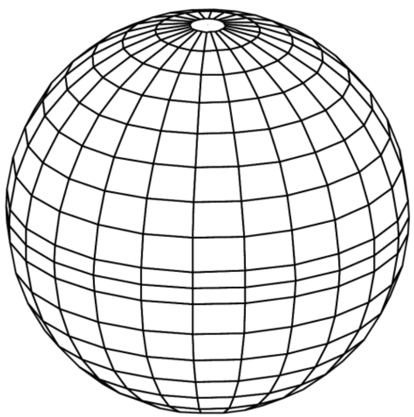


Surface Spectral Reflectances
(locally Lambertian)

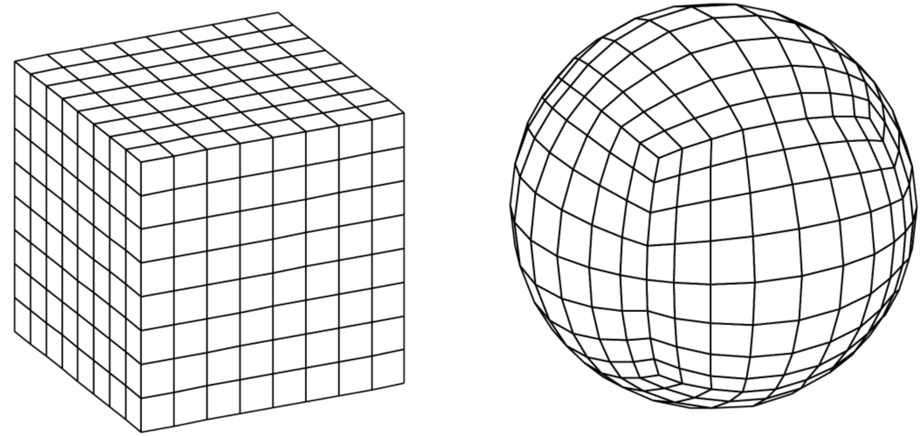
Periodic horizontal boundaries



Directional discretization - tabulating directional radiance

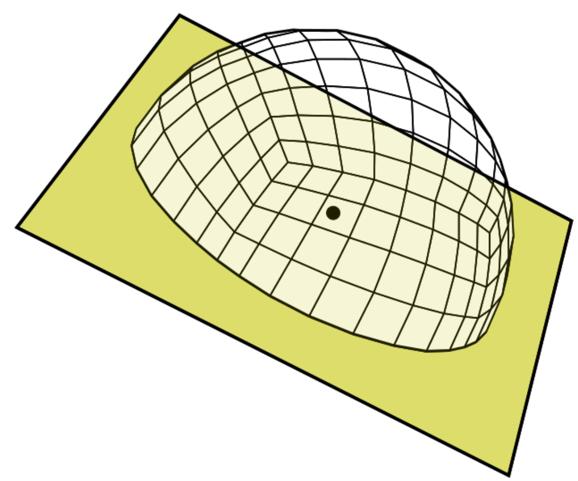


HydroLight standard

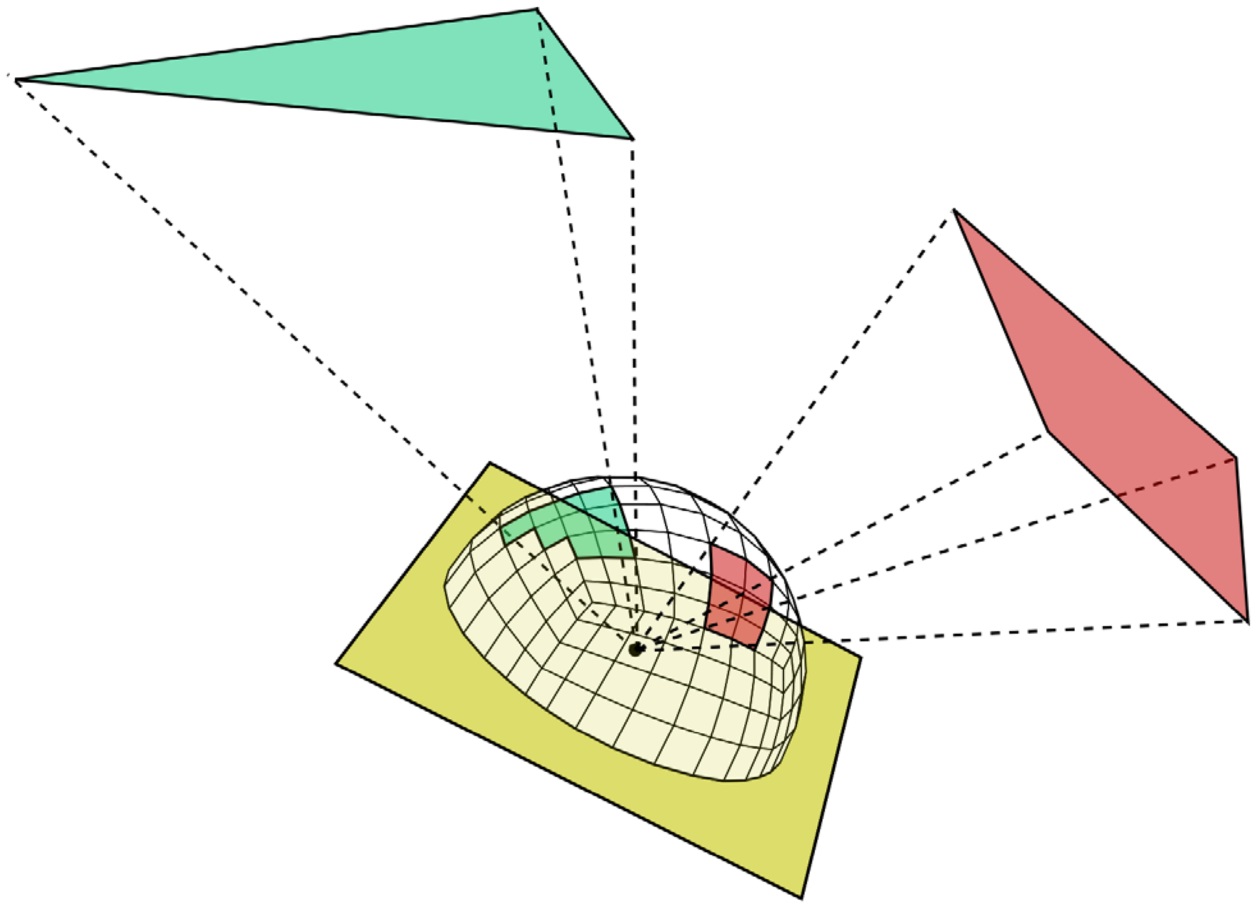


Cubic 8-partition

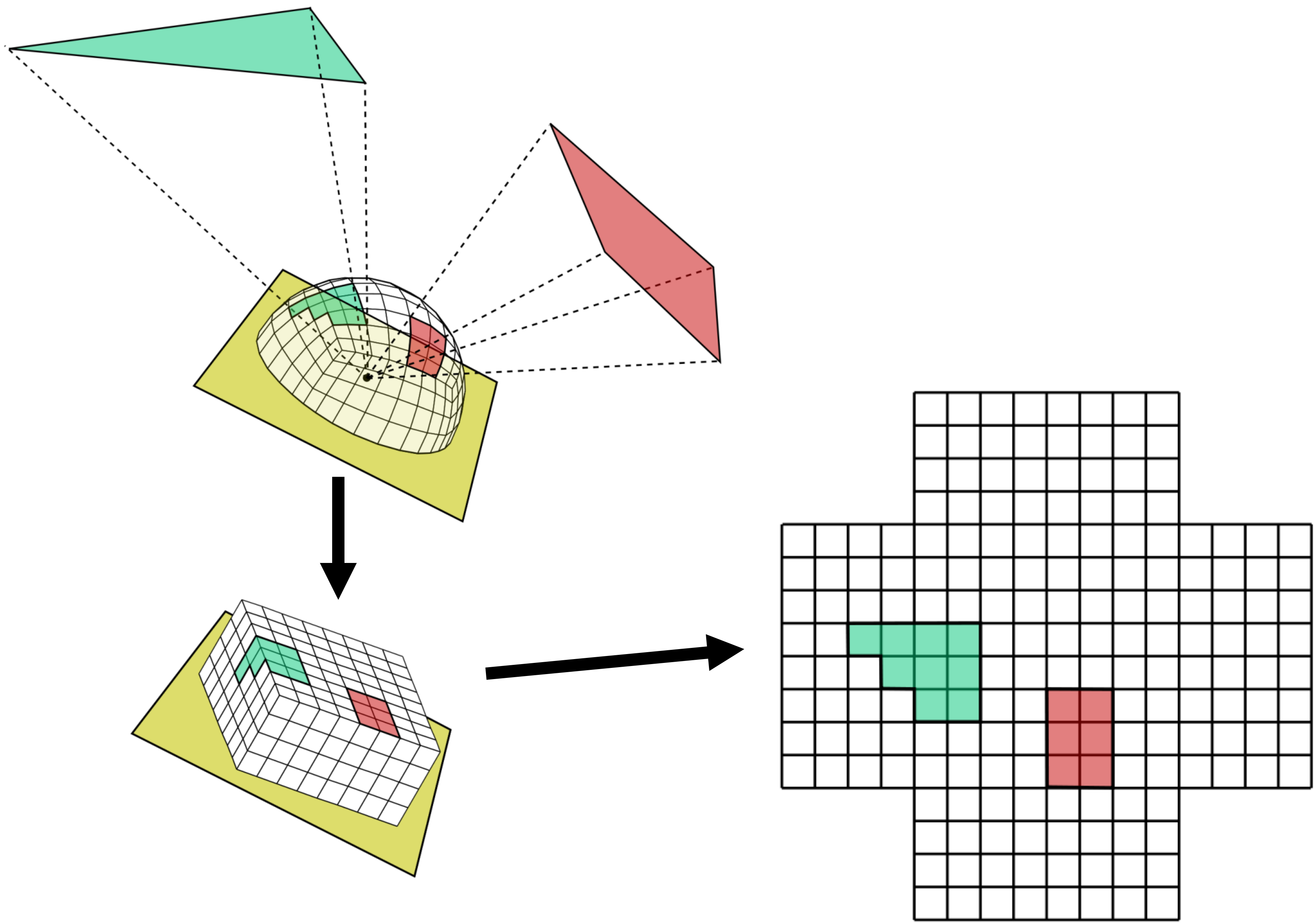
For surfaces the orientation is
dependent on surface patch orientation



