Progress Installing 3D Canopy Radiation in CESM/CLM4

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Outline

- General concepts
- Algorithmic details
- Data
- Some results

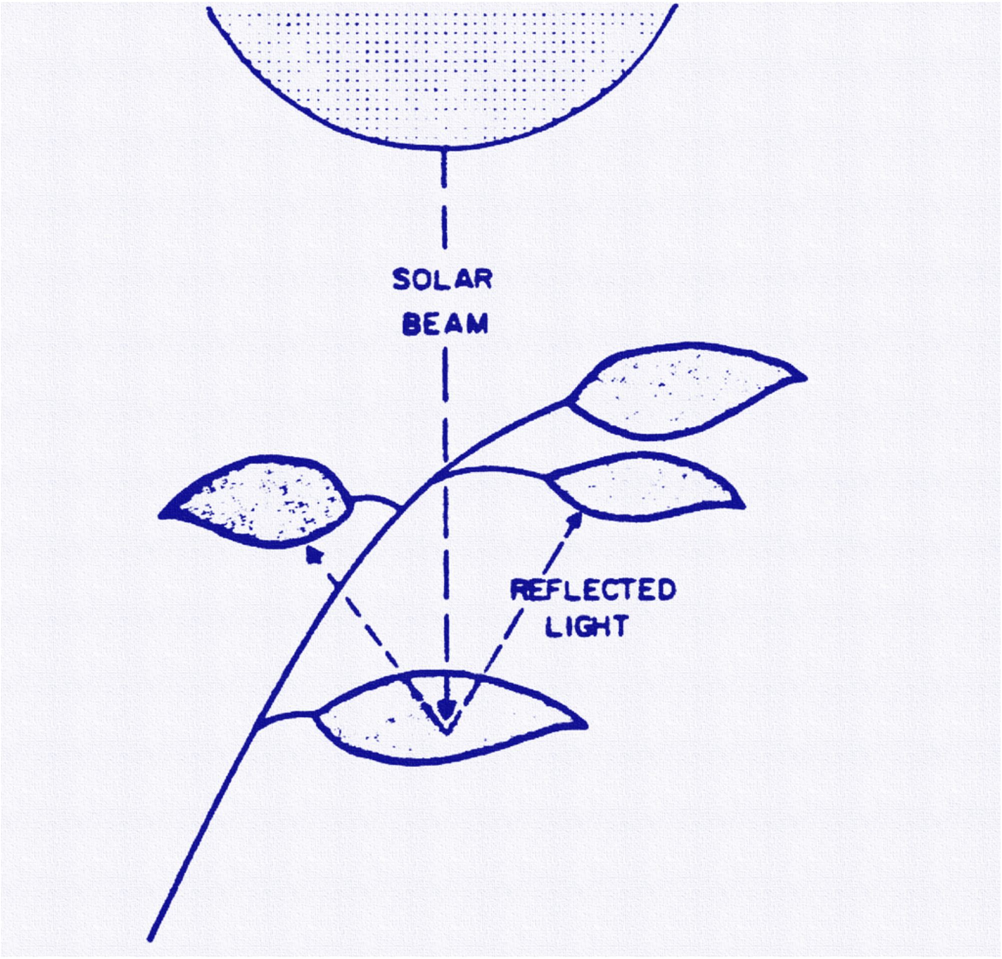
General Concepts- Overview

- Canopy radiation on a large scale is strongly affected by the heterogeneous structure of canopies.
- Given the total surface albedo obtained from satellite data, canopy heterogeneity will strongly affect the partitioning of radiation between ground and canopy with important consequences for the amount of transpiration and photosynthesis occurring in the canopy and soil temperature.
- These effects should be strongest for relatively sparse vegetation and bright underlying surfaces.
- Canopy radiation in climate models has commonly followed Sellers in using leaf optical properties and a two-stream radiation model that assumes canopies can be described by a homogeneous distribution of leaves.

Overview

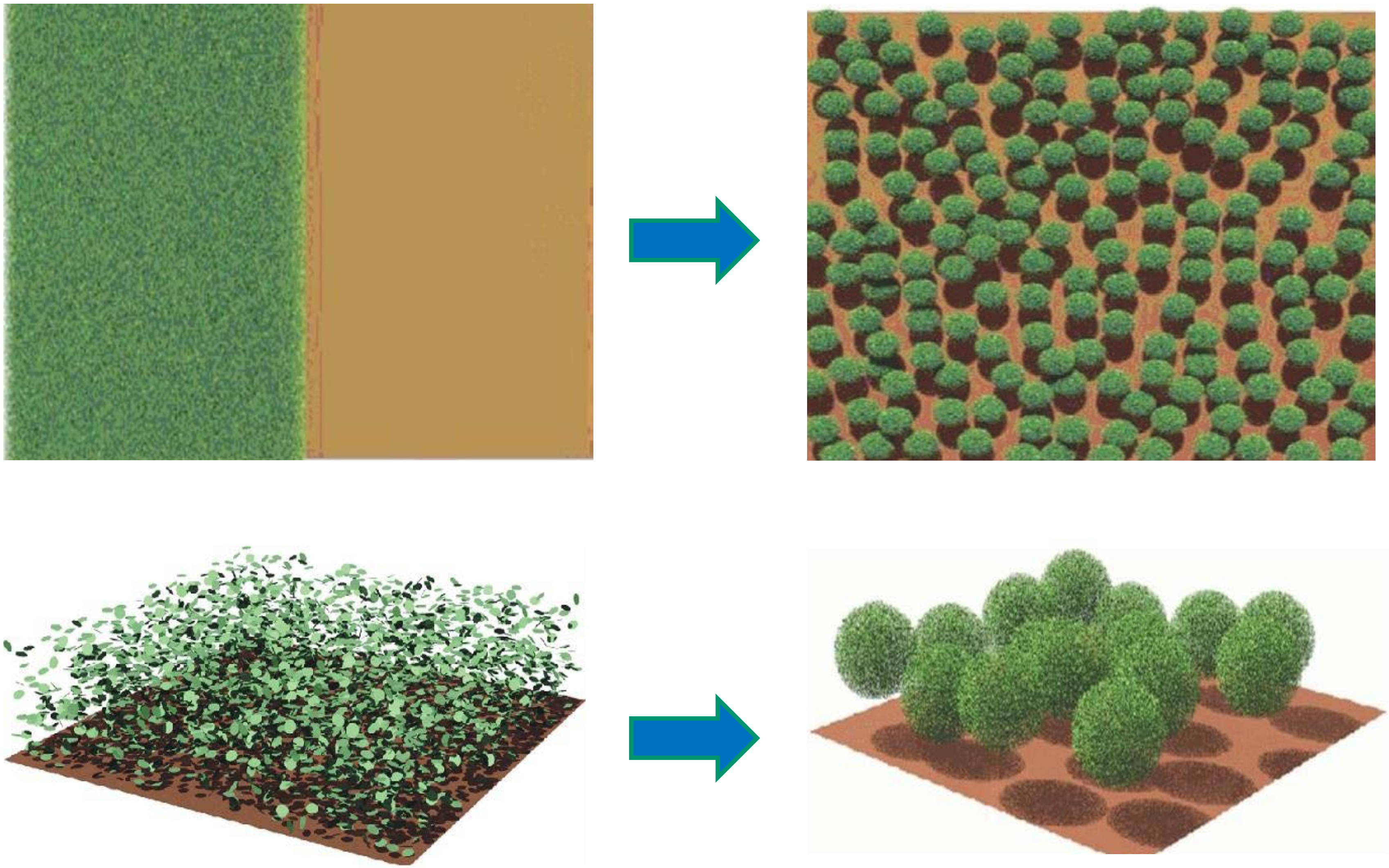
- We have been implementing a more realistic canopy heating at CLM sub-grid level based on the 3-dimensional radiation model along with modeling of leaf orientation, bush shape factors and canopy overlapping shadows.
- The overlap acts to reduce the total area covered by shadows and enlarge the sunlit gaps.
- The new scheme improves the heating of the bush canopy with an underlying black surface follows the logic of Dickinson et al. (2008), with the multi-scattered contribution described in Dickinson (2008).

