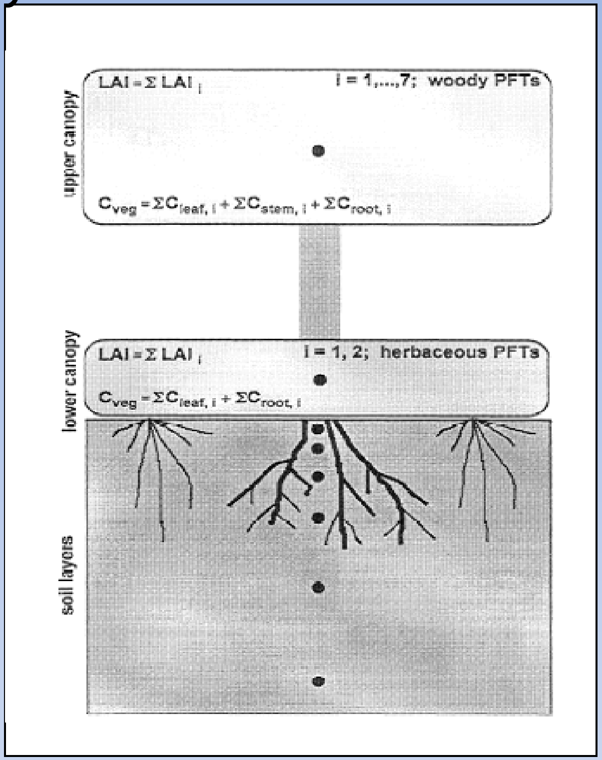
"The merits and challenges of the ED-based approach to vegetation modeling"

Paul Moorcroft and Abby Swann

representing the ED2 development team: David Medvigy, Marcos Longo, Ryan Knox, Michael Dietze, Abby Swann et al…)

The Merits

Issues with Big-Leaf Ecosystem models



<u>Non Linear Averaging</u>: big-leaf ecosystem models average over vertical and horizontal heterogeneity in the resource environments of the individual plants that make-up the plant canopy.

- This is problematic because the functions governing the ecosystem's above-ground dynamics (growth, mortality & recruitment) are non-linear functions of the plant's environment (Jensen's Inequality)

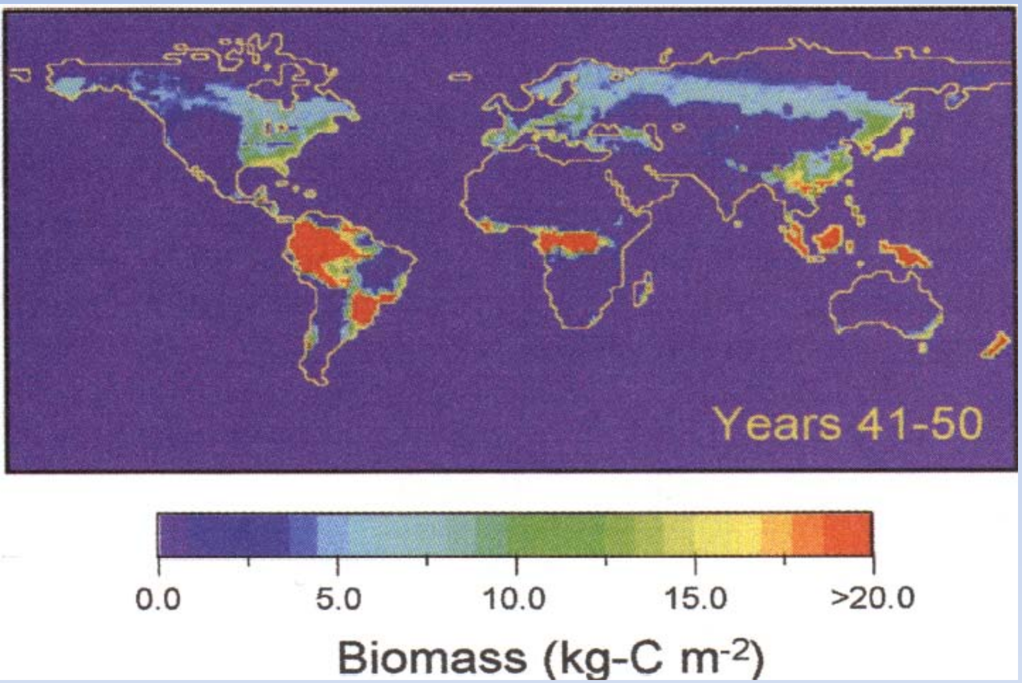
$$f(\bar{X}) \neq \bar{f}(X)$$

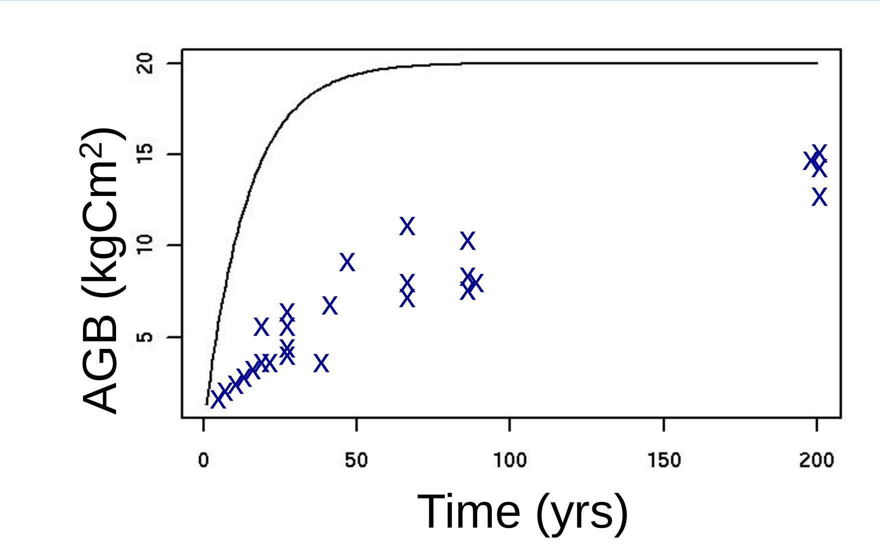
“Big-Leaf” models tend to have unrealistic long-term ecosystem dynamics