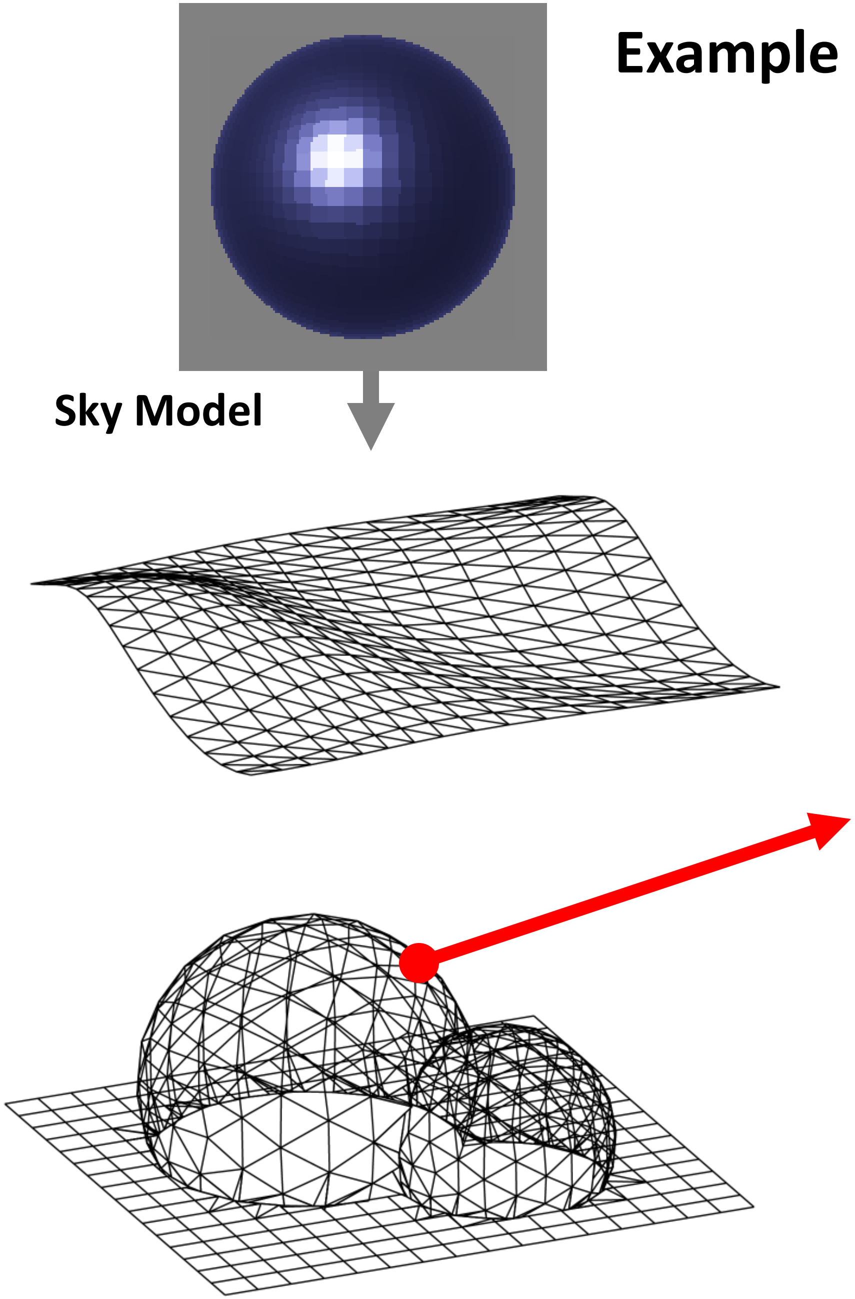
Hemicube method



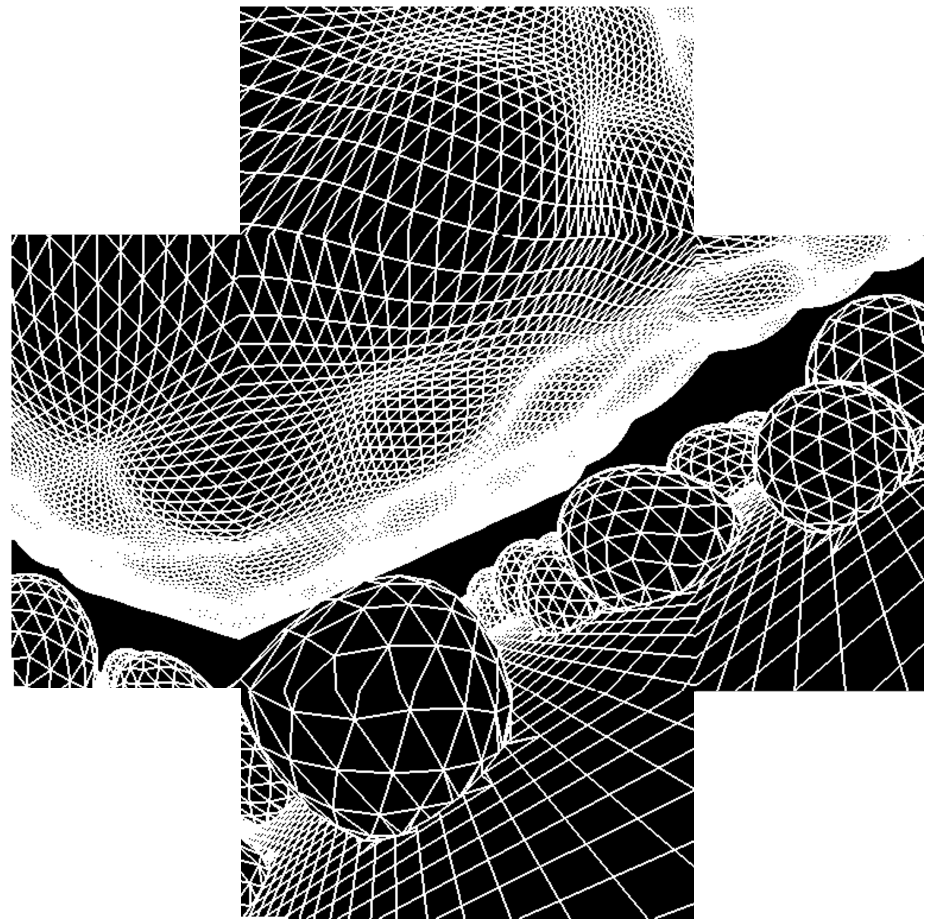
Hemicube method



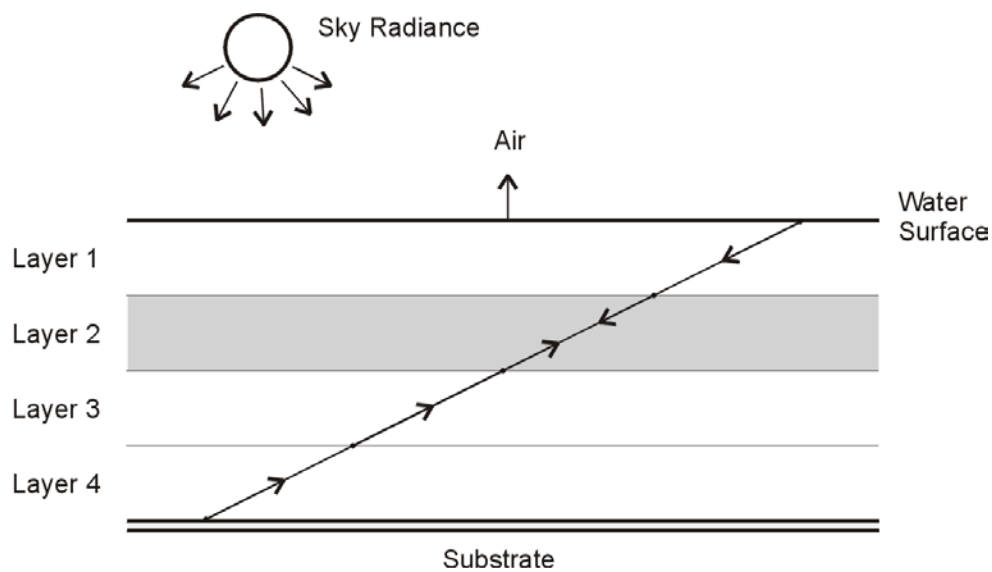
Example solution run



View from patch centre



Plane-parallel configuration: Comparison to HydroLight



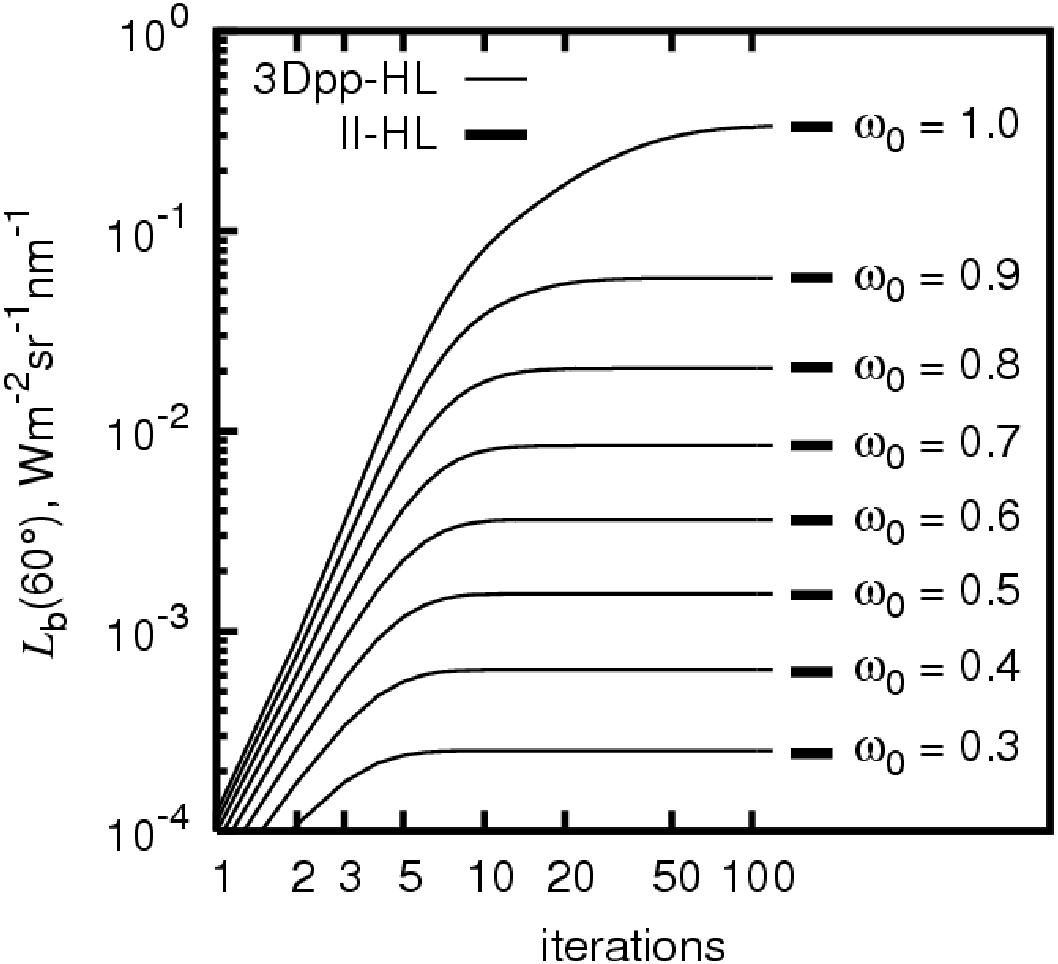
- Optical depth = 1.0
- Single scattering albedo 0 to 1 in steps 0.1
- Flat water surface
- Substrate reflectance - 70%
- Petzold's phase function
- 10 layers

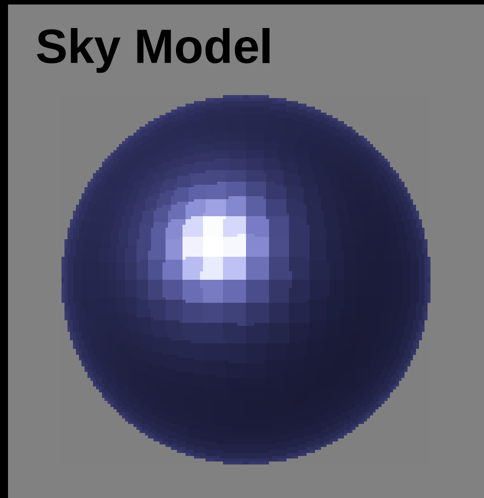
Convergence for iterations - radiance incident on substrate at 60°, i.e. L_b(60°)

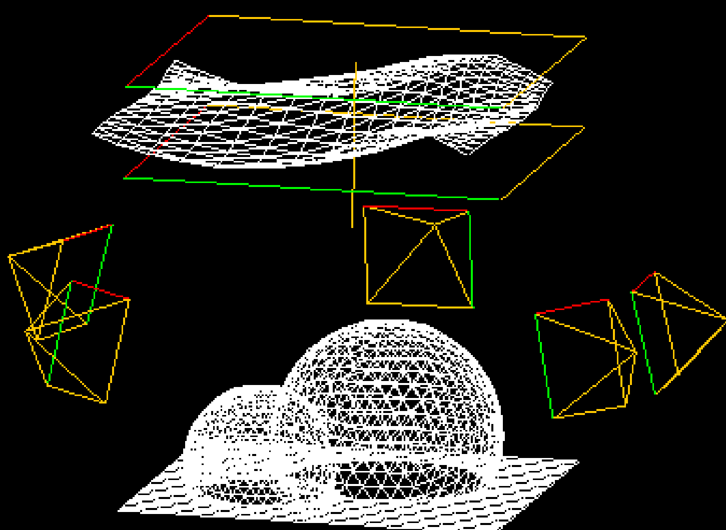
How many iterations required?

In clear waters single scattering albedo can be >0.9 in some wavelengths, but not 1.0.

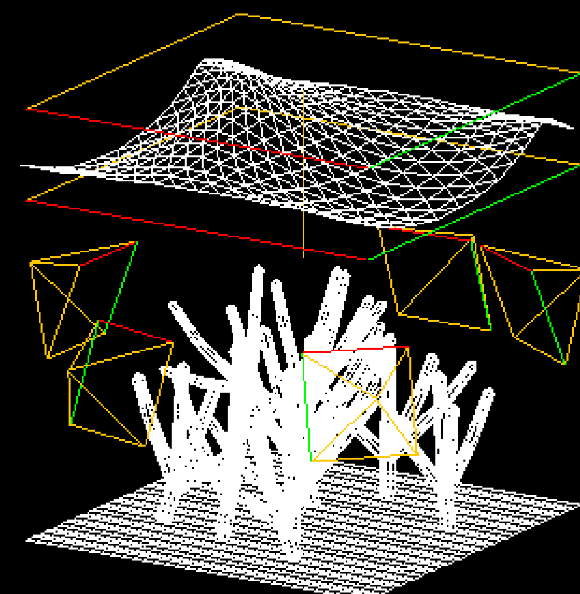
But here bottom is very reflective (70%) - light multiply scatters for longer







Dome Structures

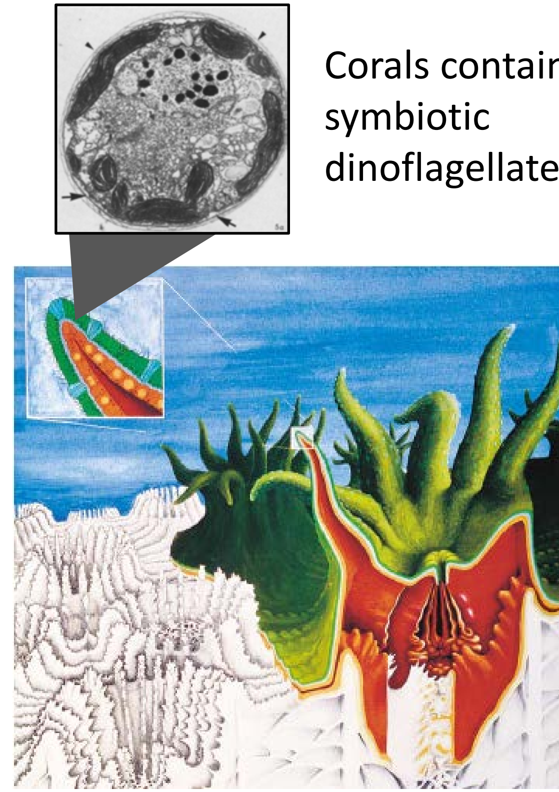


Branching Structures

Benthic Ecology - light interaction with the canopy

Corals and seagrasses are photosynthetic organisms:

- they need light to survive
- light levels govern their distribution (e.g. by depth)
- changes in light levels impact these ecosystems
- too much light can also be bad



Corals contain symbiotic dinoflagellates

<u>Important point:</u>

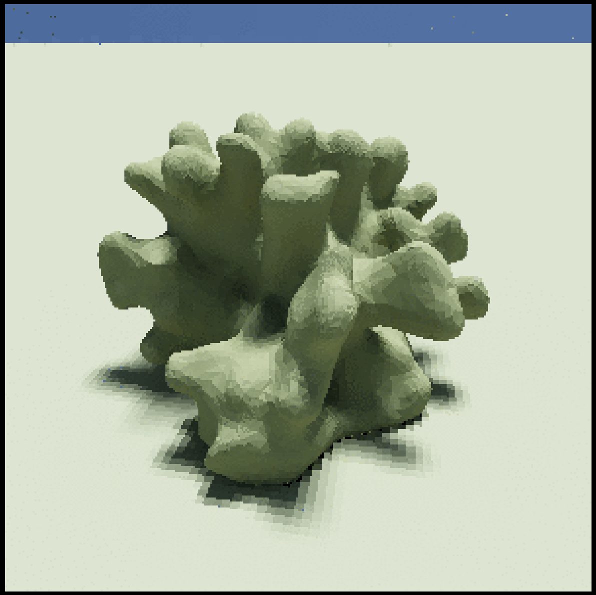
Tend to think in terms of light incident on canopy - e.g. E_d (downwelling irradiance at the bottom of the water column)

BUT: canopies are complex structures - their interaction with light is not straightforward.