Light Reflection from Leaf



Sketch of partial trapping of light reflected from a canopy leaf by overlaying leaves (Dickinson 1983)

Current Models Versus Reality



Representation of Sparse Vegetation in CLM

- In the earliest version of CLM (Dai et al. 2000), fractional vegetation had a fractional cover fc , but concept lost in order to separate the bare soil from the pfts as in LSM.
- CLM5 uses Lawrence MODIS data for land surface coverage. It defines all 17 land cover fractions at each grid even where many of fractions are zero or too small; each pft only sees the soil directly underneath it (i.e. it is 100% cover).
- As bush shadow logic only works with fractional coverage, our initial development of data combines the data for multiple pfts within a model grid to define fractional covers.

Model Implementation of Bush Logic

- Given grid square has multiple pft fractions, these fractions are divided into height classes:

  tall for trees,

  intermediate for shrubs and

  short for grasses, crops and everything else.

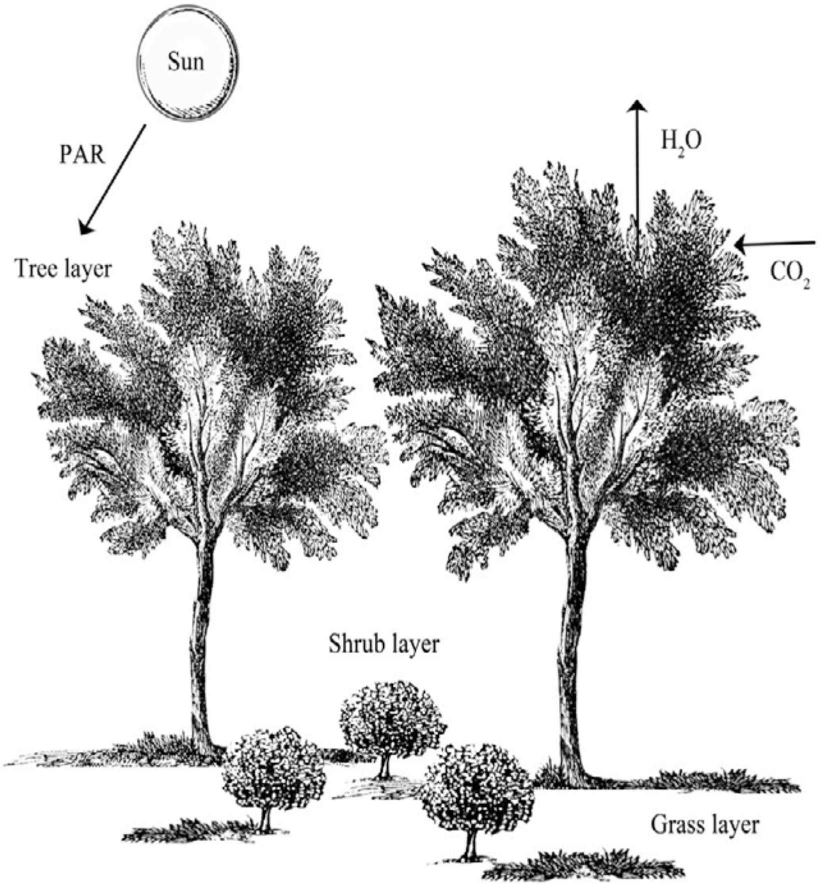
- Shading rules are that:

  tall shades all lower pfts,

  intermediate shades short and bare soil while

  short vegetation shades only bare soil.

3D Canopy Structure



CLM Plant Functional Types

0 Not Vegetated

1 Needleleaf Evergreen Temperate Tree
2 Needleleaf Evergreen Boreal Tree
3 Needleleaf Deciduous Boreal Tree
4 Broadleaf Evergreen Tropical Tree
5 Broadleaf Evergreen Temperate Tree
6 Broadleaf Deciduous Tropical Tree
7 Broadleaf Deciduous Temperate Tree
8 Broadleaf Deciduous Boreal Tree

9 Broadleaf Evergreen Shrub
10 Broadleaf Deciduous Temperate Shrub
11 Broadleaf Deciduous Boreal Shrub

12 C3 Arctic Grass
13 C3 Non-Arctic Grass
14 C4 Grass
15 Corn
16 Wheat

Examples of Bush Shadow

Algorithmic Details-Shadow Area

- The starting building block is a single spherical bush. Its relative area of shadow cast on the ground is fc/coszen, where fc is the fractional cover of the geometric vegetation and coszen is cosine of sun angle.
- The ground shadow with overlap can be modeled by a large number of possible statistical models. The simplest is to assume an exponential distribution of bush separations
- Overlap has two effects: 1) it reduces the fractional area of the surface not receiving sunlit; 2) it increases the optical paths and so the radiation absorbed by the canopy.
- Area of non-overlapping shadow spherical bush casts on ground to direct beam:

  shadow_gd = [1-exp(-fc/coszen)]/[1-fc*exp(-1/coszen)]
- Area of non-overlapping shadow spherical bush casts on ground to diffuse beam:

  shadow_gi = [1-exp(-2*fc)]/[1-fc*exp(-2)]
- area of shadow bush casts on sky

  shadow_sky = shadow_gi

Canopy Reflectance, Transmittance & Scattering

rhol = leaf reflectance
taul = leaf transmittance (optical depth)
ws = fractional weight of stem in vai = esai/(elai+esai)
wl = fractional weight of leaf in vai = elai /(elai+esai)
rhols = leaf-stem reflectance = rhol*wl + rhos*ws
tauls = leaf-stem optical depth = taul*wl + taus*ws

tau0 = optical depth for single bush = 3/4*G*vai
vai = veg area index = elai + esai
G = geometric blocking parameter (0.5 for uniform distribution of orientation)
taud = optical depth for direct beam = (tau0*fc)/(coszen*shadow=_gd)
taui = optical depth for diffuse beam = (2*tau0*fc)/(shadow_gi)
ϖ = fraction of intercepted radiation scattered = tauls + rhols
T (vai) = unscattered transmittance through bush (analytic expression)