<u>Unrealistic timescales of response:</u>

e.g. Above-ground biomass dynamics of evergreen tree spp. in IBiS

Comparison against observations at San Carlos (tropical forest) $2^oN, 68^oW$





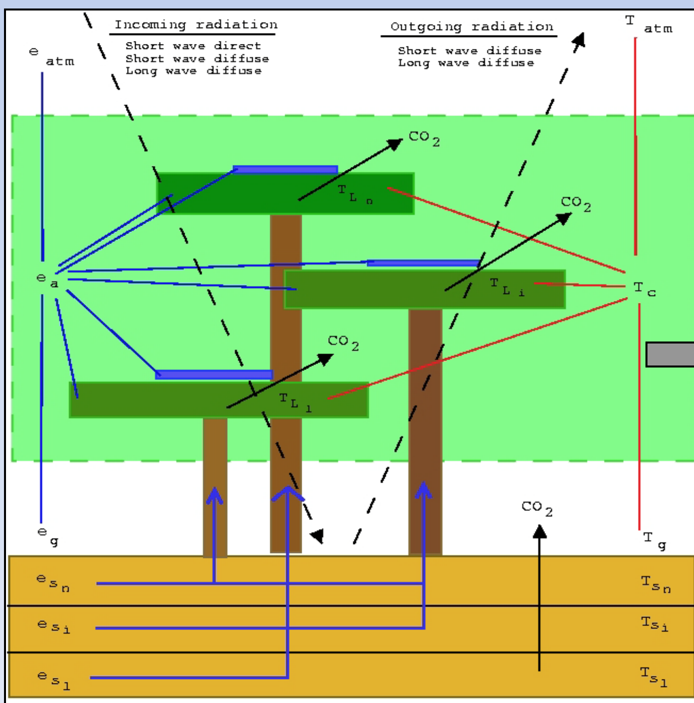
<u>Homogeneous Ecosystems:</u> In big-leaf models there is a single environmental niche within each climate grid cell. Gause competitive exclusion principle → homogeneous ecosystems.

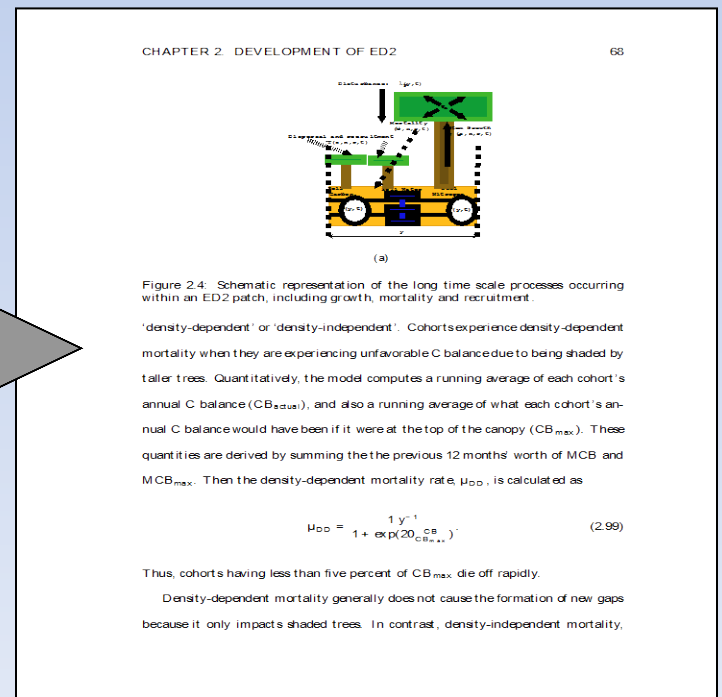
Symptoms of non-linear averaging in big-leaf biosphere models

1. Incorrect timescales of ecosystem response: transitions between ecosystem states occur too rapidly.
2. Lack of diversity: homogenous ecosystems comprised of single plant functional types.
3. Difficult parameterize: few ecosystem measurements are made at scale of climate grid-cells.

Ecosystem Demography (ED2) Model

(Moorcroft et al. 2001)
Medvigy et al. 2009)





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(a)

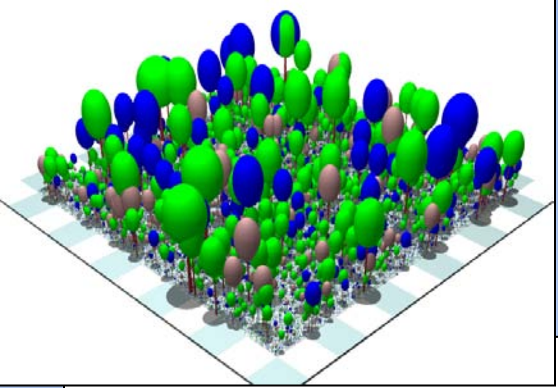
Figure 2.4: Schematic representation of the long time scale processes occurring within an ED2 patch, including growth, mortality and recruitment.

'density-dependent' or 'density-independent'. Cohorts experience density-dependent mortality when they are experiencing unfavorable C balance due to being shaded by taller trees. Quantitatively, the model computes a running average of each cohort's annual C balance (CB_{actual}), and also a running average of what each cohort's annual C balance would have been if it were at the top of the canopy (CB_{max}). These quantities are derived by summing the the previous 12 months' worth of MCB and MCB_{max}. Then the density-dependent mortality rate, μ_{DD}, is calculated as

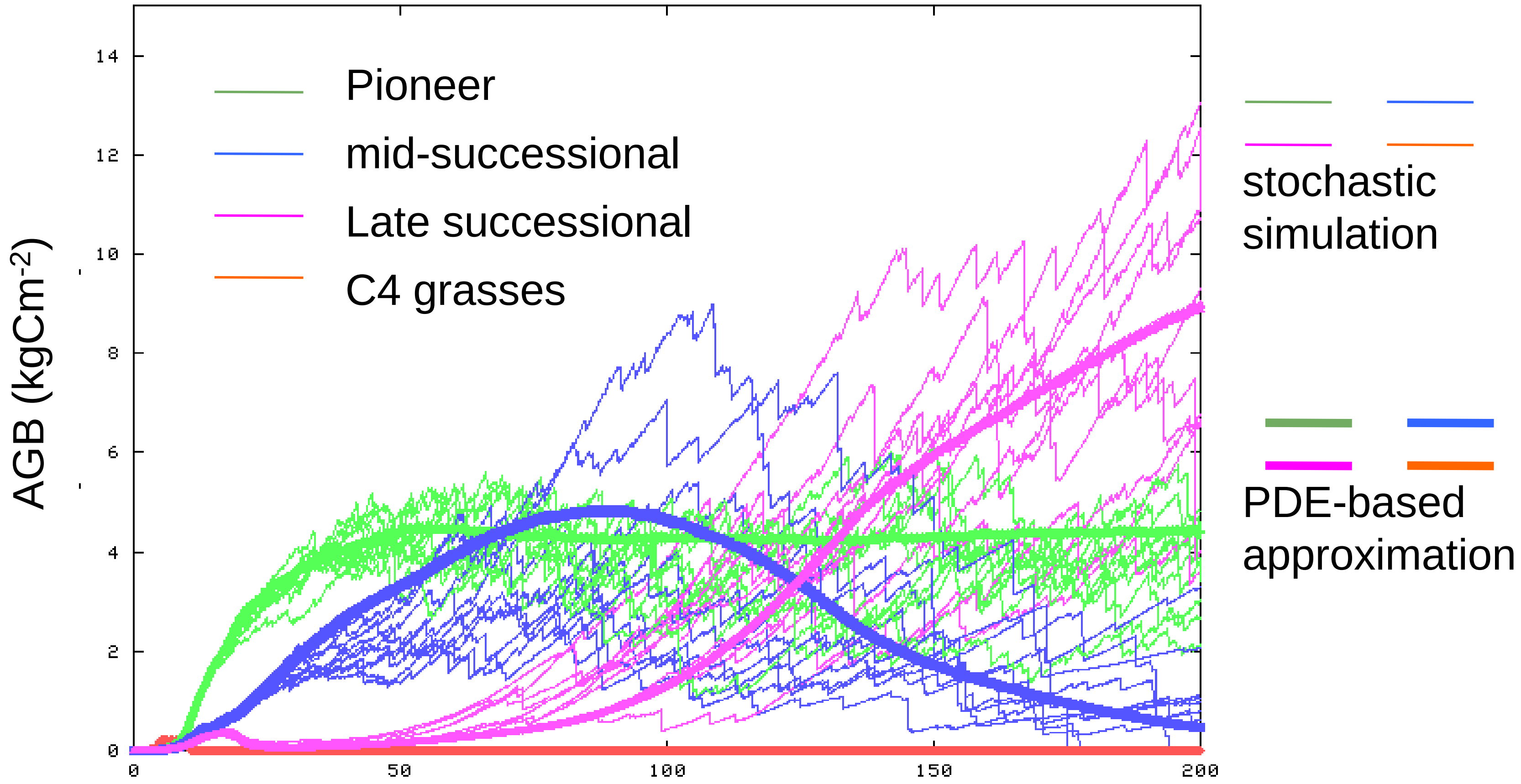
$$\mu_{DD} = \frac{1\ y^{-1}}{1 + \exp(20 \frac{CB}{CB_{max}})}. \quad (2.99)$$