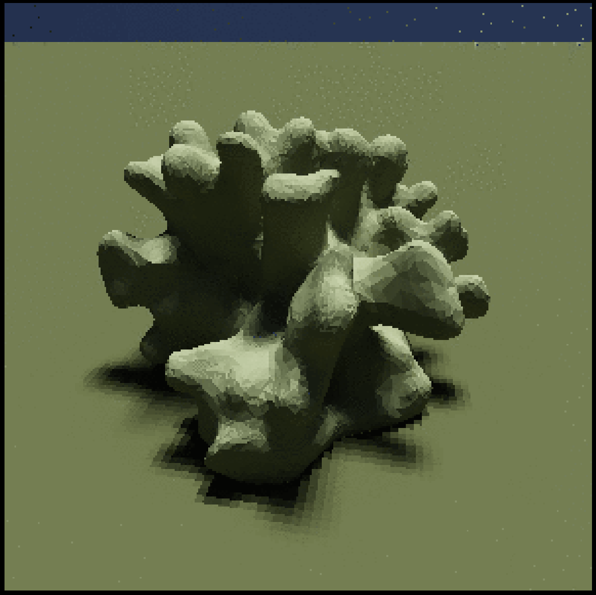
Coral stress and bleaching

- Temperature and light stress
- Importance of reflection from surrounding substrates ? (Ortiz et al. 2009, *Coral Reefs*)
- What does the surface of the coral "see" ?

Veal *et al*. CT Scanning of coral skeletons (Univ. Queensland)

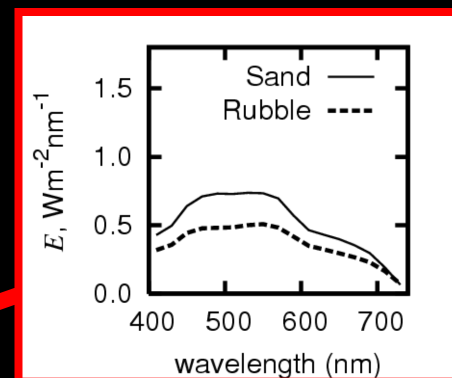


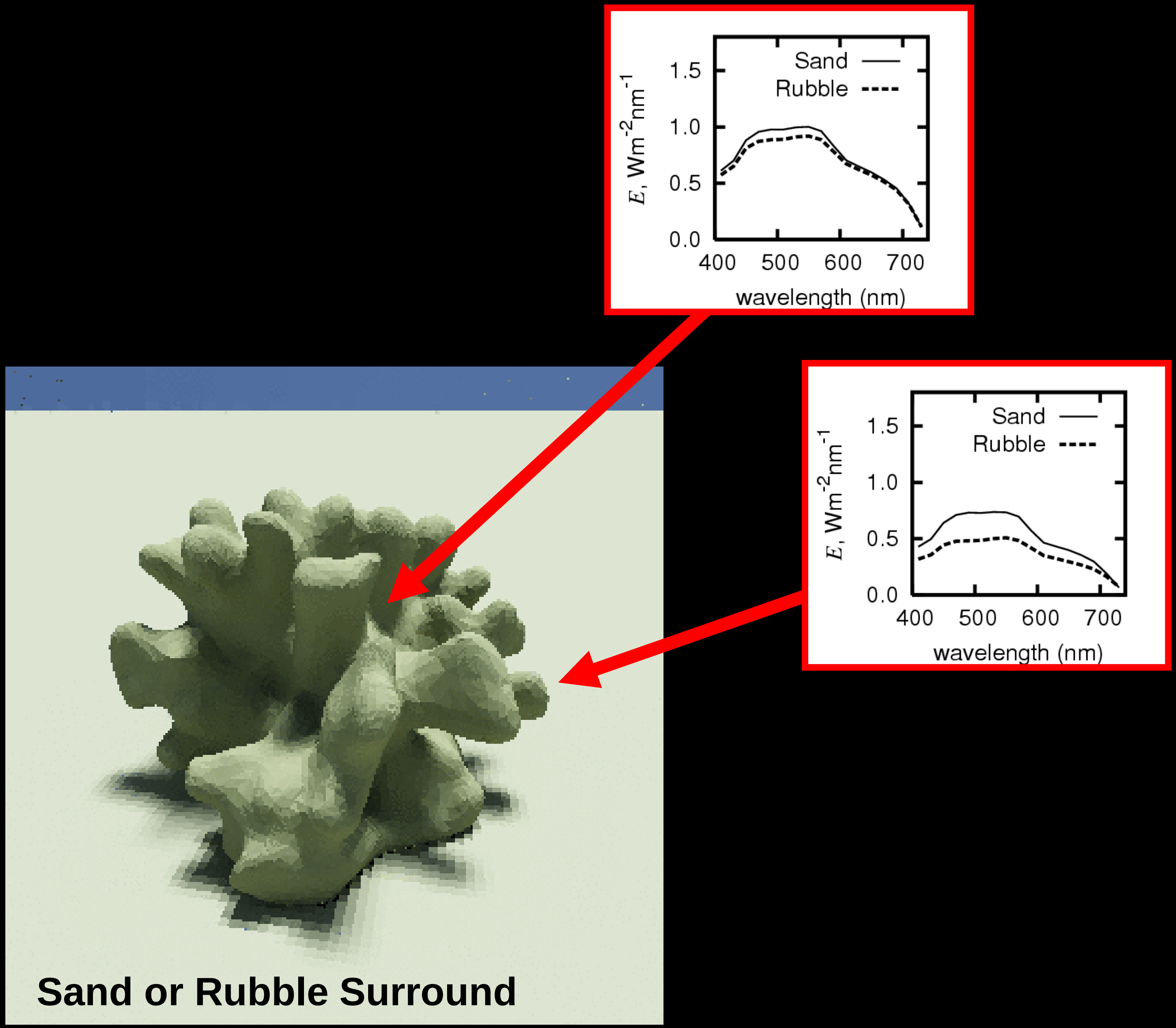
sand surround



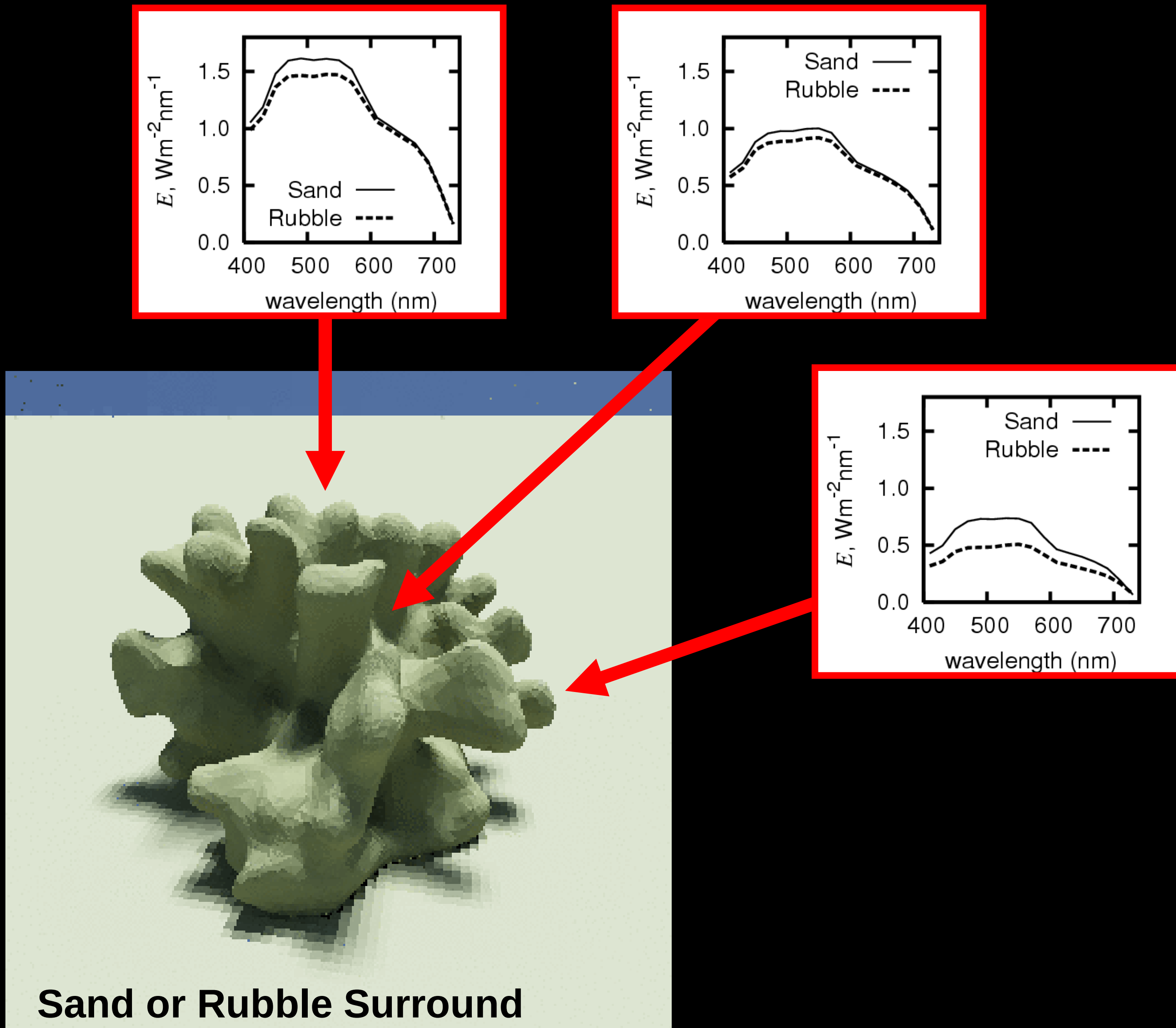
dead coral / turf surround


Sand or Rubble Surround


Sand
Rubble
1.5
1.0
0.5
0.0
E, Wm-2nm-1
400
500
600
700
wavelength (nm)



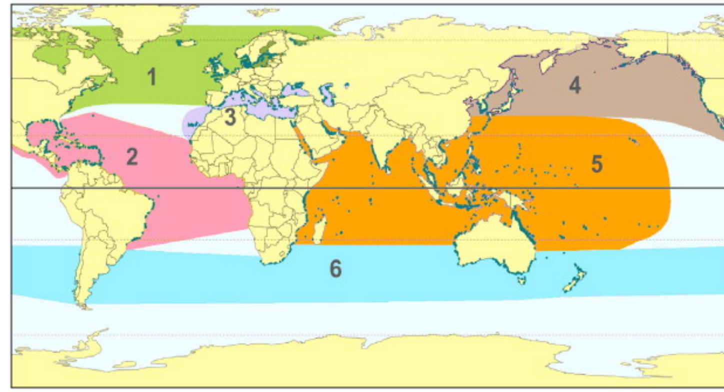
Sand
Rubble
E, Wm-2nm-1
1.5
1.0
0.5
0.0
400
500
600
700
wavelength (nm)
Sand
Rubble
E, Wm-2nm-1
1.5
1.0
0.5
0.0
400
500
600
700
wavelength (nm)
Sand or Rubble Surround



E, Wm-2nm-1
1.5
1.0
0.5
0.0
400 500 600 700
wavelength (nm)
Sand
Rubble
E, Wm-2nm-1
1.5
1.0
0.5
0.0
400 500 600 700
wavelength (nm)
Sand
Rubble
E, Wm-2nm-1
1.5
1.0
0.5
0.0
400 500 600 700
wavelength (nm)
Sand
Rubble
Sand or Rubble Surround

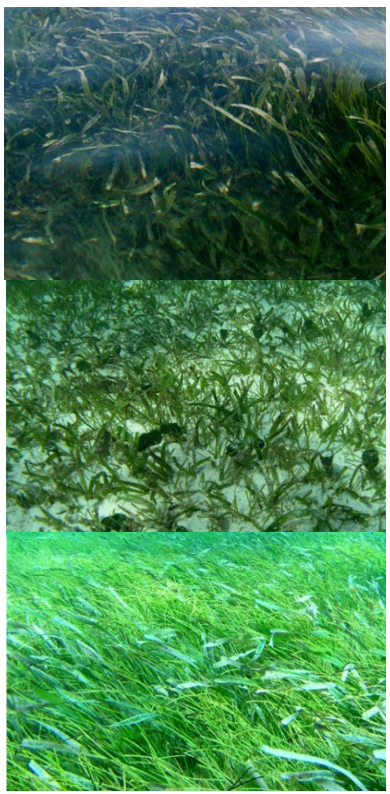
Seagrass canopies

- Found on every continent except Antarctica
- Major importance with respect to ‘blue carbon’
- Indicator of environmental change
- Connected to other ecosystems - e.g. coral reefs



Short *et al.* 2007, JEMBE, 350, 3-20

Thalassia testudinum



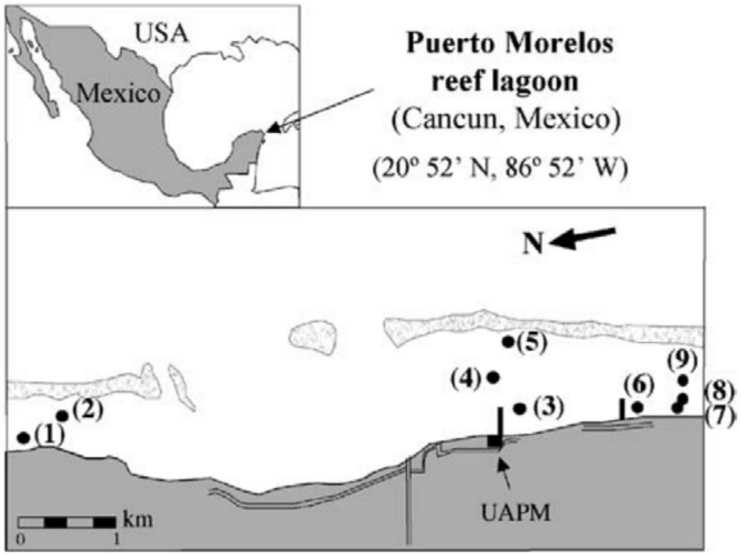
Leaf Area Index (LAI)

- important descriptor, LAI = area of leaf ÷ substrate area

factors affecting canopy light interaction

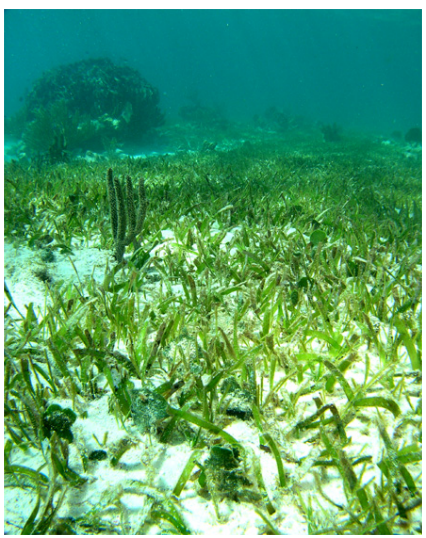
- Leaf level reflectance
- Canopy structure
- Canopy position
- Substrate (sand) reflectance
- Epiphytes
- Dead parts (senescence)
- Trapped sediment
- Water column....