Multiscattering logic

- Incident photon, if attenuated (1-T) is scattered with probability ϖ
- The scattered radiation either escapes from the canopy or is again attenuated.
- Can construct probabilities at each scattering:
- Pa +pe =1.
-

Single Scattering Terms

- Single scatter forward for direct beam
  phi_1f_d = [1- (1 + 2taud + 2taud*taud*exp(-2taud)] / (taud*taud)
- Single scatter backward for direct beam
  phi_1b_d = 0.5[1 - T(2taud)]
- Single scatter average for direct beam
  phi_1a_d = 0.5[phi_1b_d + phi_1f_d]
- Single scatter forward for diffuse beam
  phi_1f_i = [1 - (1 +2taui + 2taui*taui)*exp(-2taui)] / (taui*taui)
- Single scatter backward for diffuse beam
  phi_1b_i = 0.5*[1 - T(2taui)]
- Single scatter average for diffuse beam
  phi_1a_i = 0.5[phi_1b_i + phi_1f_i]

Approximate Double Scattering Terms

- Double scatter forward direct beam

  phi_2f_d = 1/3-T(2taui)+2T(3*taui)/3
- Double scatter backward direct beam

  phi_2b_d = 4phi_1f_d/3 + T(2*taui)T(4taui)/9 -10T(taud)/9
- Double scatter average direct beam

  phi_2a_d = 0.5[phi_2b_d + phi_2f_d]
- Double scatter forward diffuse beam

  phi_2f_i =1/3-T(2taui)+2T(3*taui)/3
- Double scatter backward diffuse beam

  phi_2b_i = 4phi_1f_i/3 + T(2taui)+T(4taui)/9 -10*T(taud)/9
- Double scatter average diffuse beam

  phi_2a_i = 0.5[phi_2b_i + phi_2f_i]

Multiple Scattering Terms

- Probability of absorption after 2 scattering (direct beam)
  pad = 1-phi_2a_d/[1 - ftdd –]
- Probability of absorption after 2 scattering (diffuse beam)
  pai = 1-phi_2a_i /[1 - ftdi -]
- Multi-scatter forward direct beam
  phi_mf_d = phi_2f_d + omega*pad*phi_2a_d/[1-omega*pad]
- Multi-scatter backward direct beam
  phi_mb_d = phi_2b_d + omega*pad*phi_2a_d/[1-omega*pad]
- Multi-scatter average direct beam
  phi_ma_d = 0.5[phi_mb_d + phi_mf_d]
- Multi-scatter forward diffuse beam
  phi_mf_i = phi_2f_i + omega*pai*phi_2a_i/[1-omega*pai]
- Multi-scatter backward diffuse beam
  phi_mb_i = phi_2b_i + omega*pai*phi_2a_i/[1-omega*pai]
- Multi-scatter average diffuse beam
  phi_ma_i = 0.5[phi_mb_i + phi_mf_i]

Total sphere scattering, Forward, Backward, Average & Difference

- Backward fraction of 3D scat rad in all direction for direct beam

  phi_totb_d = rhols*phi_1b_d + phi_mb2_d
- Forward fraction of 3D scat rad in all direction for direct beam

  phi_totf_d = tauls*phi_1f_d + phi_mf2_d
- Total radiation scattered in all direction per direct beam

  phi_tot_d = phi_totf_d + phi_totb_d
- Forward - backward difference in scattered radiation per direct beam

  phi_dif_d = phi_totf_d - phi_totb_d
- Backward fraction of 3D scattering radiation in all direction for diffuse beam

  phi_totb_i = rhols*phi_1b_i + phi_mb2i
- Forward fraction of 3D scattering radiation in all direction for diffuse beam

  phi_totf_i = tauls*phi_1f_i + phi_mf2i
- Total radiation scattered in all direction per diffuse beam

  phi_tot_i = phi_totf_i + phi_totb_i
- Forward - backward difference in scattered radiation per diffuse beam

  phi_dif_i = phi_totf_i - phi_totb_i

Unscattered Beam Transmission Terms

- Transmission for unscattered direct beam

  ftdd = 0.5[1.0 - (2taud+1)exp(-2taud)] / [taud*taud]
- Direct beam reaching ground without scattering

  ftdd0 = shadow_gd*fdn_id
- Downward diffused flux of direct beam through canopy

  fdn_id = 0.5[phi_tot_d + 0.5*coszen*coszen*phi_dif_i]
- Direct beam reaching ground after scattering

  ftid0 = 1.0 - shadow_gd*(1 - ftdd)
- Transmission for unscattered diffuse beam

  ftdi = 0.5[1.0 - (2taui+1)exp(-2tau_i)] / [taui*taui]
- Transmission for scattered direct beam

  ftid = ftid/(1-probm)

Scattered Beam Transmission Terms

- Diffuse beam reaching ground after scattering

  ftii0 = 1.0 - shadow_gi*[1 - ftdi - fdn_ii]

- Transmission for scattered diffuse beam

  ftii = ftii0/(1-probm)

- Downward diffused flux of diffused beam through canopy

  fdn_ii = 0.5[phi_tot_i + 0.125*phi_dif_i]

- Indirect diffused flux of diffuse beam

  fback_ii = 0.5[phi_tot_i - 0.125*phi_dif_i]

- Probability of ground-reflected diffuse beam will reflect downward

  probm = fback_ii*shadow_sky*albgri

Absorption Terms

- Direct flux absorbed by canopy after reflection from ground

  fabd_gr = shadow_sky*(ftdd0*albgrd + ftid0*albgri)*fabi
- Direct flux absorbed by canopy after multiple reflections from ground

  fabd_gr = fabd_gr/(1-probm)
- Diffuse flux absorbed by canopy after reflection from ground

  fabi_gr = shadow_sky*(ftii0*albgri)*fabi
- Diffuse flux absorbed by canopy after multiple reflections from ground

  fabi_gr = fabi_gr/(1-probm)
- Canopy absorption for direct beam

  fabd = shadow_gd*[1.0 - ftdd - phi_tot_d]

  = fabd + fabd_gr
- Canopy absorption for diffuse beam

  fabi = shadow_gi*[1.0 - ftdi - phi_tot_i]

  = fabi + fabi_gr

Surface Albedo

- Surface albedo for direct beam

  albd = [1.0 – fabd – (1-albgrd)*ftdd – (1-albgri)*ftid]

- Surface albedo for diffuse beam

  albi = [1.0 – fabi – (1-albgri)*ftii]

