GEOG:4470 Ecological Climatology
Lab 3: Net Radiation
Due: 5:00 p.m. on February 28, 2020

Goals:
- Continue practicing programming in R.
- Calculate shortwave and longwave radiation in a plant canopy for sunlit and shaded leaves.
- Calculate the net radiation of the plant canopy.
- Think about how ecosystem structure (leaf area index and orientation) affects intercepted and net radiation of the canopy.

New R tools:
- The `library` function: load functions from an existing R package.
- The `seq` function: create a sequence of values, `from` one value `to` another `by` an increment.
- The `apply` function: apply a function all rows or columns of a data frame or matrix.

Hints:
- Follow best practices for creating graphs (units, labels, etc.), *even if you are not explicitly told to do some in the question*.
- Don't forget units!
- Include an informative legend on all graphs.
- When in doubt, check (and copy-paste-modify) your code from previous labs!

Inputs:
- Outputs from Lab 2 (top-of-canopy direct/diffuse PAR/NIR)
- Leaf area index (LAI)
- Leaf angle distribution (x)
- Air temperature (Ta), soil temperature (Tsoil), vapor pressure deficit (VPD), and cloud cover

0. Load the data and ecological model

Double-click your Labs.Rproj file to open RStudio and begin where we left off after Lab 2. Download Lab3_Dannenberg.R from ICON, and save it to your Labs folder, replacing my last name with your last name. Also save eco_model.R from ICON to your Lab folder.

Open both of these files in RStudio so that they are visible in the code editor. In the Lab3_<last name>.R code, run all of the lines from the previous labs (through line 23). Once this is done, we can pick up where we left off.

In this lab, we will use three new functions from eco_model.R:

- `compute_canopy_intercepted_shortwave_rad()`: computes shortwave absorption by sunlit and shaded leaves
- `compute_longwave_rad()`: computes longwave emission from the canopy, air, and soil
- `compute_canopy_net_rad()`: computes net radiation of the canopy

1. Sunlit and shaded leaf area

Run lines 25-45. This section computes the sunlit and shaded portions of the canopy based on leaf area index (`lai`) and the leaf angle distribution (`x`), which by default is set as 1, indicating a "spherical" leaf angle distribution. (Values less than 1 indicate more horizontally-oriented leaves; values greater than 1 indicate more vertically-oriented leaves.) In brief, this section of code computes the probability that a beam of light could pass through the canopy unimpeded and uses this to estimate how many leaves are directly lit by the sun, and how many are in the shade.

Make a plot of sunlit_lai and shaded_lai (on the same graph) with date on the x-axis. Note: you may have to change the y-axis limits to get them on the same graph. You can do this by manually setting the limits using the `ylim` option in the plot function (e.g., `plot(dat$Date, sunlit_lai, type='l', ylim=c(0,5))`). Describe the variation of sunlit and shaded LAI. How does it vary daily and seasonally?

2. Calculate intercepted shortwave radiation by the canopy.

Run the `compute_canopy_intercepted_shortwave_rad()` function. Examine the output data frame. The outputs include (all in W m^{-2}): absorbed PAR by sunlit leaves, absorbed PAR by shaded leaves, absorbed NIR by sunlit leaves, and absorbed NIR by shaded leaves. Plot these outputs as a time series, either in separate graphs or a single graph (up to you). Describe the daily and seasonal distributions of these four components of canopy shortwave radiation. How and why do they vary daily and/or seasonally?

3. Calculate net radiation of the canopy.

Run both the `compute_longwave_rad()` and `compute_canopy_net_rad()` functions. The first uses Stefan-Boltzmann's law to estimate emitted longwave radiation by the canopy, air, and soil surface based on their temperatures (and cloudiness, for air). The second uses the canopy shortwave radiation and the longwave radiation to compute the net radiation of the ecosystem, including sunlit and shaded Rnet per m^2 leaf area, total canopy Rnet (the sum of the sunlit and shaded components multiplied by their total leaf areas), Rnet of the forest floor, and Rnet of the whole stand (canopy+floor).

Make a time series graph of canopy, floor, and stand net radiation. How do these vary daily and seasonally? Based on your knowledge of the surface energy balance (Rnet = H + LE + G), what do you think happens to this net radiation? What would be the effects on the ecosystem?

4. Do something fun.

There are a lot of variables that go into these functions: leaf area index, leaf angle distribution, air/soil temperature, etc. Think of a simple experiment you could run using these models but changing one or more of these input variables. Modify the functions or inputs to run this experiment. What did you test (i.e., what is your research question)? What did you expect to happen? What actually happened?

Submit your answers as a PDF document (Lab3_<your lastname>.pdf) on the Assignments page of ICON. Also submit your final R script (Lab3_<your lastname>.R) with your assignment.