Thalassia, Puerto Morelos reef lagoon, Mexico.

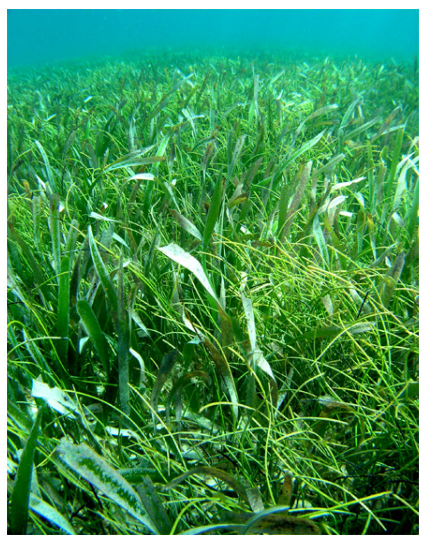


Available data:

1) Shoot density (no. per m^2)
2) Leaf length distribution
3) Canopy height
4) Optical properties along leaf length
5) Photosynthesis-irradiance curves
6) Underground biomass



Low LAI



High LAI

LAI range: 0.5 – 4.7

Depth: 0.5 m to 4 m

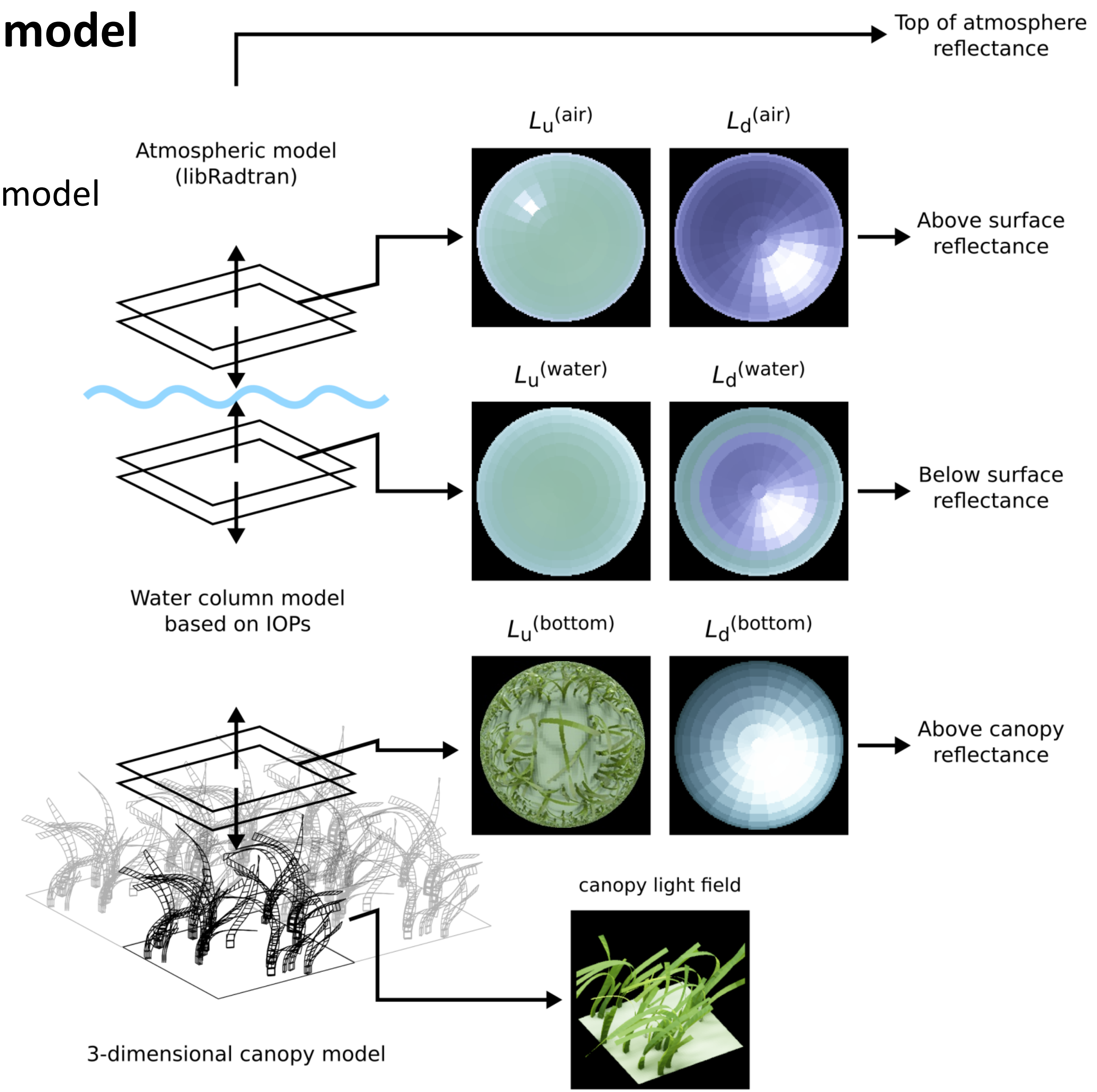
Enriquez & Pantoja-Reyes 2005, *Oecologia* **145**: 235-243.

Radiative transfer model

Coupled models:

- 3D *Thalassia* canopy model
- Water column model
- Atmospheric model

[Hedley & Enriquez 2010, L&O, 55, 1537-1550]



Leaf optical properties

<u>Available data:</u>

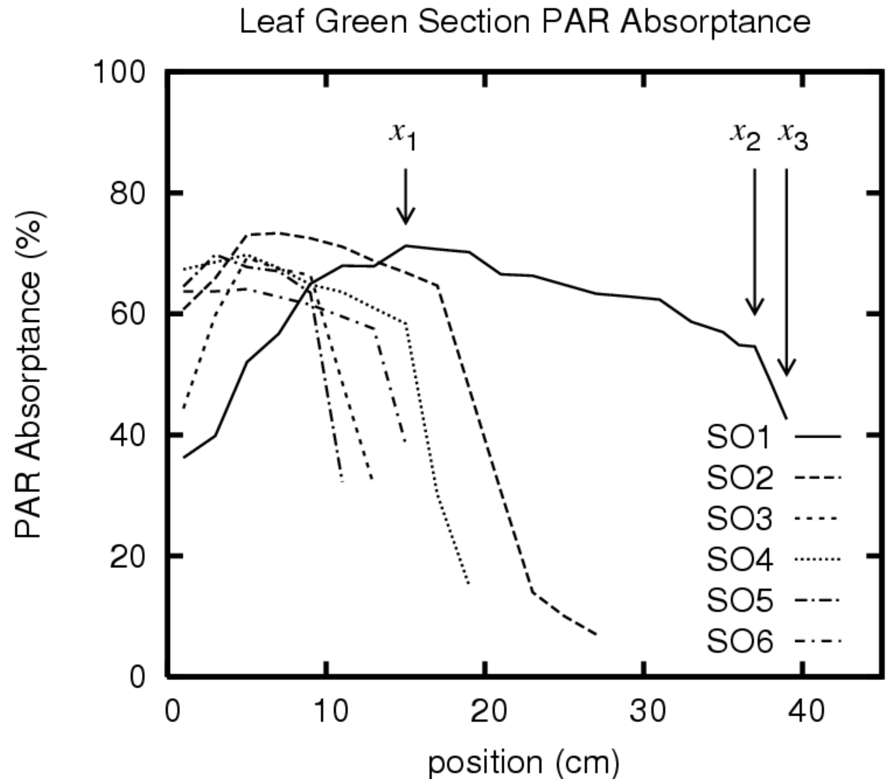
Spectral absorptance

Spectral reflectance

Non-photosynthetically active portion properties (dead part of leaves)

Epiphytes - generally not present

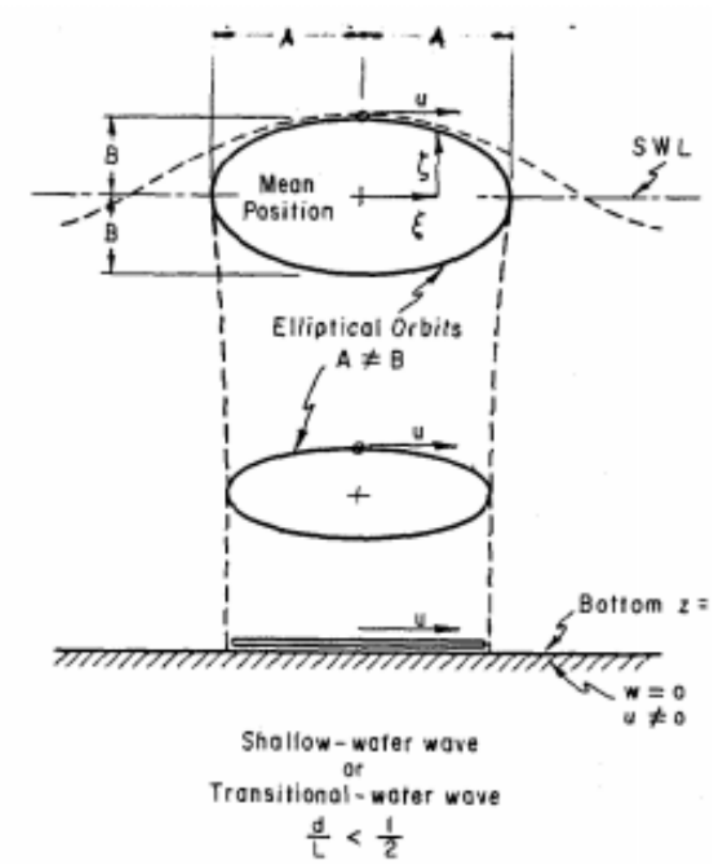
Leaves transmit light!