Radiation Input to Three Canopy Layers

- For a three canopy layers, upper story will receive a unit solar radiation input:

  $$I_u=1.0$$

- Radiation reaching the middle story is directly transmitted through the upper story and scattered downward by leaves in the upper story:

  $$I_m = I_u[1.0 - Shadow_u (1.0 - T_u - \Phi_{ud})]$$

- Similarly, the bottom story will receive I_b consisting fraction of I_m are incident on the middle story, plus direct transmission and downward diffuse scatter:

  $$I_b = I_m[1.0 - Shadow_m (1.0 - T_m - \Phi_{md})]$$

- The ground will receive radiation fraction I_g:

  $$I_g = I_b[1.0 - Shadow_b (1.0 - T_b - \Phi_{bd})]$$

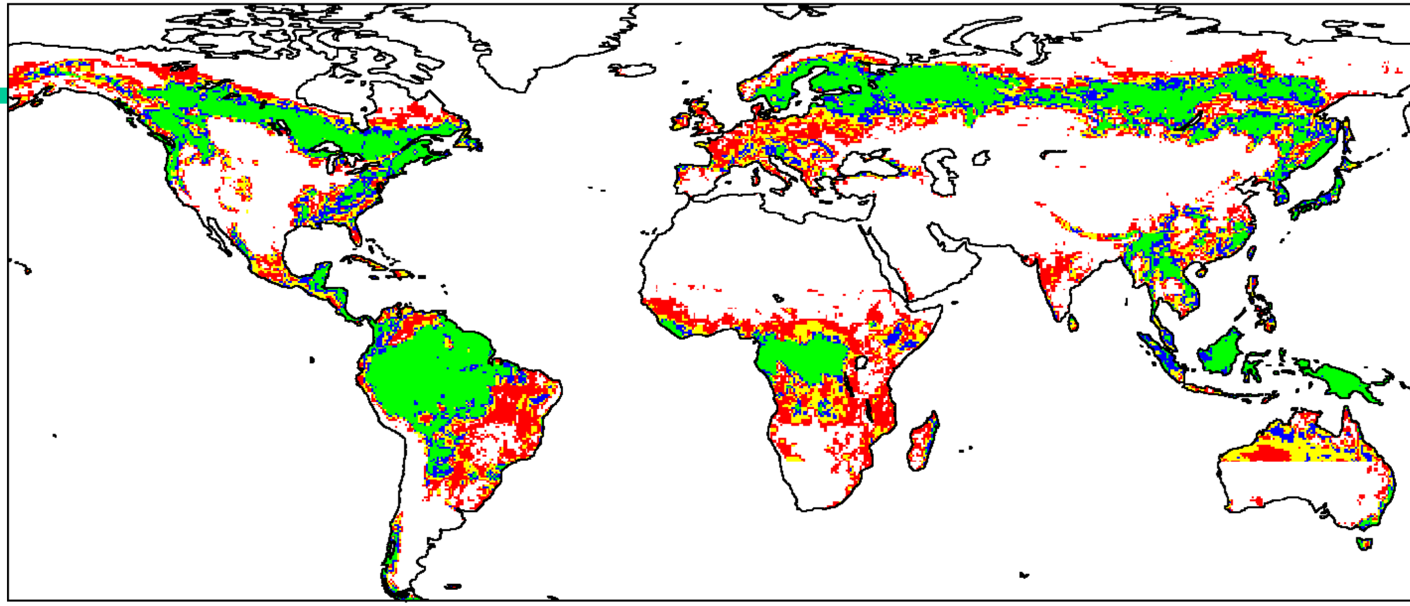
Radiation Input to Three Canopy Layers

- CLM has separate calculations for direct and diffuse incident beams. The fraction of an incident direct beam scattered downward is added to the diffuse fluxes.
- Radiation reflected from the ground can interact with any of the canopy layers, according to the fraction of ground it shadows and be reflected back to the ground.
- Each layer absorbs a fraction of the radiation incident on it or reflected from the ground according to the same logic as for a single layer.
- 3-D calculation considers all the pfts together. Each layer uses properties that are weighted average over its contributing pfts.
- Radiative absorption occurs at the ground and in each layer.