Thus, cohorts having less than five percent of CB_{max} die off rapidly.

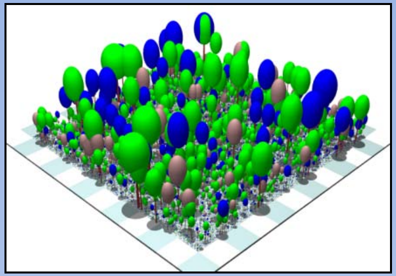
Density-dependent mortality generally does not cause the formation of new gaps because it only impacts shaded trees. In contrast, density-independent mortality,



ED Model simulator dynamics at San Carlos (tropical forest) 2°N,68°W: trajectory of above-ground biomass



(Moorcroft et al. 2001)



ED2: a size- and age-structured terrestrial biosphere model

PDE:

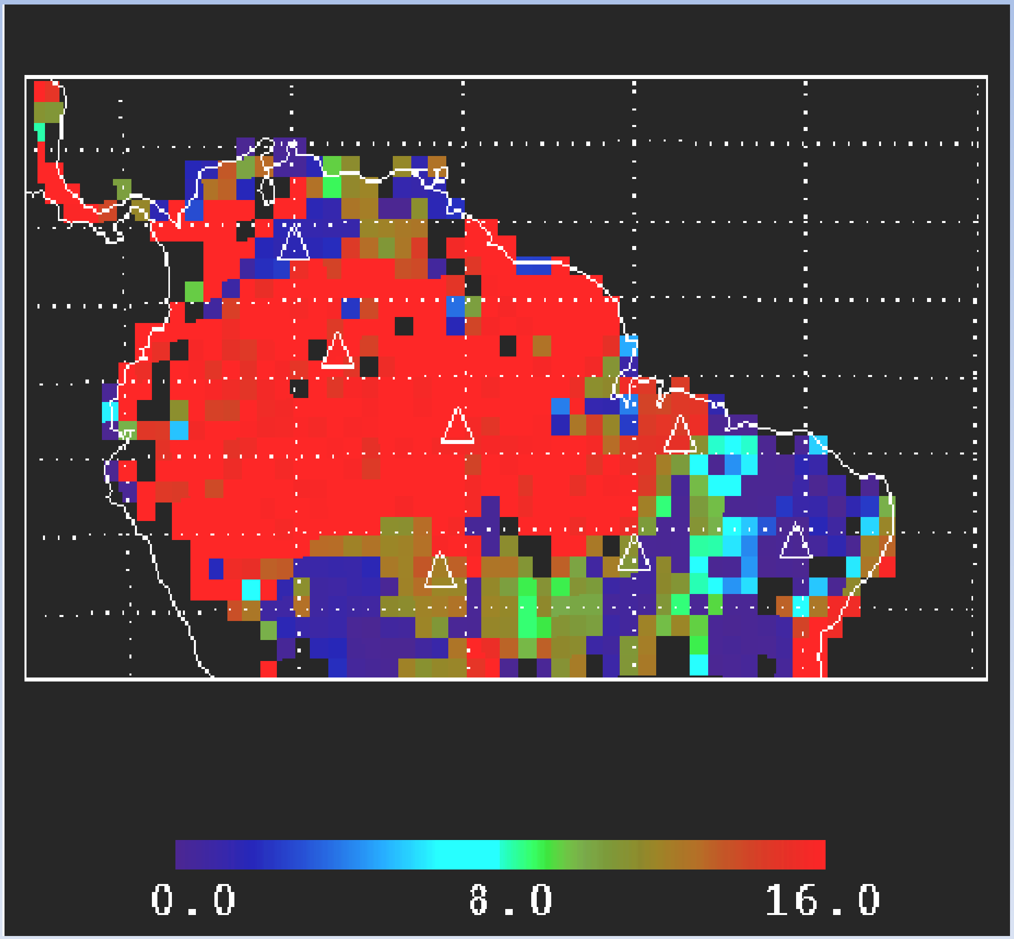
$$\underbrace{\frac{\partial n^{(i)}(z,a,t)}{\partial t}}_{\text{ch. in density of plant type } i} = \underbrace{-\frac{\partial}{\partial z}\left[g(z,a,t)n^{(i)}(z,a,t)\right]}_{\text{growth}} \underbrace{-\frac{\partial}{\partial a}n^{(i)}(z,a,t)}_{\text{ageing}} \underbrace{-\mu(z,a,t)n^{(i)}(z,a,t)}_{\text{mortality}}$$