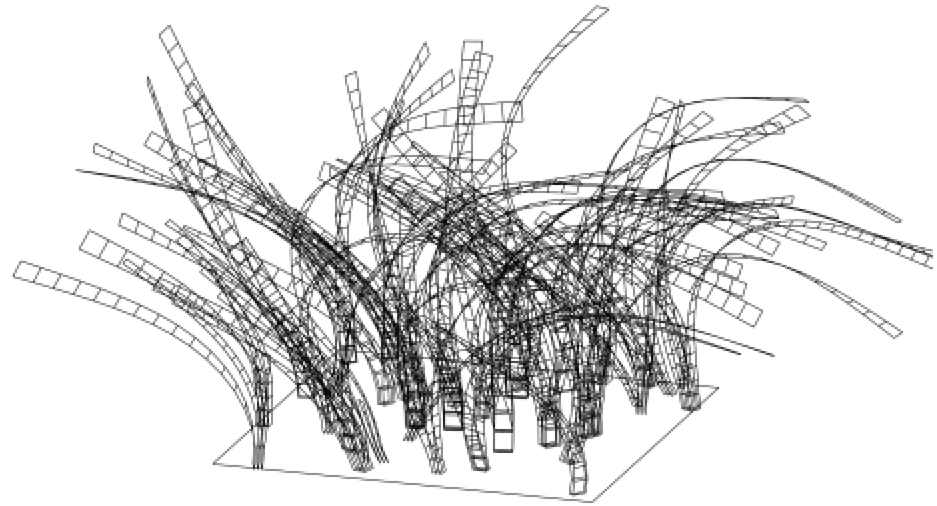


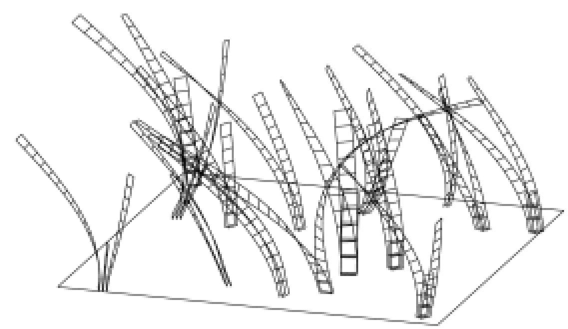
Idealised *Thalassia* leaf

Canopy structure

- flexible strips in a simple wave motion model

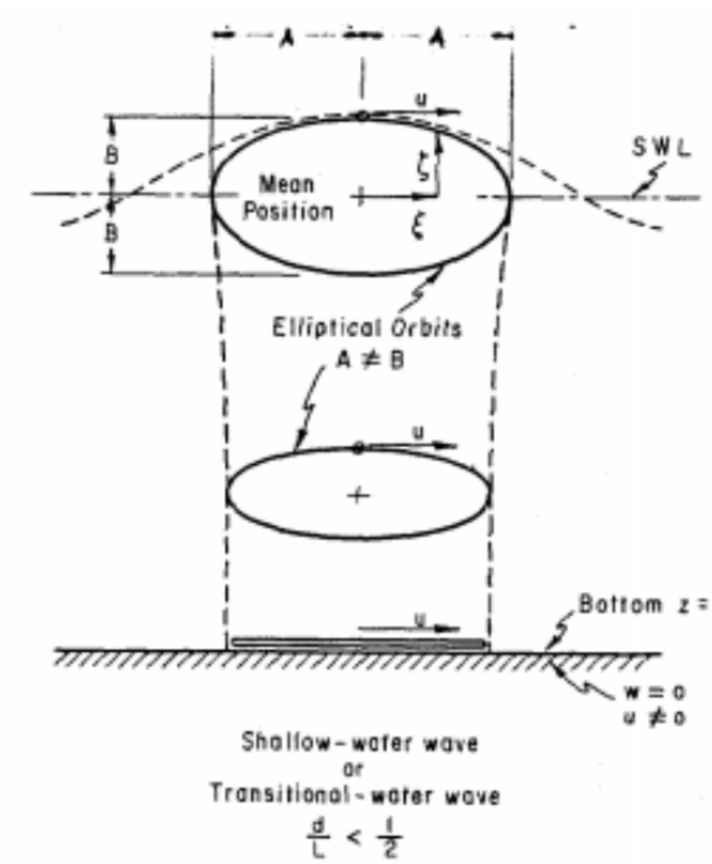


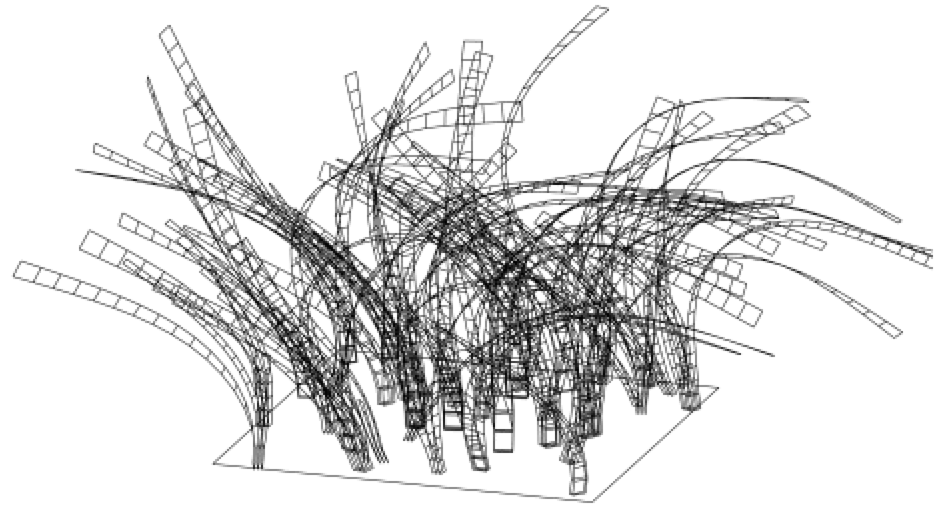


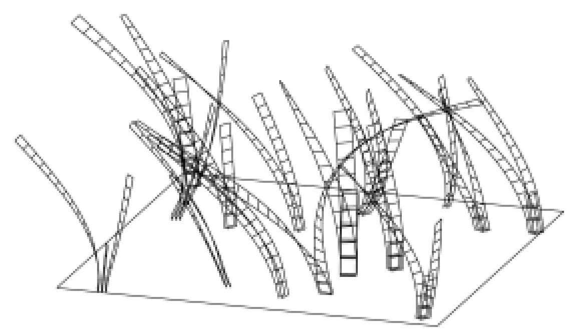


Canopy structure

- flexible strips in a simple wave motion model

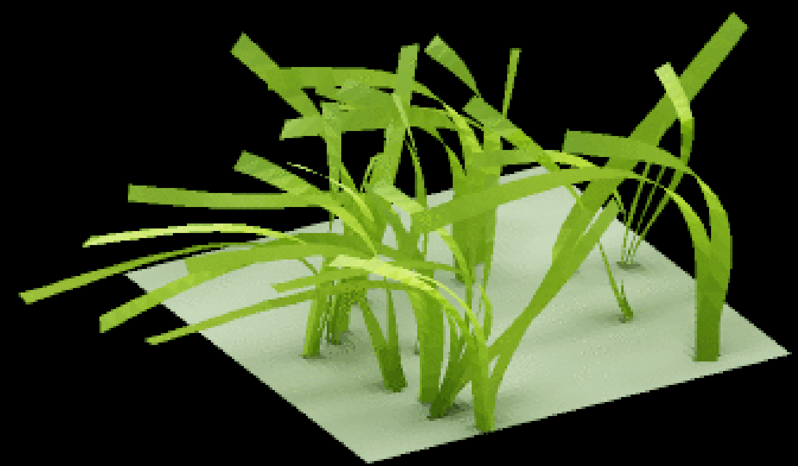






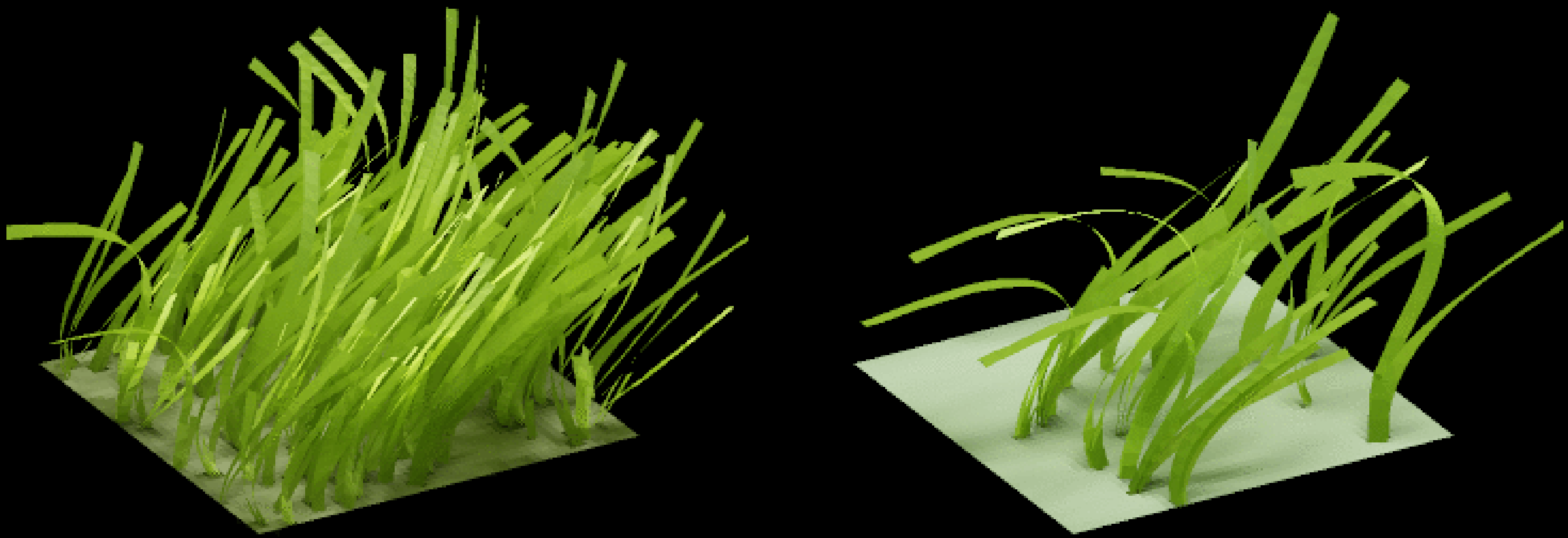
Model outputs for two sites (17 bands reduced to RGB)

LAI 4.5, depth 0.5 m



LAI 1.0, depth 1.5 m

Model outputs for two sites (17 bands reduced to RGB)

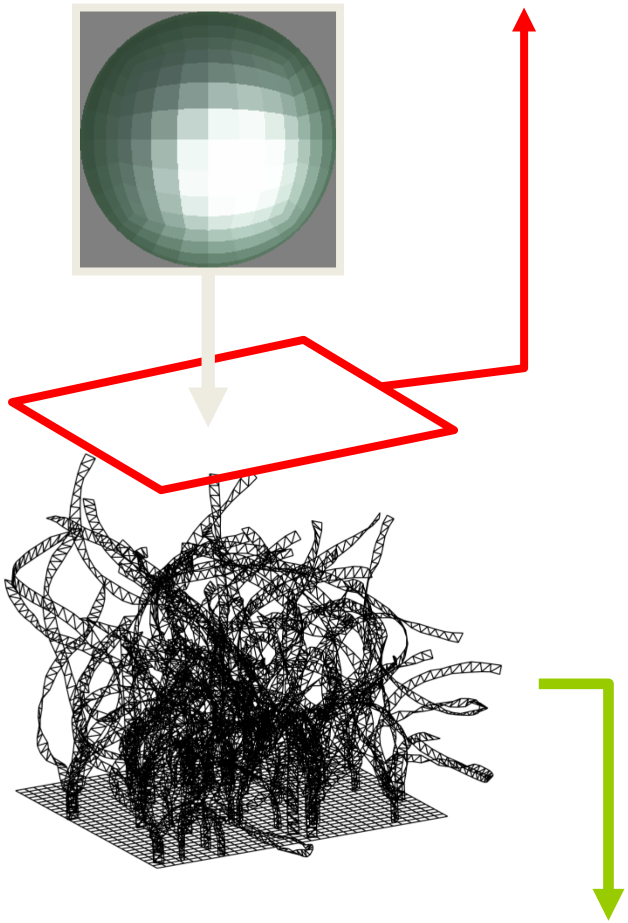


LAI 4.5, depth 0.5 m

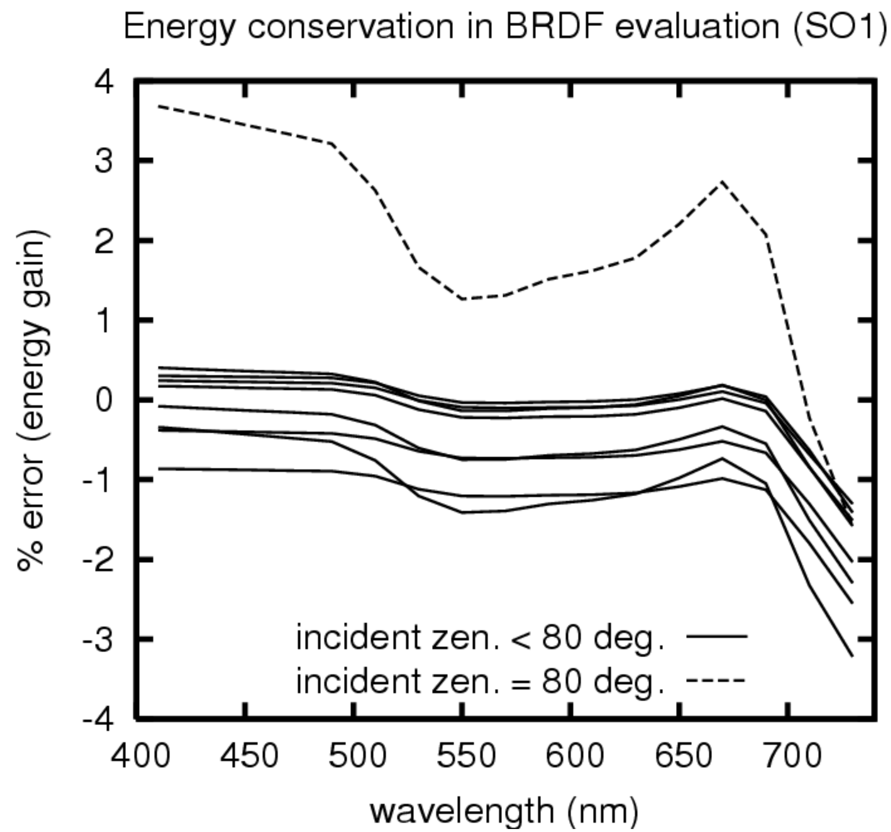
LAI 1.0, depth 1.5 m

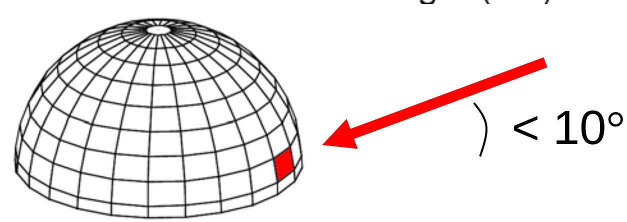
Energy conservation test

ENERGY IN = ENERGY OUT



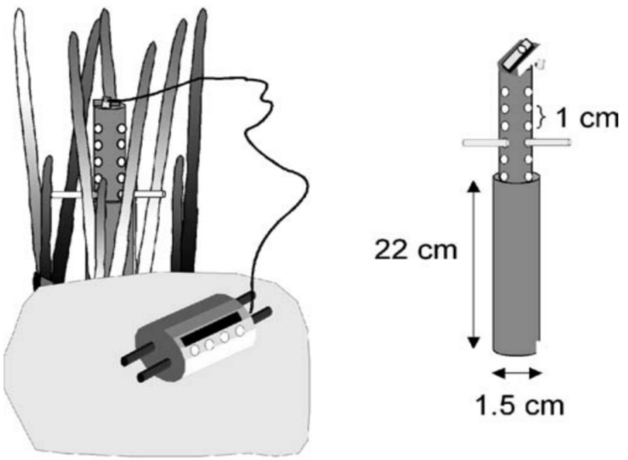
+ ENERGY ABSORBED



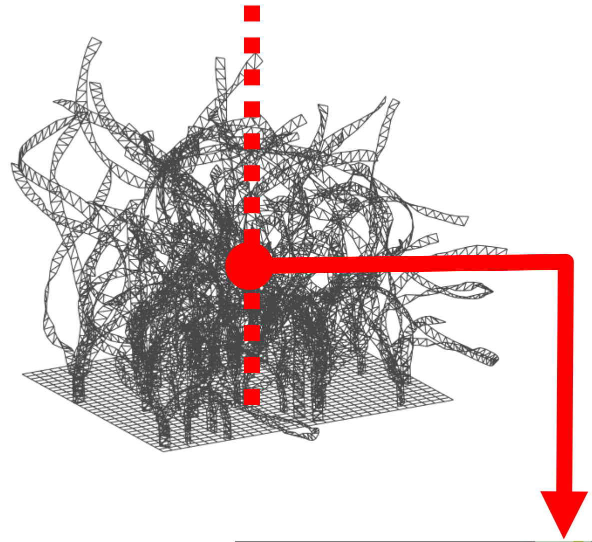


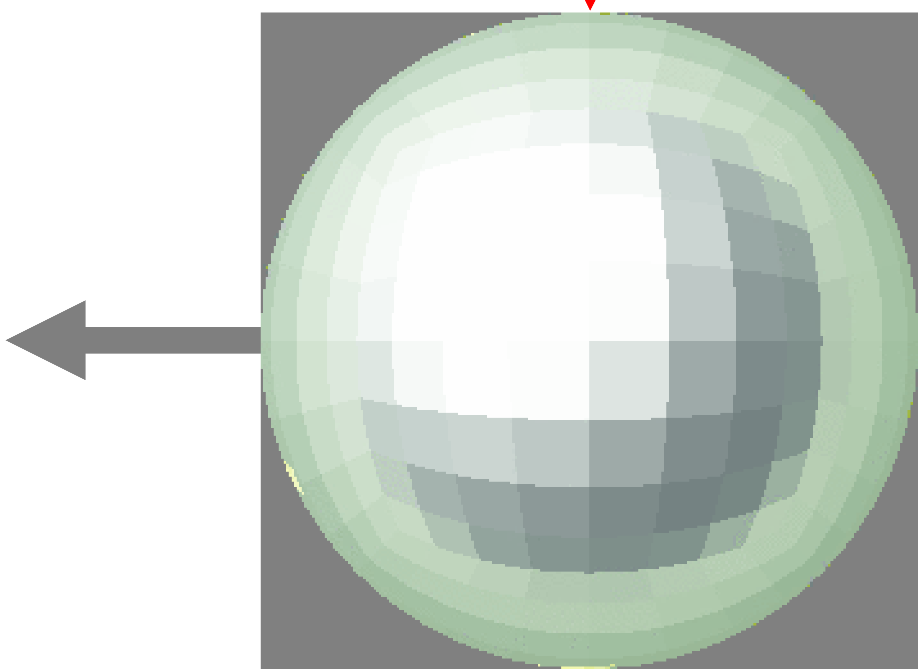
For the most significant wavelengths and incident angles, errors < 1%