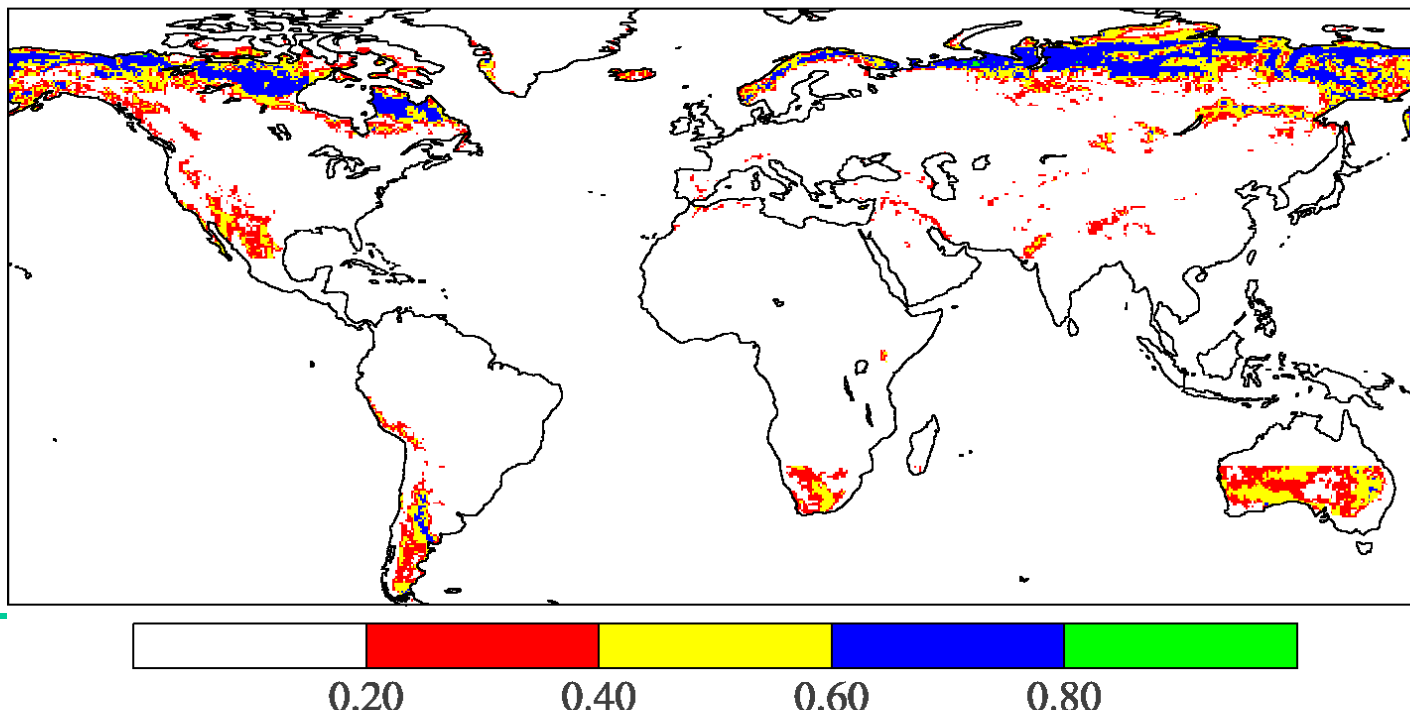
DATA

- Simplest choices are that vegetation completely homogeneous, corresponding to current tiling or completely heterogeneous, i.e. vegetation uniformly distributed across smallest unit of observation.
- From MODIS, fractional cover data at 1 km –needs to be done.
- Current CLM pft data is a 0.25 deg. We take the tiles at this resolution and assume uniform distribution. Not very accurate but equally or more plausible than the homogeneous assumption.
- Next level of detail would be to identify some tiles as homogeneous and some as completely heterogeneous.
- Any more elaborate statistical model would require a rework of the radiation shading model.

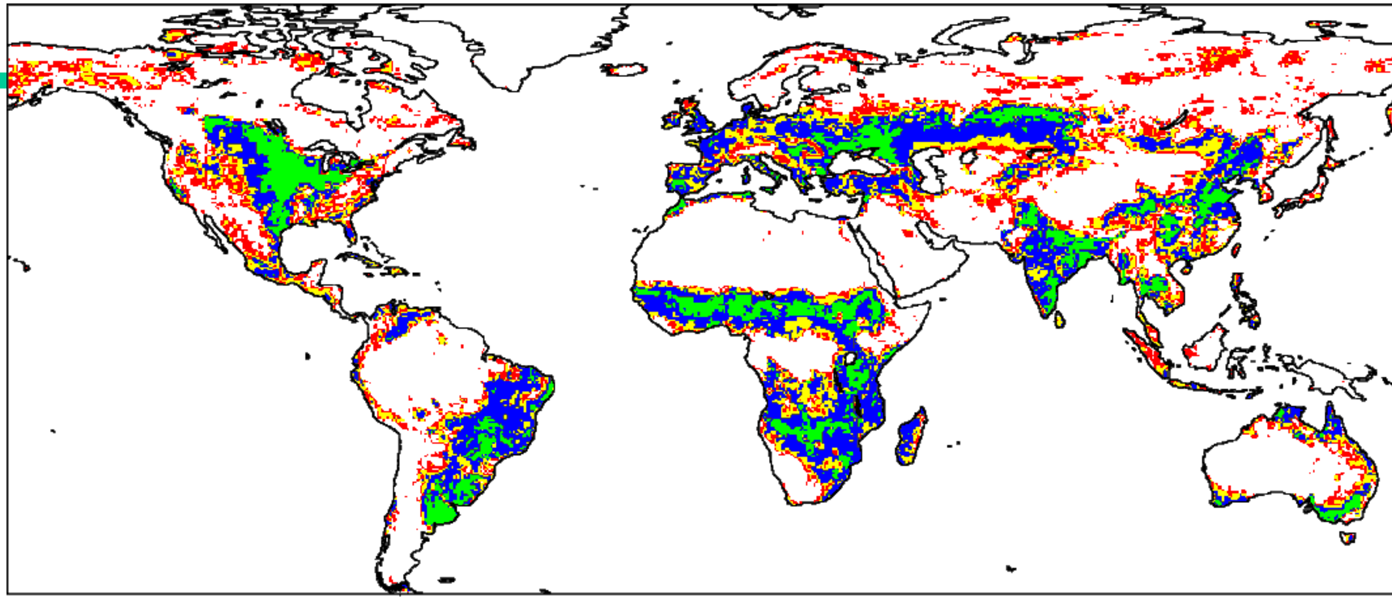
Fractional Coverage of Tree Layer at 0.25 Deg Resolution



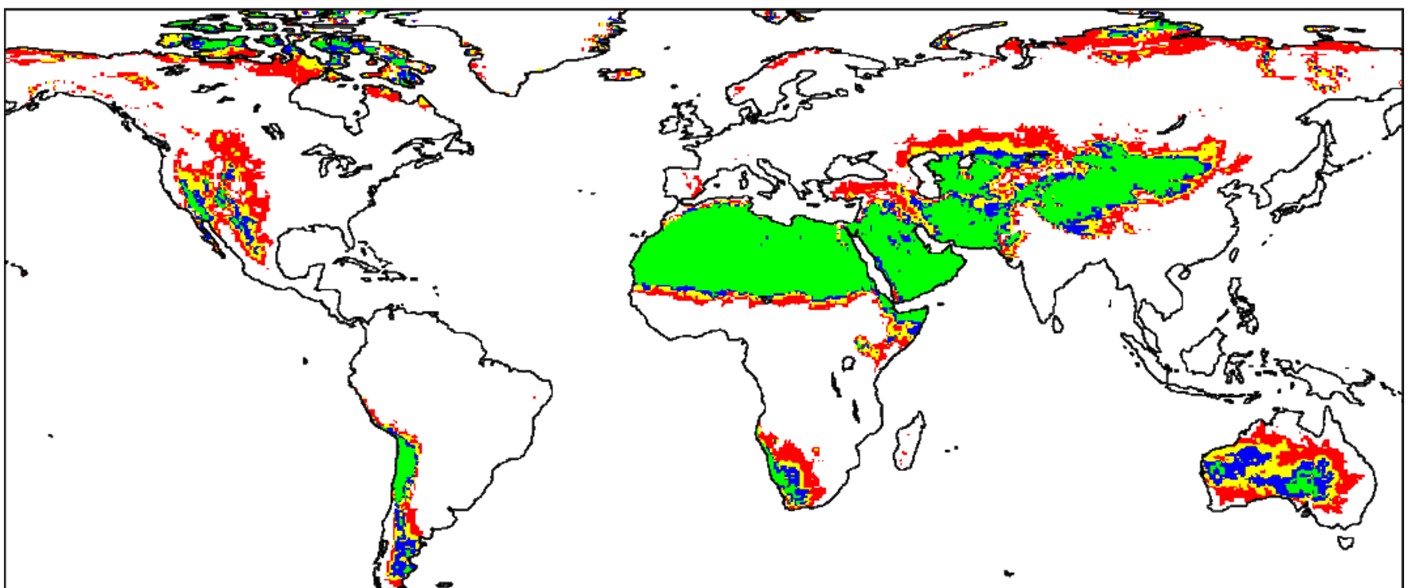
Fractional Coverage of Bush Layer at 0.25 Deg Resolution