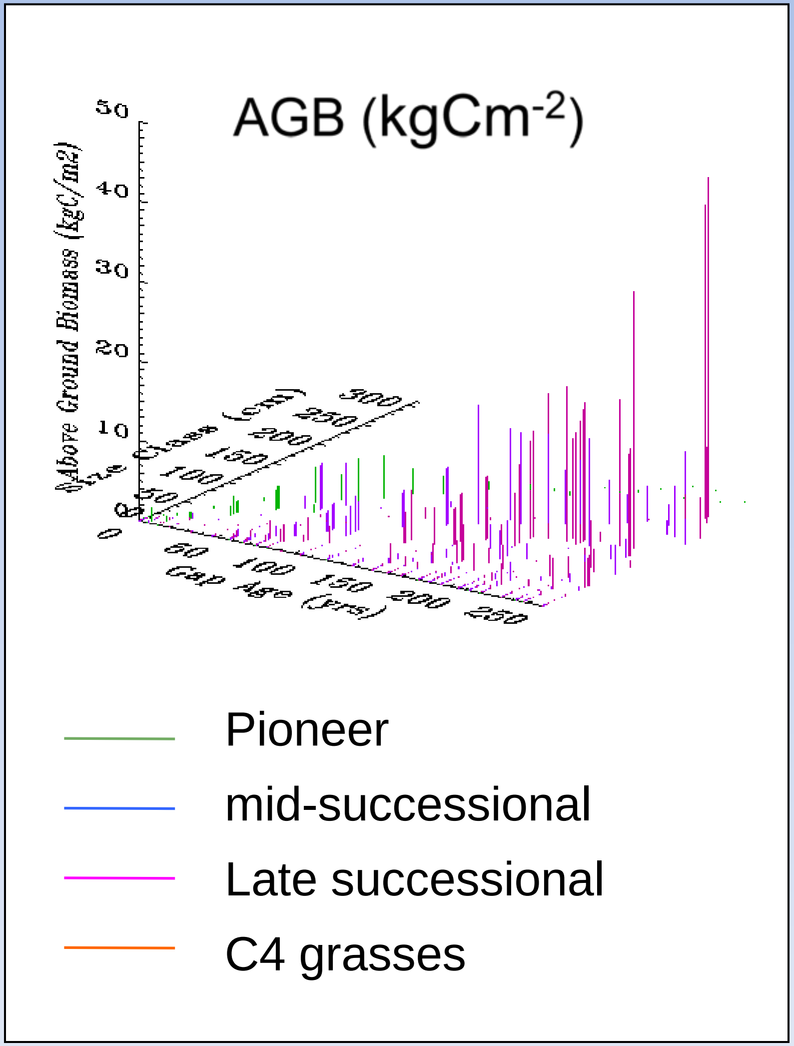
PDE:

$$\underbrace{\frac{\partial p(a,t)}{\partial t}}_{\text{ch. landscape age distribution}} = \underbrace{-\frac{\partial}{\partial a}p(a,t)}_{\text{ageing}} \underbrace{-\lambda(a,t)p(a,t)}_{\text{disturbance}}$$

- accurately captures the behavior of a corresponding individual-based model by tracking the dynamic horizontal & vertical sub-grid scale heterogeneity in canopy structure.

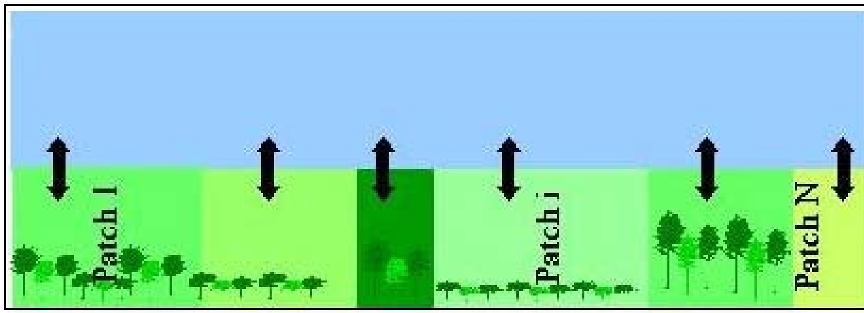
ED Model: Regional pattern of above-ground biomass (AGB) after a 200 year simulation ($kgCm^{-2}$)





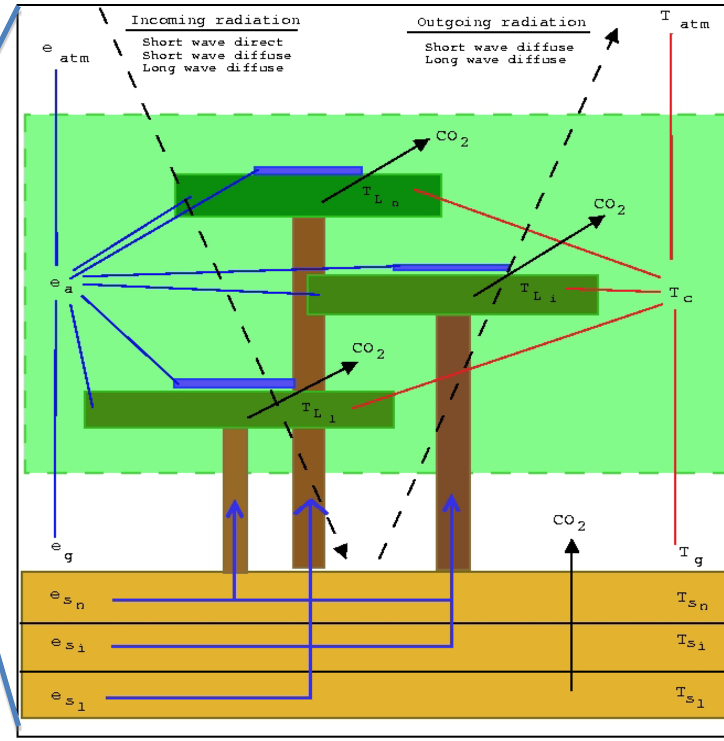
Formal approach to scaling vegetation dynamics: summary

ED structured biosphere model



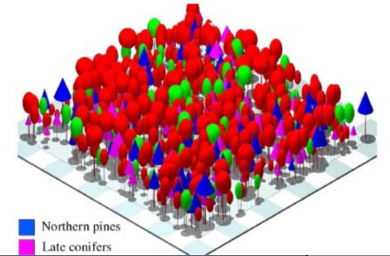
$$\frac{\partial n^{(i)}(z,a,t)}{\partial t} = -\frac{\partial}{\partial z}\left[g(z,a,t)n^{(i)}(z,a,t)\right] - \frac{\partial}{\partial a}n^{(i)}(z,a,t)$$
$$-\mu(z,a,t)n^{(i)}(z,a,t)$$

$$\frac{\partial p(a,t)}{\partial t} = -\frac{\partial}{\partial a}p(a,t) - \lambda(a,t)p(a,t)$$