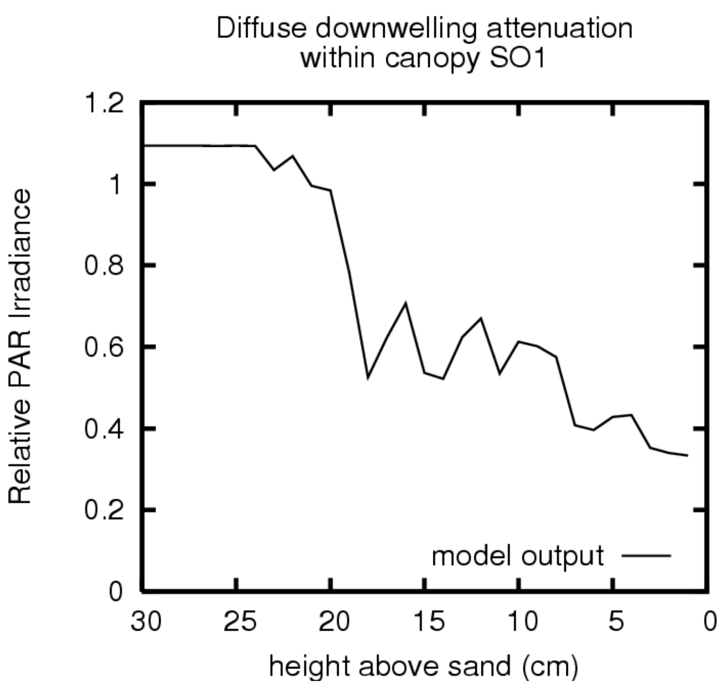
Empirical test: within-canopy diffuse attenuation, k_d



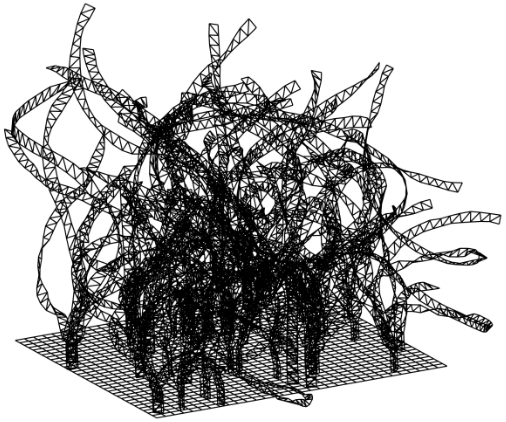
Enriquez & Pantoja-Reyes, 2005, Oecolgia 145, 235-243

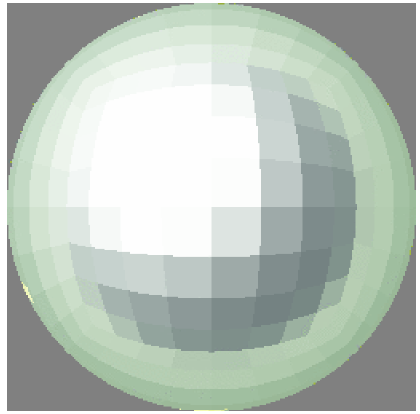


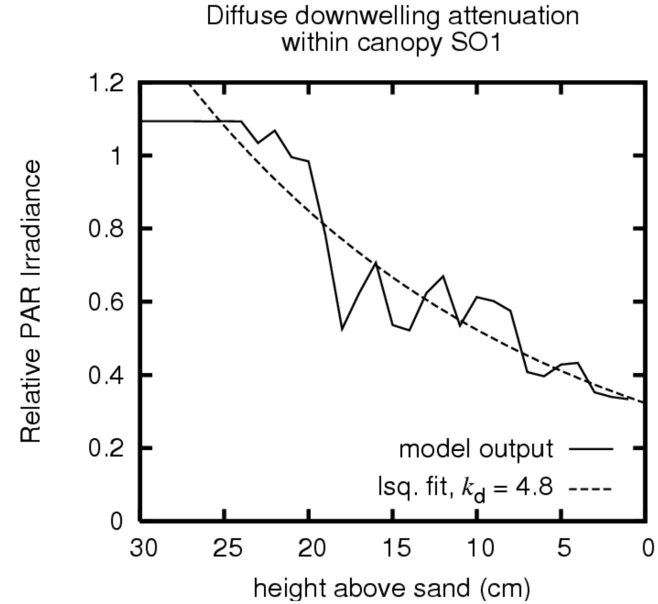




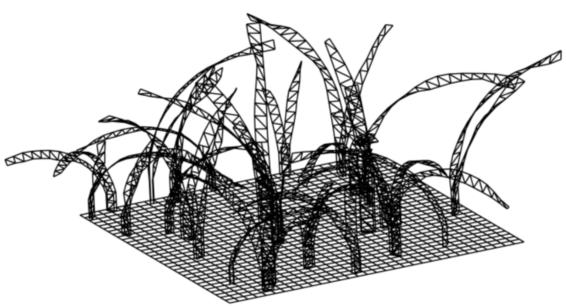
SO1 (1 m depth)

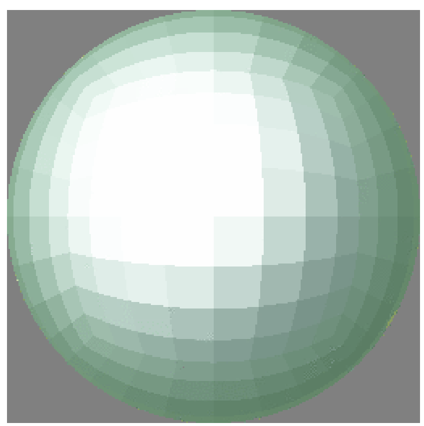


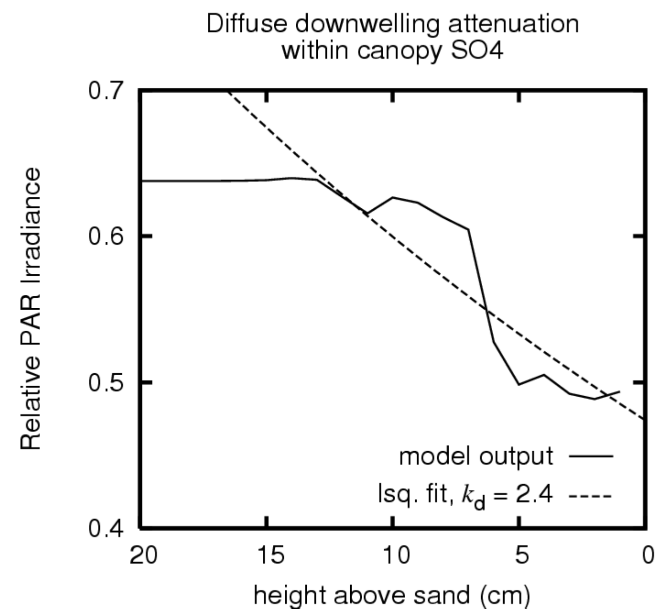




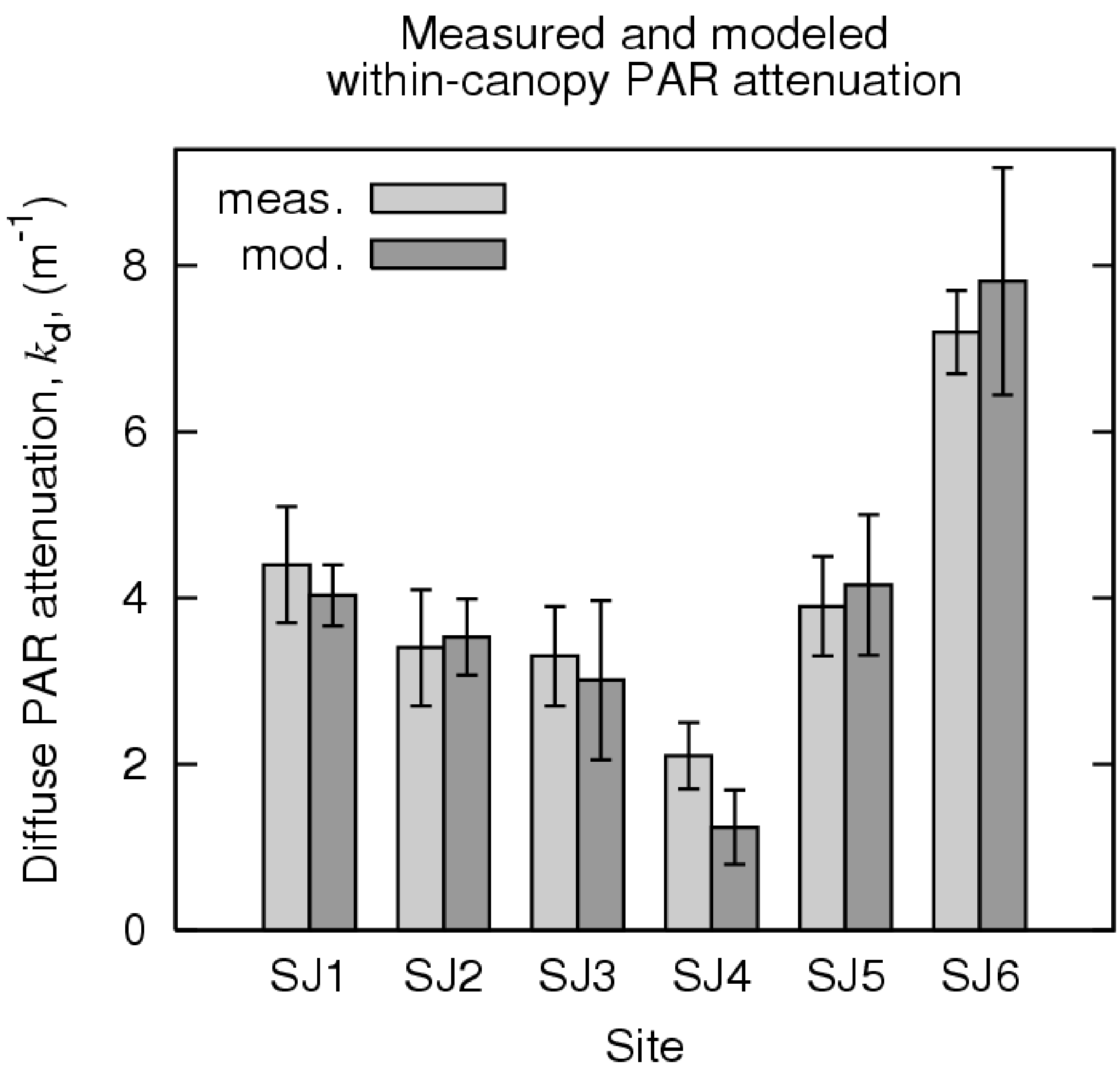
SO4 (3 m depth)