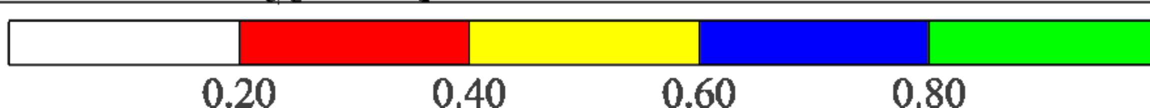


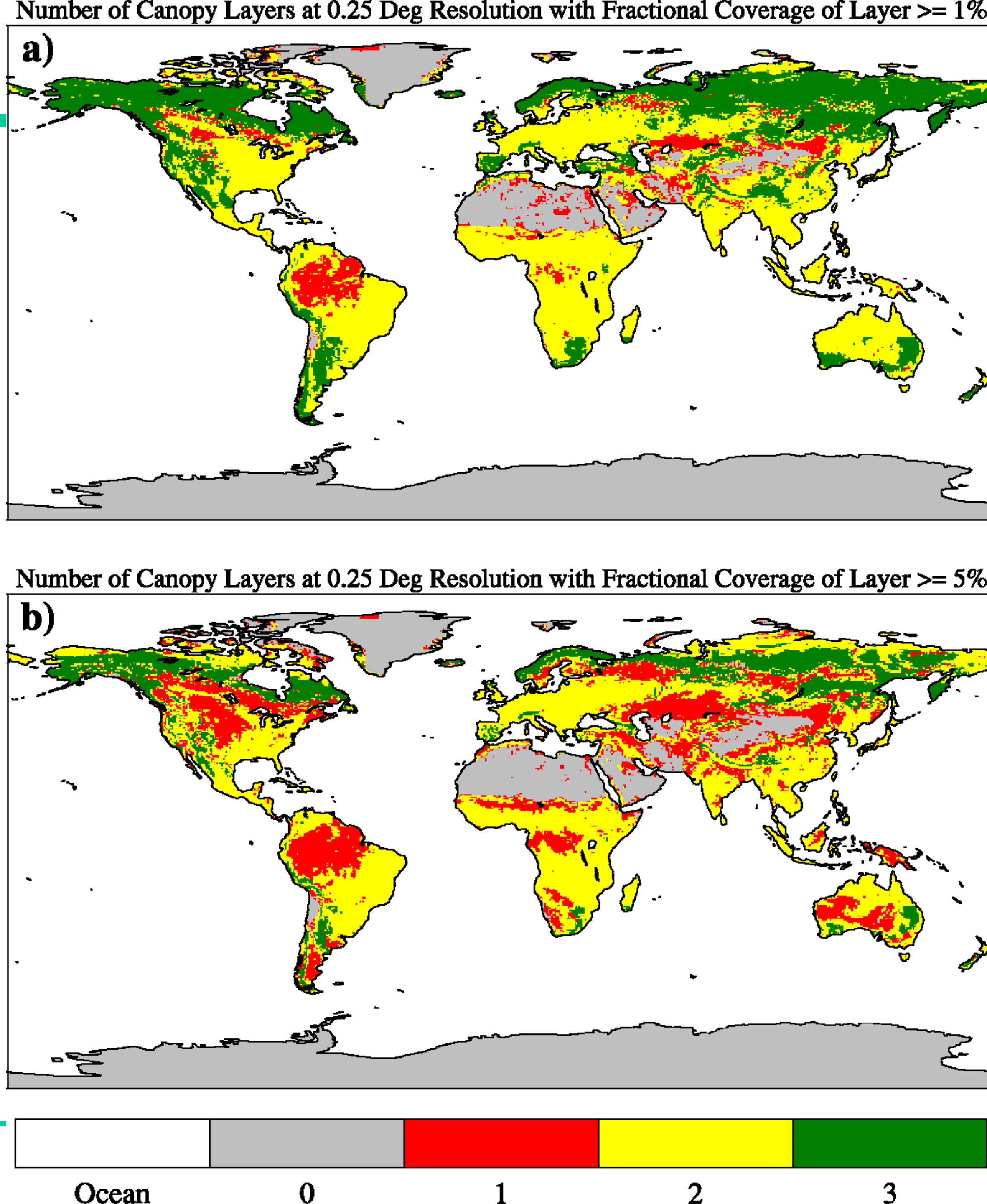
Fractional Coverage of Grass Layer at 0.25 Deg Resolution