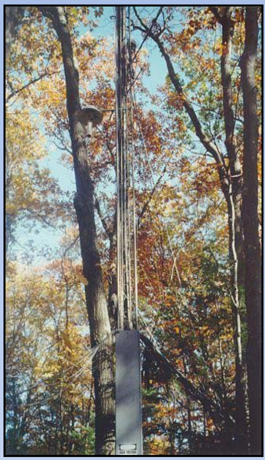


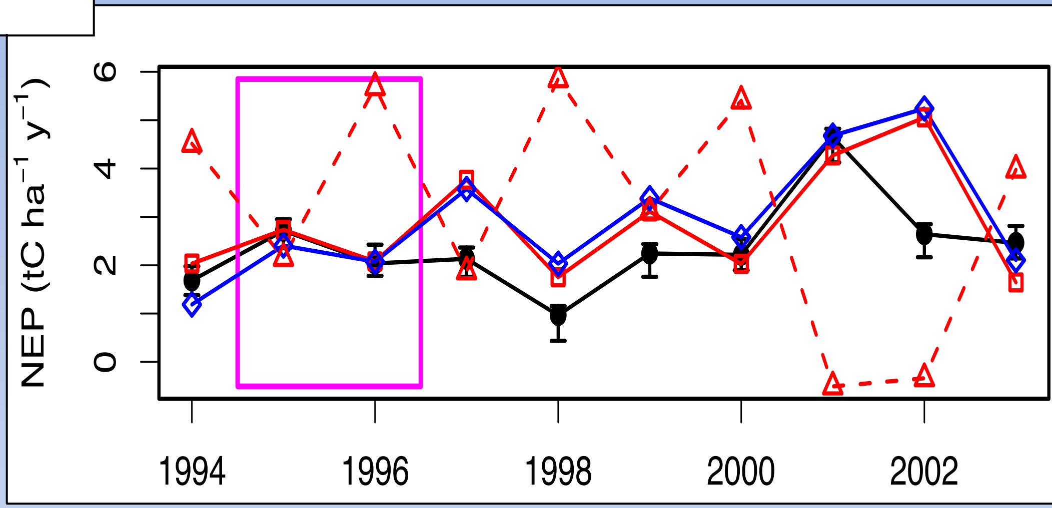
3 important benefits:

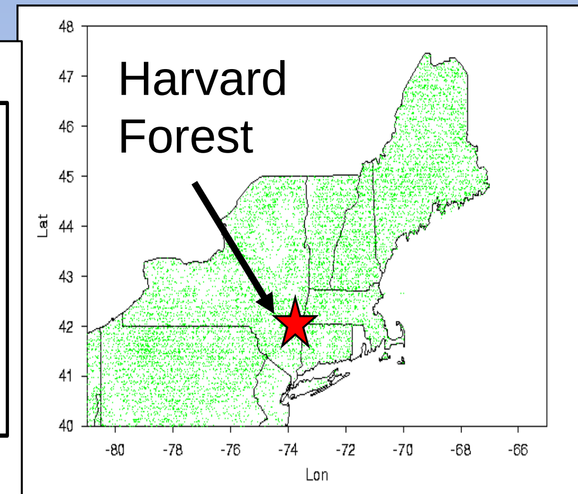
- realistic short-term and long-term vegetation dynamics.
- functionally diverse ecosystems
- improved ability to constrain the model with empirical measurements that results in improved predictive abilities.

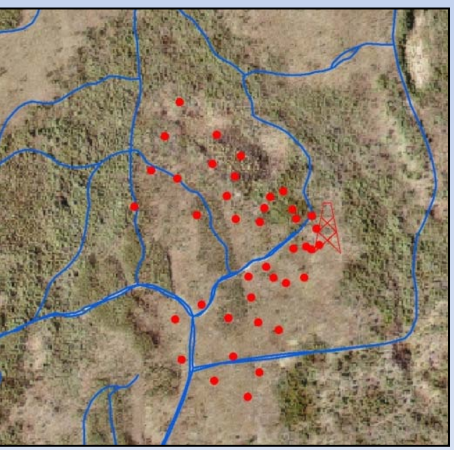


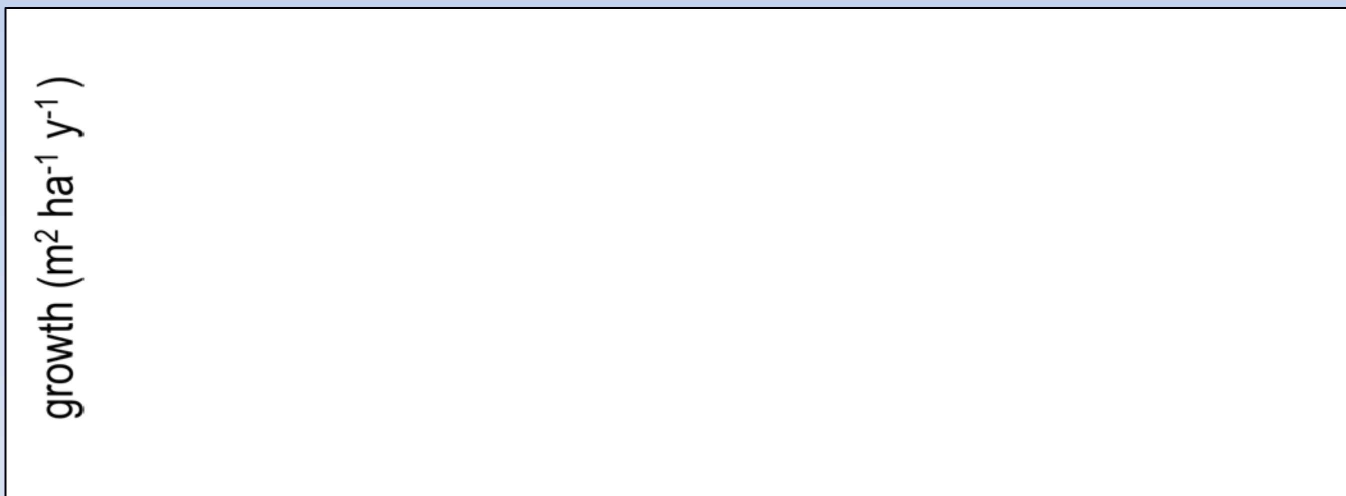
Summary: Harvard Forest: 10-yr simulations (1992-2001)







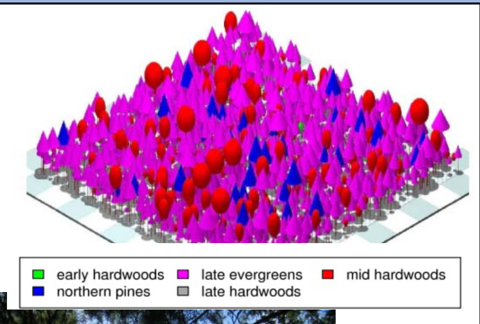


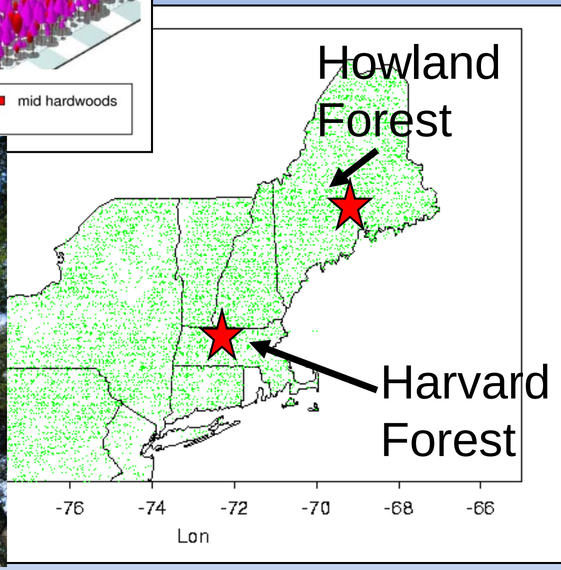


Demonstrated improved predictability in time. But what about in space?