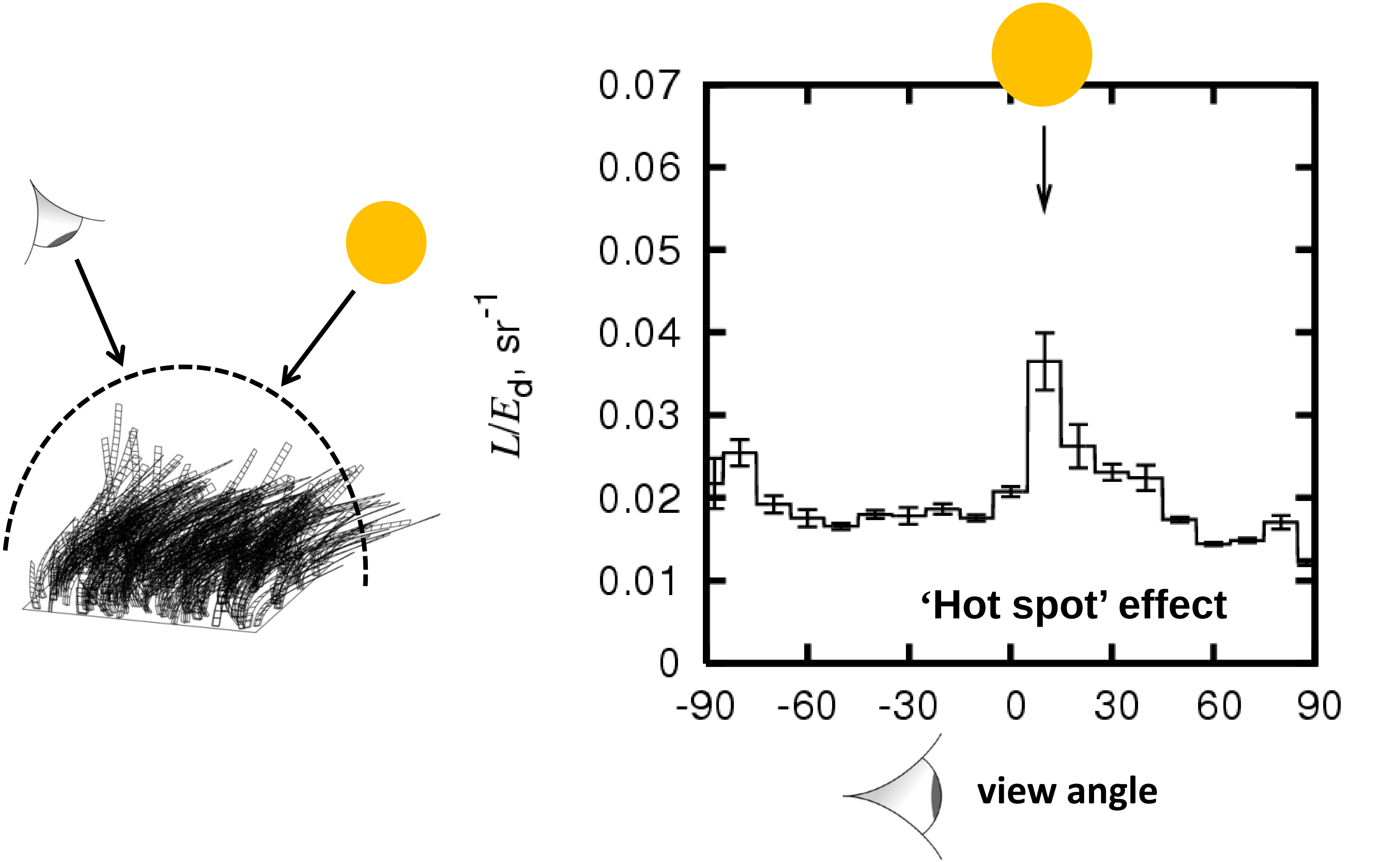


PAR K_d (within-canopy diffuse attenuation)

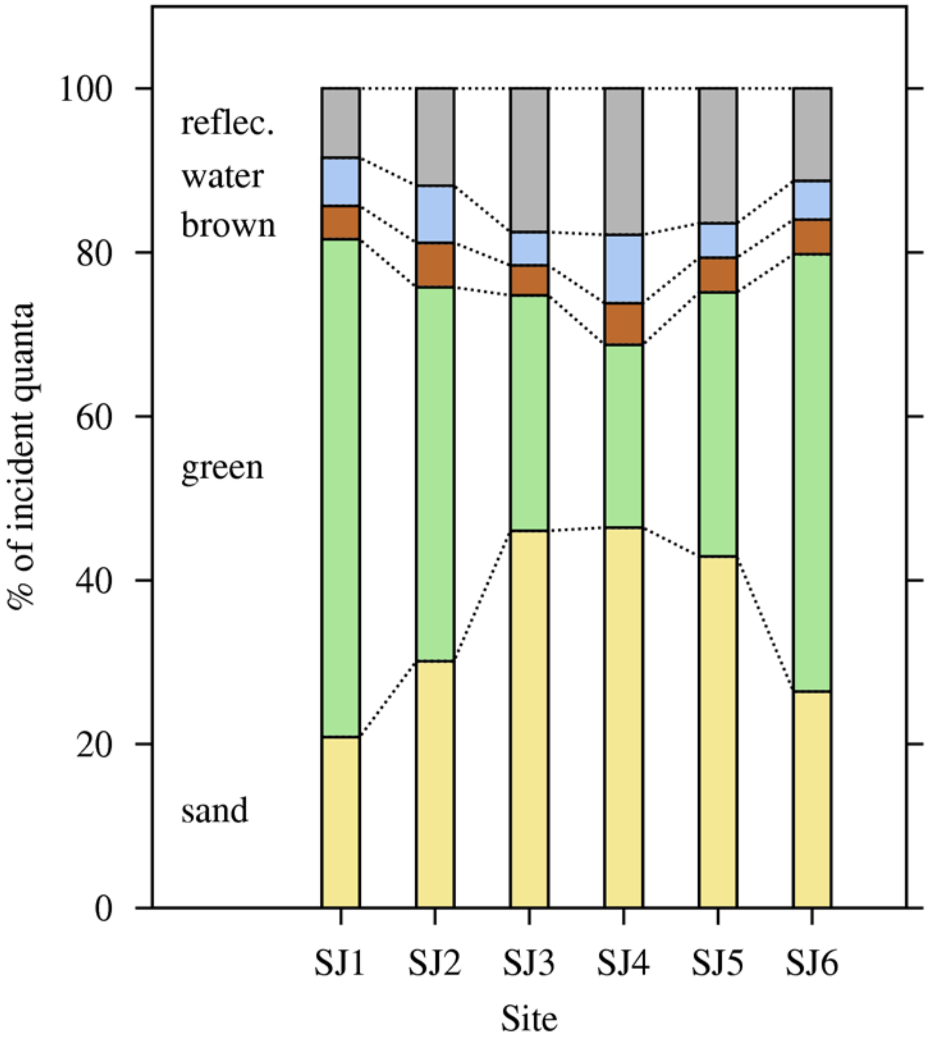


(Hedley & Enríquez, 2010, *Limnology & Oceanography*)

Bi-directional reflectance distribution function

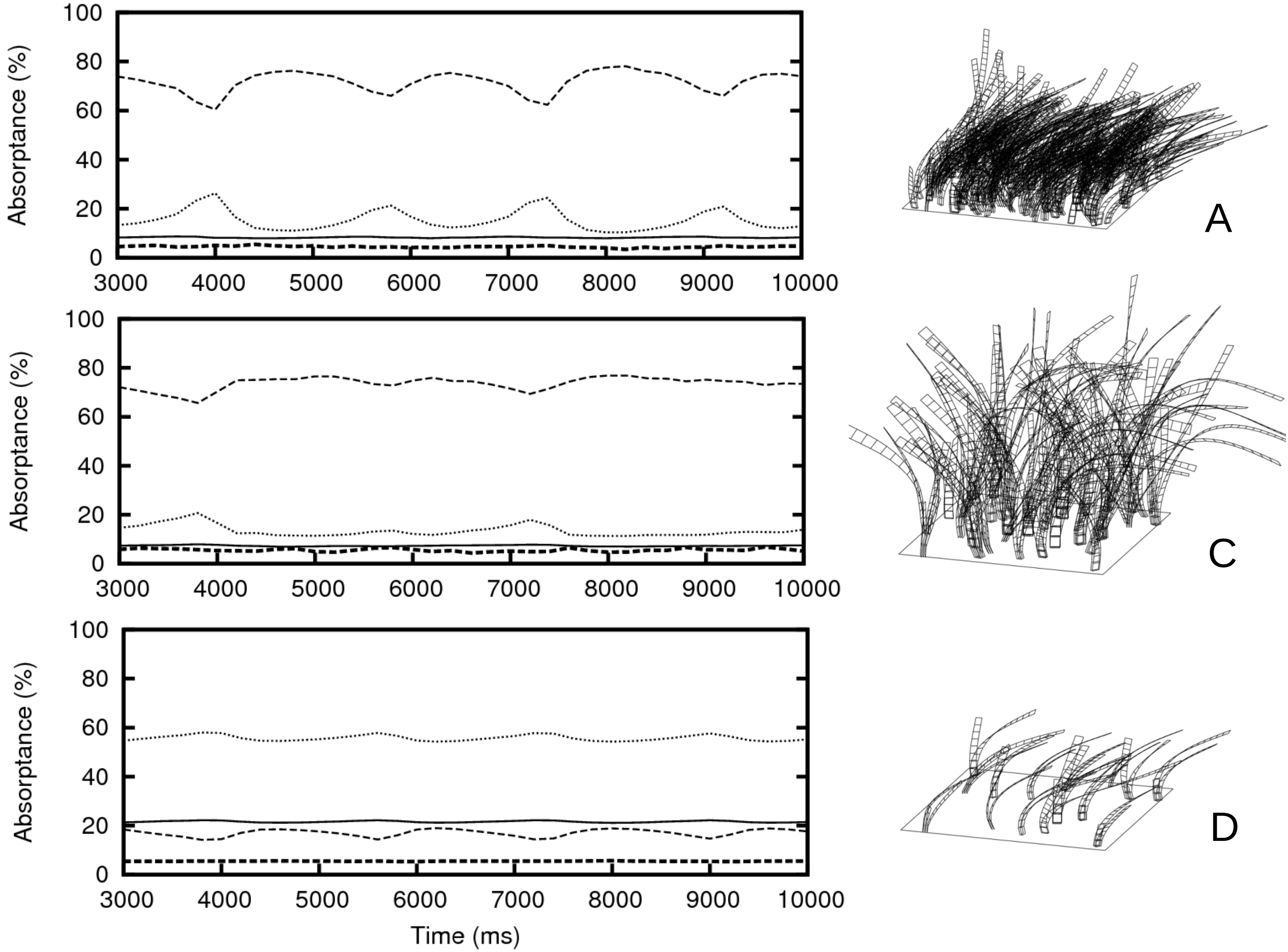


PAR Absorption Breakdown

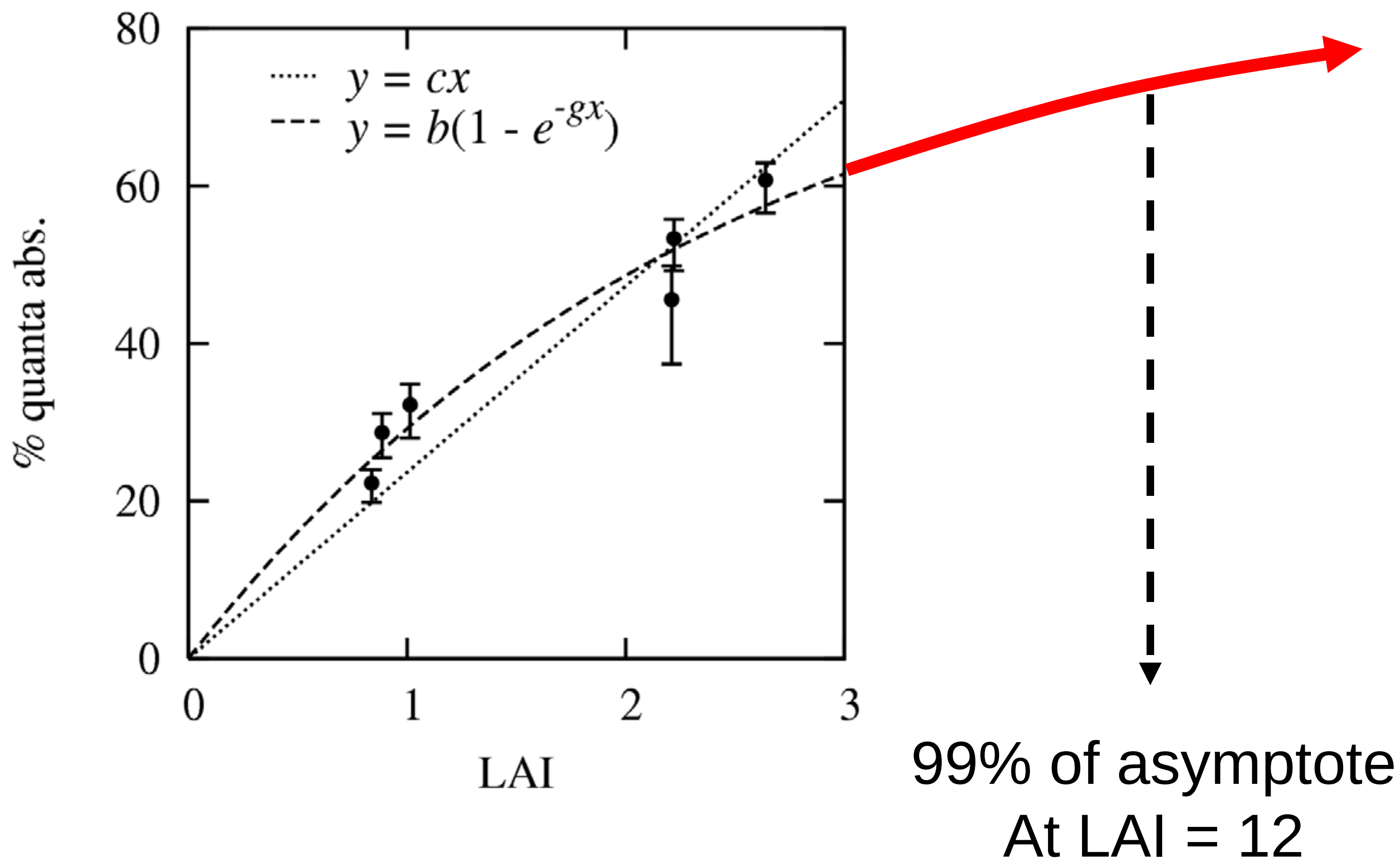


(Hedley & Enríquez, 2010, *Limnology & Oceanography*)