Fractional Coverage of Bare Soil at 0.25 Deg Resolution



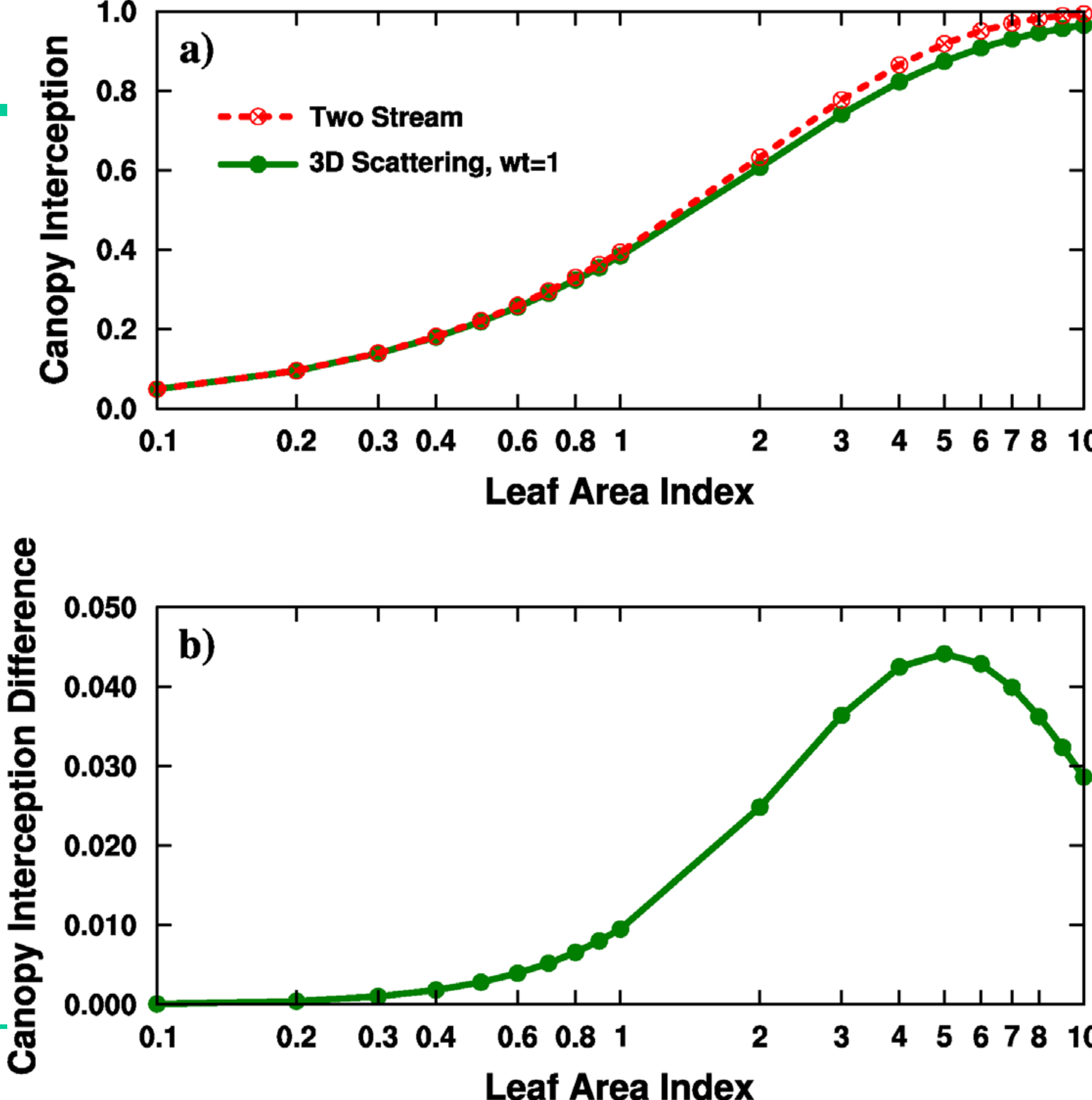




Number of Canopy Layers at 0.25 Deg Resolution with Fractional Coverage of Layer >= 1%
a)
Number of Canopy Layers at 0.25 Deg Resolution with Fractional Coverage of Layer >= 5%
b)
Ocean
0
1
2
3

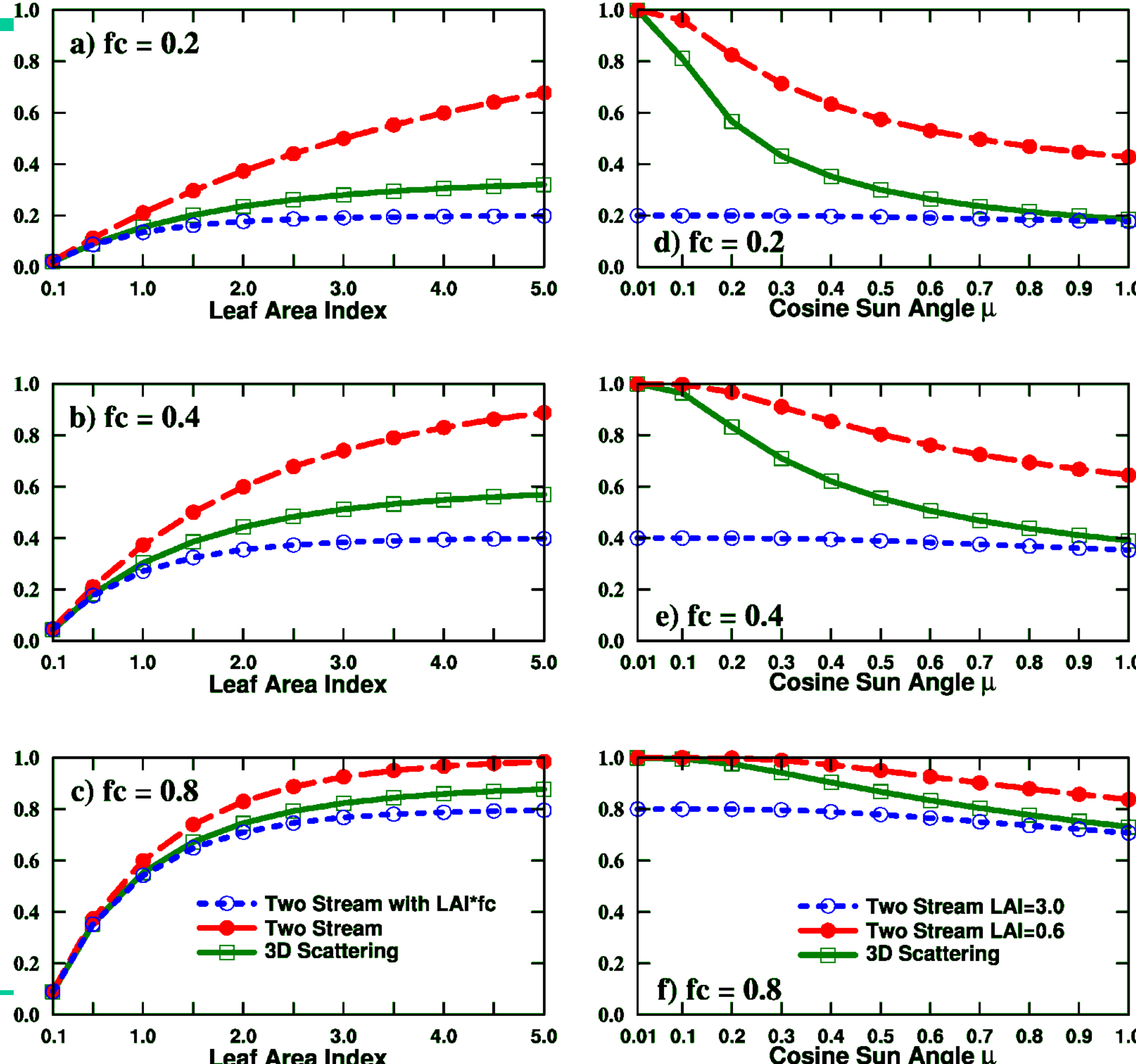
Some Results

- Figures from a comparison of 3D with 1D. Radiation stand-alone.