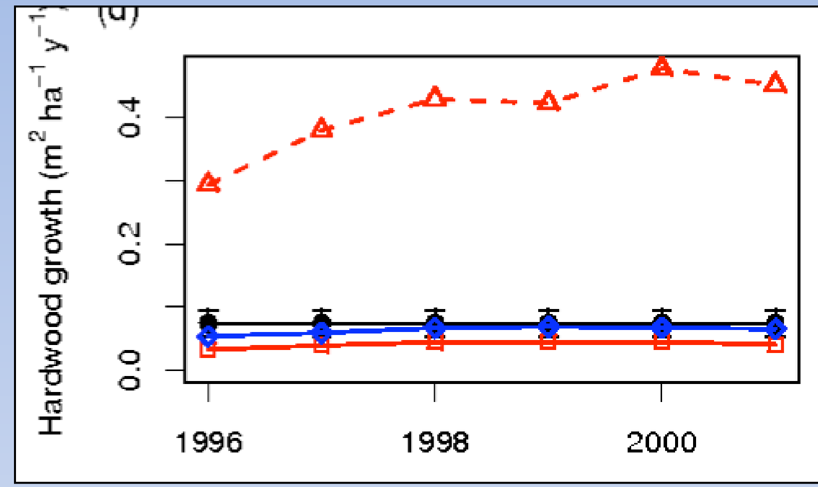
Howland Forest (45ºN, -68º W)

(no changes in any of the model parameters)

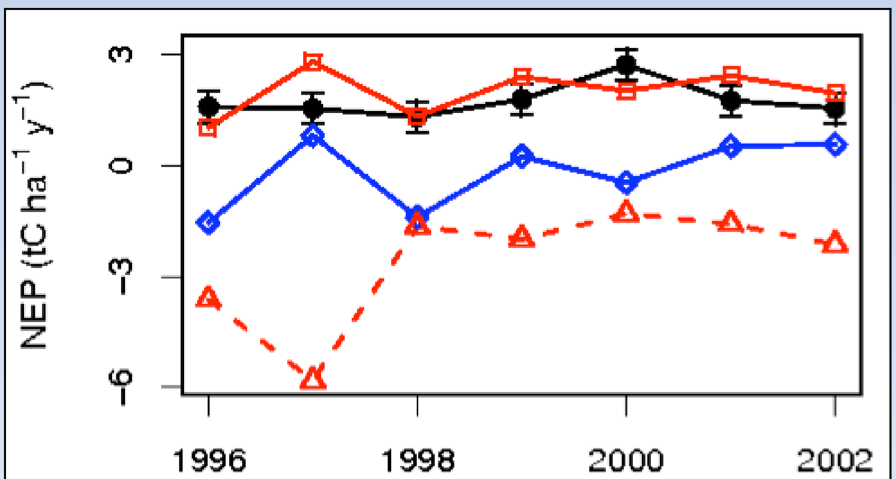




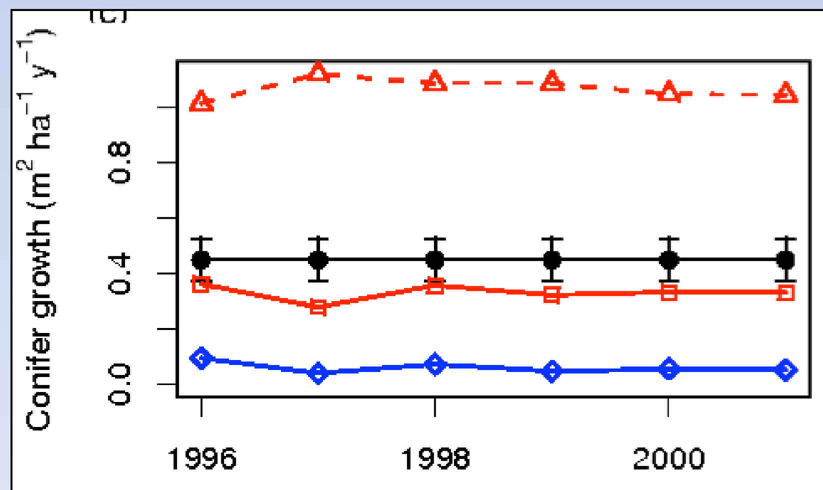
hardwood basal area increment (tC ha^{-1} mo^{-1})



net carbon fluxes (NEP)



conifer basal area increment (tC ha^{-1} mo^{-1})

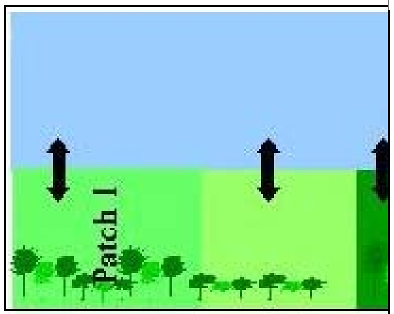


The Challenges

(Moorcroft et al. 2001, Moorcroft 2006, Medvigy et al. 2009)