Energy absorption breakdown

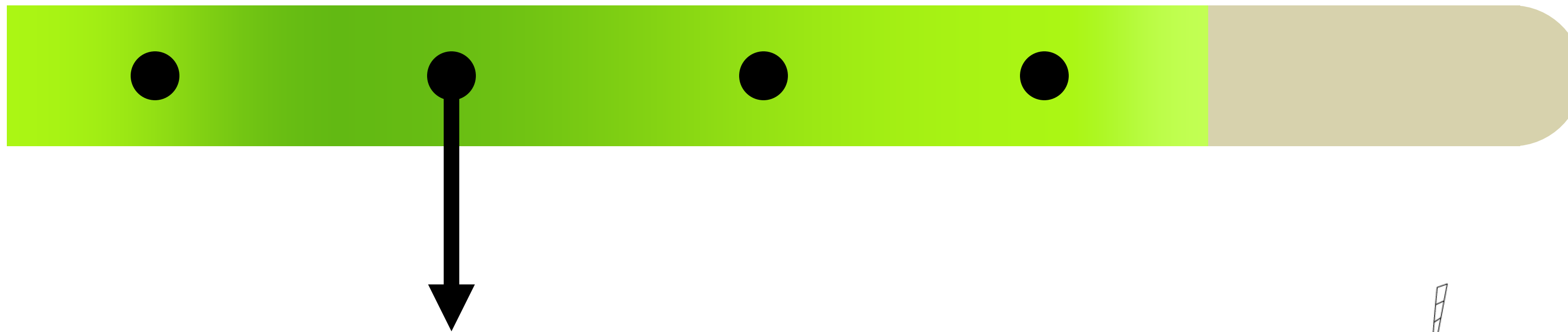


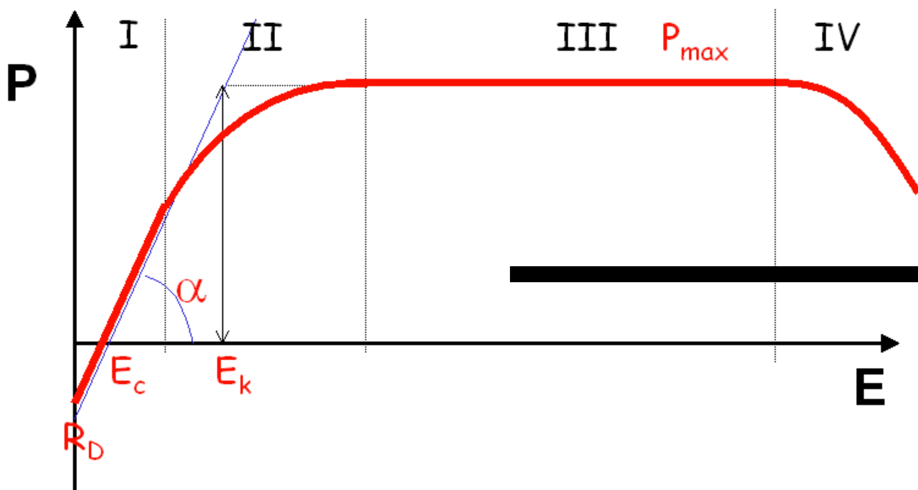
PAR absorption as a function of LAI



(Hedley & Enríquez, 2010, *Limnology & Oceanography*)

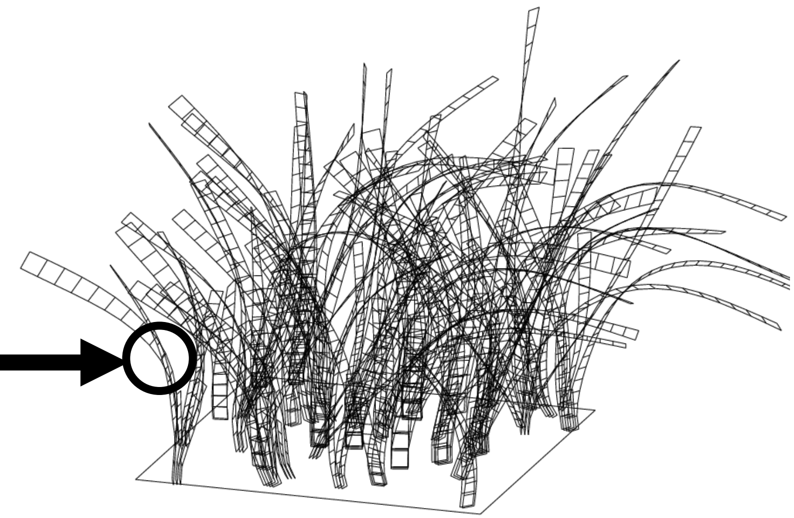
Idealised *Thalassia* leaf





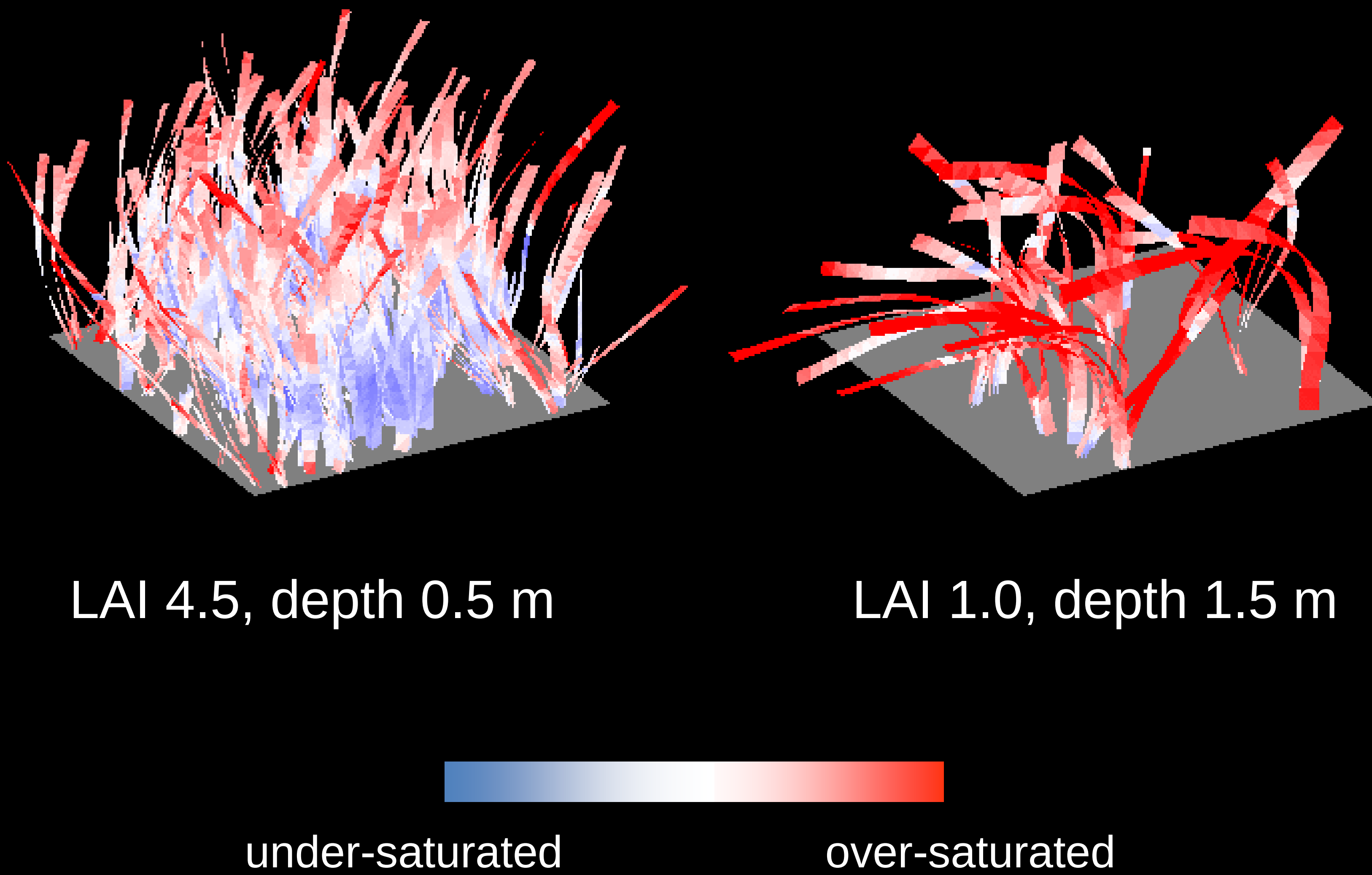
P vs. E curve

(oxygen production per unit area)

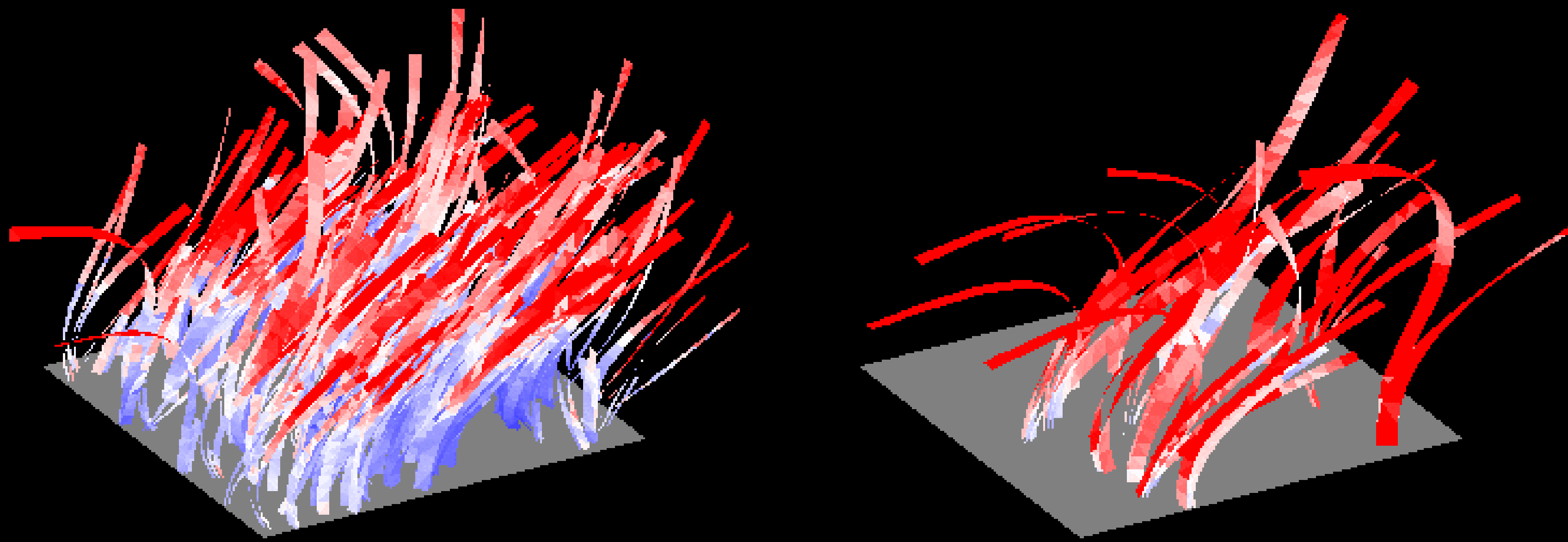


- **Important: non-linear**
- **And in *Thalassia* does not vary much**

Photosynthetic saturation state of leaves



Photosynthetic saturation state of leaves



LAI 4.5, depth 0.5 m

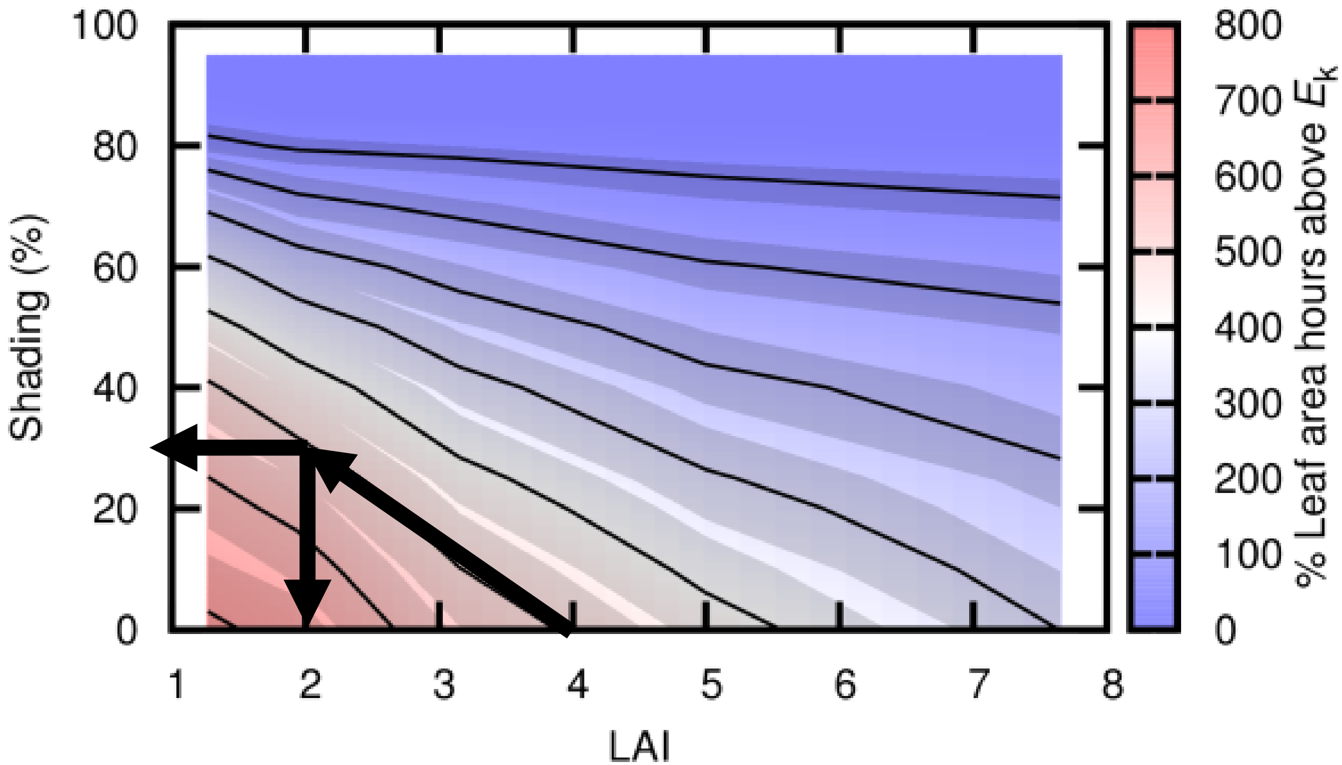
LAI 1.0, depth 1.5 m

under-saturated

over-saturated

LAI vs. shading trade-off : equivalent leaf level irradiances

- For example shading of canopies (dredging events for example)
- Canopies thin out: LAI ↓ but leaf level light ↑



- LAI of 4 is equivalent to LAI of 2 with 30% shading
- Canopy thinning out under reduced light may be acclimatory response

[Hedley, McMahon, Fearns, 2014, *PloS ONE* 9(10): e111454]

Summary points

- Method to approach full 3D radiance distribution $L(x, y, z, \theta, \phi, \lambda)$
- Canopy structure effects are relevant at remote sensing scales
- Benthic photobiology requires consideration of canopy structure
- Canopy thinning should be interpreted in the context of light environment