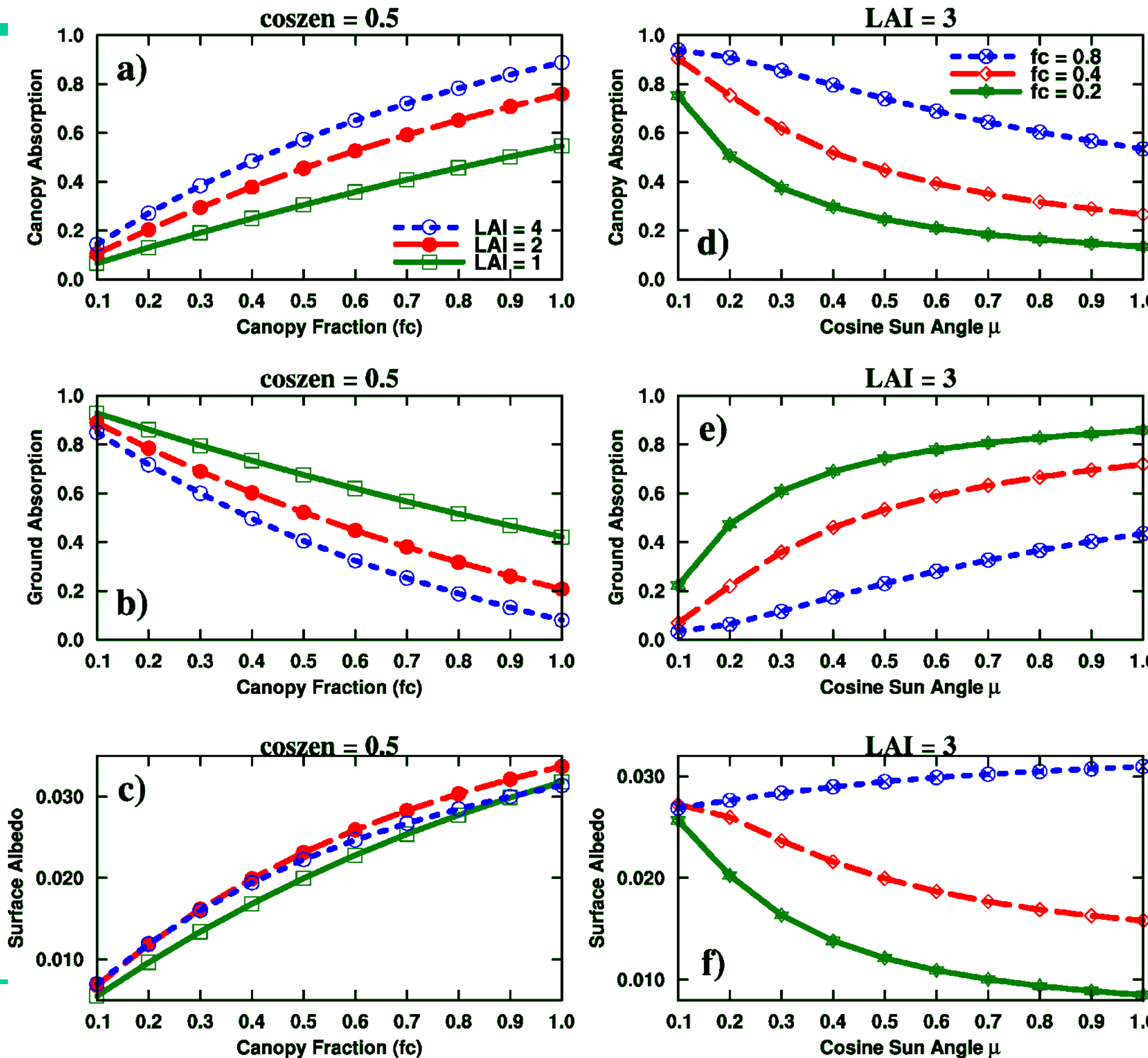


a)
Two Stream
3D Scattering, wt=1
Canopy Interception
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.6
0.8
1
2
3
4
5
6
7
8
10
Leaf Area Index
b)
Canopy Interception Difference
0.050
0.040
0.030
0.020
0.010
0.000
Leaf Area Index

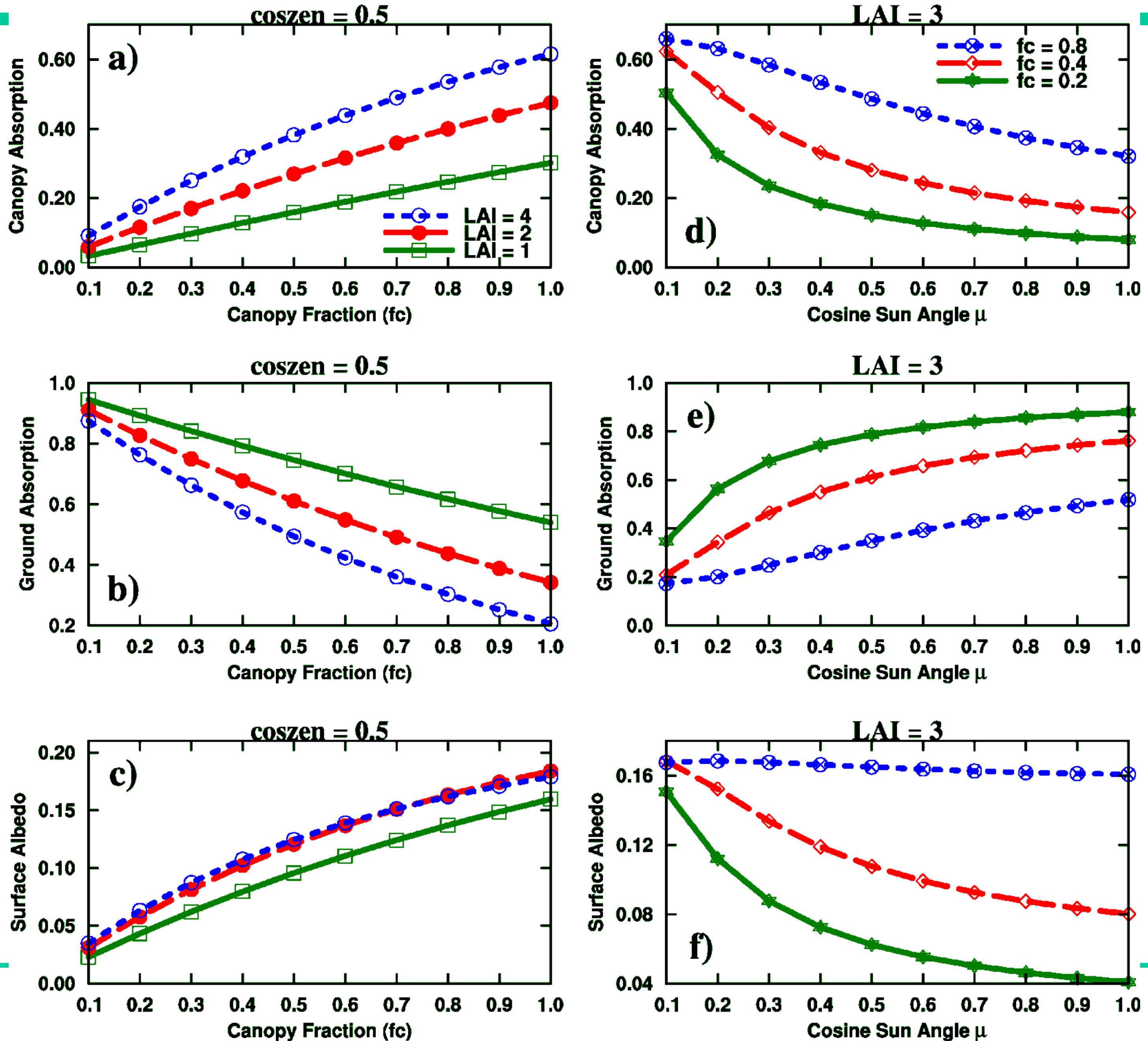
Canopy Absorption (the ordinate) for a Black Canopy
Ground Albedo = 0.2



Canopy Absorption - Ground Albedo = 0.0
Leaf Reflectance = 0.1 - Leaf Transmittance = 0.05



Canopy Absorption - Ground Albedo = 0.0
Leaf Reflectance = 0.45 - Leaf Transmittance = 0.25



Leaf Area Index = 3 - coszen = 0.5