Formal approach to scaling vegetation dynamics: summary

ED structured



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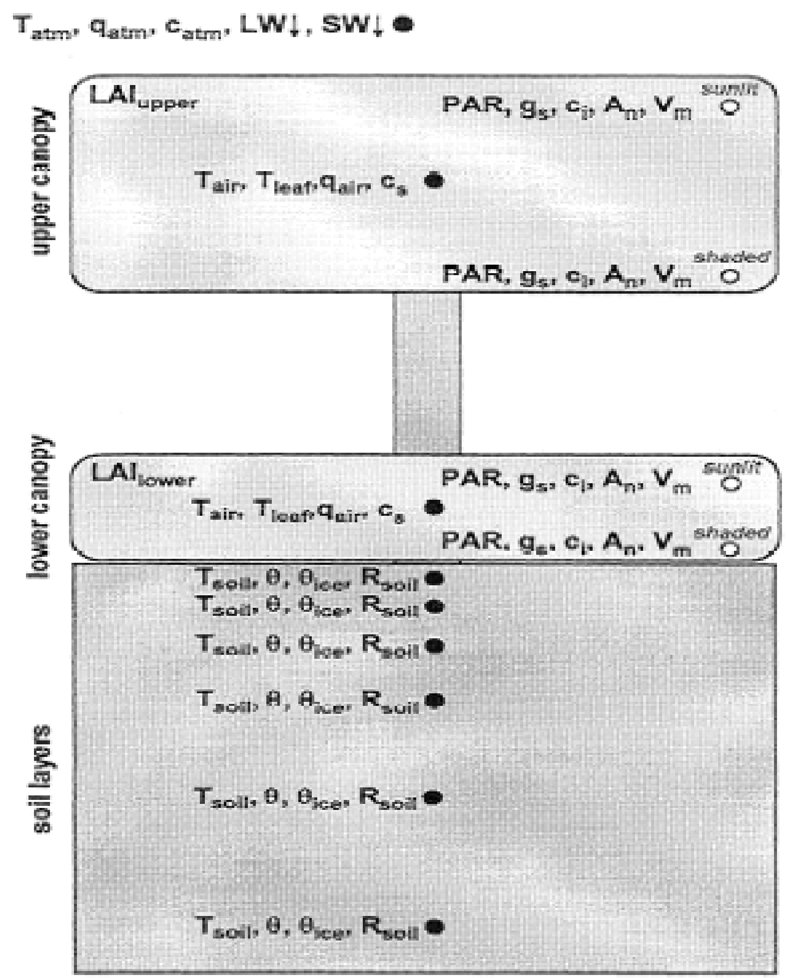
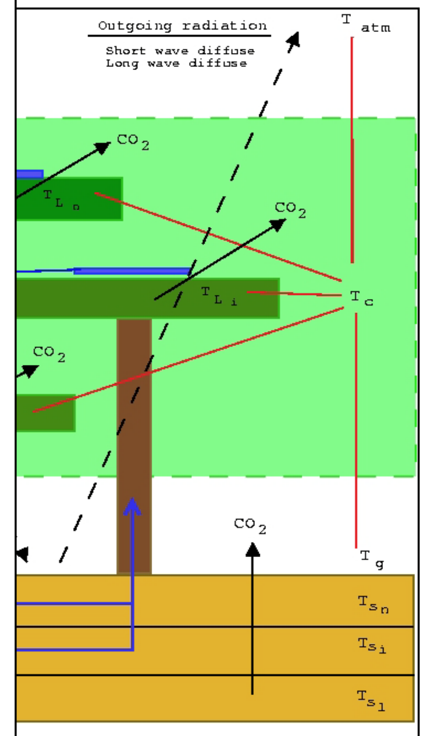


scale: 1° x 1° (~10^4 km^2)

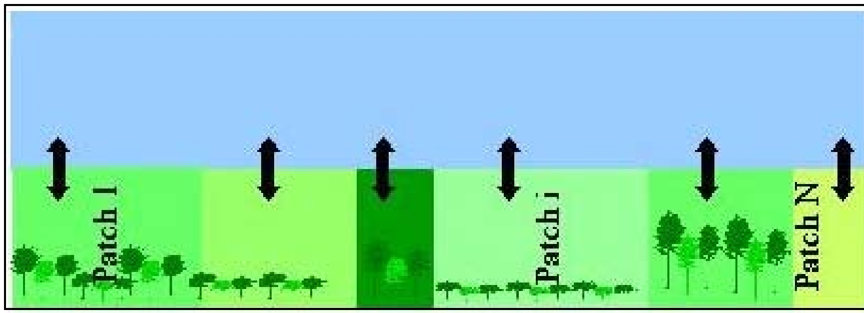


3 important benefi

- realistic long-
- functionally d
- improved ability to constrain the model with empirical measurements that results in improved predictive abilities.

The principal challenge associated with size and age-structured biosphere models such as ED2 is the computational challenges arising from the disaggregated nature of the ecosystem (plant canopy & soil column).

ED structured biosphere model



$$\frac{\partial n^{(i)}(z,a,t)}{\partial t} = -\frac{\partial}{\partial z}\left[g(z,a,t)n^{(i)}(z,a,t)\right] - \frac{\partial}{\partial a} n^{(i)}(z,a,t)$$

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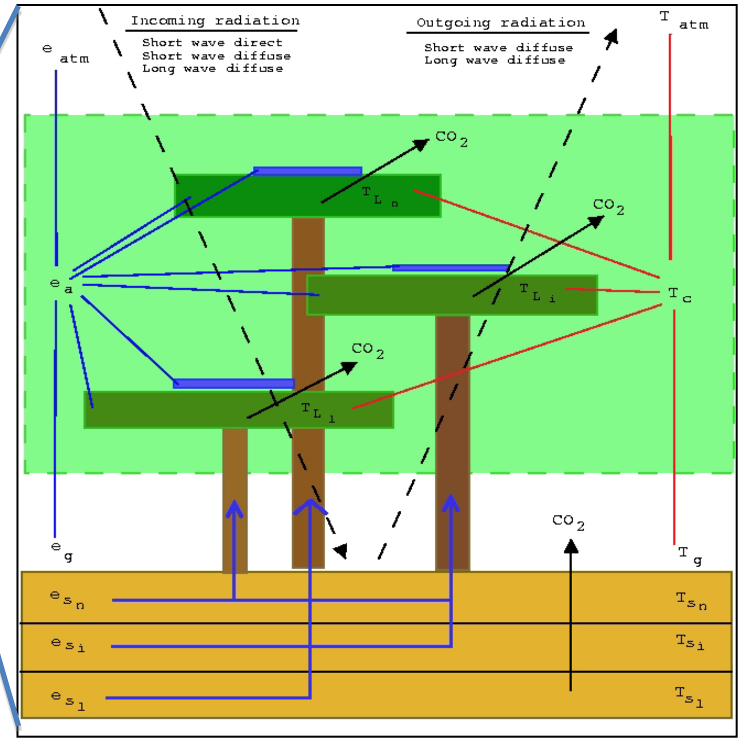
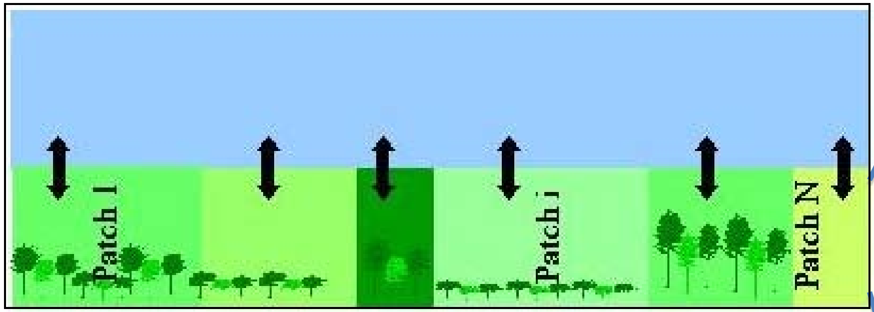


The additional challenge is that, due to the formal scaling that is embodied in the ED2 dynamical equations, the structure, composition, and resulting biophysical and biogeochemical functioning of the ecosystem are <u>emergent properties</u>.

ED structured biosphere model



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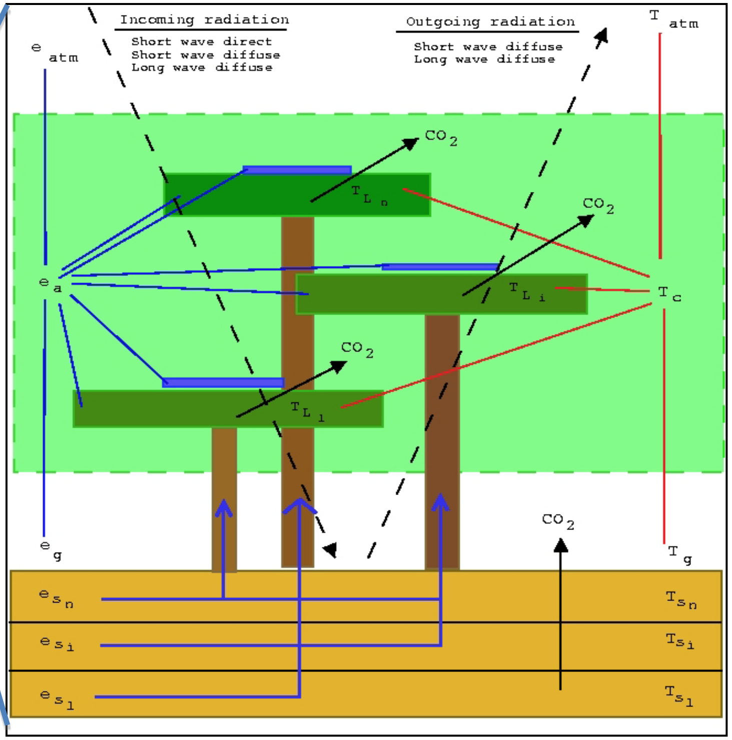
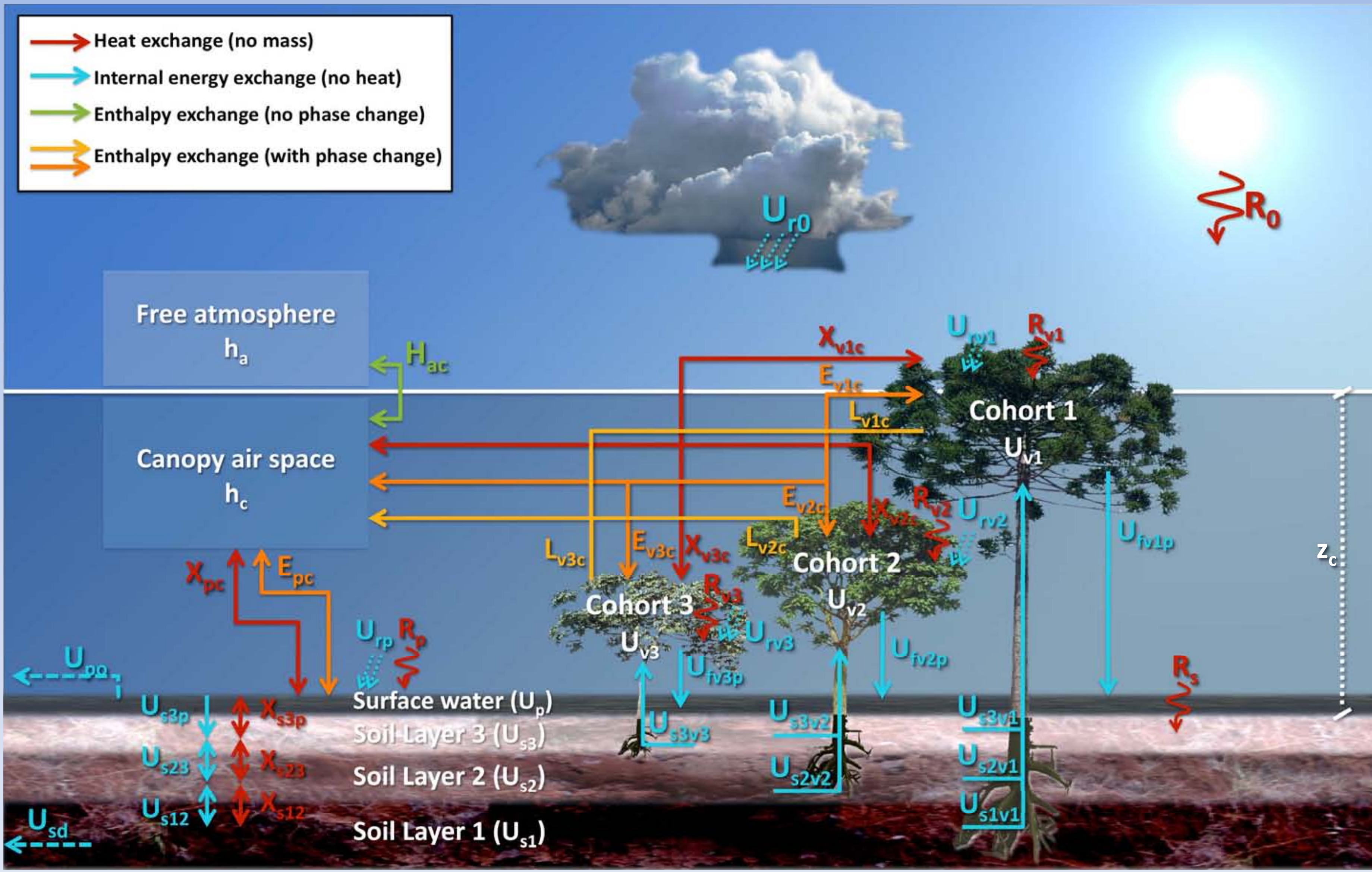


Time scales in ED-2.1

Time scale	Processes
Seconds – 15 minutes (dynamic, always less than ↓)	Canopy air space Snow/pounding layers Soil layers Leaf boundary layer
2 - 15 minutes	Photosynthesis Radiation Meteorological forcing (interpolated if necessary)
Daily	Growth of active tissues Leaf phenology Storage Plant “maintenance”
Monthly (cohort dynamics)	Structural growth Reproduction (cohort creation) Mortality Fire Cohort fusion/fission/extinction
Yearly (patch dynamics)	Anthropogenic disturbance (patch creation) Tree fall disturbance (patch creation) Patch fusion

ED2 – Energy budget for each horizontal tile



Ecosystem Demography

Benefits

• realistic long-term vegetation dynamics.

• functionally diverse ecosystems

• improved ability to constrain the model with empirical measurements that results in improved predictive abilities.

Challenges

• disaggregated canopy

•Some dynamics in the ecosystem are emergent properties – this can make it harder to paramterize the model**

**It may be harder to tune but its closer to the truth!

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References:

Moorcroft *et al*. 2001. *Ecological Monographs* 74:557-586.
Moorcroft 2006. *Trends in Ecology and Evolution* 21:400-407
Medvigy et al. (2009) *JGR Biogeosciences 114: G01002*
Medvigy et al. (2010) *Proceedings of the National Academy of Sciences* 107:8275-8280.

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