Theory

1. Shortwave Radiation

Given the shortwave radiation intercepted by sunlit leaves and shaded leaves for PAR and NIR, the total absorbed radiation for PAR can be estimated as

$$R_{par} = L_{sunlit} R_{sunlit\_par} + L_{shaded} R_{shaded\_par}$$

where

$$R_{sunlit\_par} = \alpha_{par}(K_b(\theta) Q_{ob\_par} + \overline{Q}_{sc\_par} + \overline{Q}_{d\_par})$$

$$R_{shaded\_par} = \alpha_{par}(K_b(\theta) \overline{Q}_{sc\_par} + \overline{Q}_{d\_par})$$

Similarly, we have absorbed the total absorbed radiation for NIR as

$$R_{nir} = L_{sunlit} R_{sunlit\_nir} + L_{shaded} R_{shaded\_nir}$$

where

$$R_{sunlit\_nir} = \alpha_{nir}(K_b(\theta) Q_{ob\_nir} + \overline{Q}_{sc\_nir} + \overline{Q}_{d\_nir})$$

$$R_{shaded\_nir} = \alpha_{nir}(K_b(\theta) \overline{Q}_{sc\_nir} + \overline{Q}_{d\_nir})$$

The total shortwave radiation absorbed by the canopy is

$$R_{canopy} = R_{par} + R_{nir}$$

The shortwave radiation entering the forest floor from canopy includes direct par, diffuse par, direct nir and diffuse nir. Given the reflectance of forest floor, ρ_s, the absorbed shortwave radiation on the forest floor is

$$R_{floor} = \rho_s (T_{par} + T_{nir})$$

Where

$$T_{par} = Q_{ob\_par} \exp(-K_b(\theta)\sqrt{\alpha_{par}} L) + Q_{od\_par} \exp(-K_d \sqrt{\alpha_{par}} L)$$

$$T_{nir} = Q_{ob\_nir} \exp(-K_b(\theta)\sqrt{\alpha_{nir}} L) + Q_{od\_nir} \exp(-K_d \sqrt{\alpha_{nir}} L)$$

2. Longwave Radiation

Any object with temperature greater than $0^{o}K$ emits radiation. The total amount of energy emitted by a blackbody is given by Stefan-Boltzmann's law:

$$E = \sigma T^4$$

For real world objects, they are not as efficient emitting radiation as a blackbody. We call the real-world object a grey body. The ratio of the total amount of energy emitted by a real-world object to that of a blackbody is called emissivity.

$$\varepsilon = \frac{E_g(T)}{E_b(T)}$$

Therefore, as long as we know the emissivity of a real-world object, we can estimate its total amount of energy emitted at a given temperature as

$$E = \varepsilon \sigma T^4$$

Scientists found that the emissivity for the real-world objects is pretty close to 1. For vegetation canopy, ε_{canopy}=0.98; for forest floor, ε_{floor}=0.95. Therefore, the longwave radiation emitted by vegetation canopy and forest floor can be modeled as

$$E_{canopy} = \varepsilon_{canopy} \sigma T_{canopy}^4 \approx \varepsilon_{canopy} \sigma T_{air}^4$$

$$E_{floor} = \varepsilon_{floor} \sigma T_{floor}^4$$

However, the emissivity for atmosphere is more complicated as it varies with cloud cover. For clear skies, the emissivity of the atmosphere can be estimated as (Brustaert, 1975):

$$\varepsilon_0 = 1.24 \left(\frac{e_a}{T_{air}} \right)^{\frac{1}{7}}$$

Where e_a is the vapor pressure of the air in mb (1 mb =100 P_a), and T_{air} is in degrees Kelvin. For cloudy skies, the emissivity of the air is a function of cloud cover as (Unsworth and Monteith, 1975):

$$\varepsilon_{air} = (1 - 0.84c)\varepsilon_0 + 0.84c$$

Where c is the fraction of cloud cover of the sky [0,1]. Due to the fact that cloud cover is often not recorded, Song et al. (2009) developed an approach estimating the cloud cover during the day time based on the total transmittance, τ.

$$\tau = \frac{R_{sw}}{S_0(1.0 + 0.033\cos(2\pi(J - 10.0)/365.0))\cos(\theta)}$$

Based on our work separating radiation into direct and diffuse component. We know that for a clear day, τ=0.7, i.e. c=0. When τ =0.3, the total radiation is 100% diffuse, i.e. c =1.0, thus

$$c = 1.0 - \tau / 0.7$$

Because the longwave radiation from the atmosphere arrives in all direction, it can be treated as diffuse radiation. Leaves are highly absorptive to the longwave radiation, thus the average longwave radiation plant canopy absorb is

$$L_{canopy,absorb\_air} = \frac{\varepsilon_{air} \sigma T_{air}^4 (1 - \exp(-K_d L)}{K_d L}$$

At the same time, canopy also absorb longwave radiation from the forest floor, which can be modeled similarly,

$$L_{canopy,absorb\_floor} = \frac{\varepsilon_{floor} \sigma T_{soil}^4 (1 - \exp(-K_d L)}{K_d L}$$

The total absorbed longwave radiation by the canopy is

$$L_{canopy,absorb} = L_{canopy,absorb\_air} + L_{canopy,absorb\_floor}$$

In the meantime, canopy itself is emitting longwave radiation both upward and downward.

$$L_{canopy,emit} = \frac{2\varepsilon_{canopy} \sigma T_{air}^4}{L}$$

Therefore, the net longwave radiation in the plant canopy is

$$L_{net,canopy} = L_{canopy,absorb} - L_{canopy,emit}$$

The net canopy radiation is

$$R_{net,sunlit} = R_{sunlit\_par} + R_{sunlit\_nir} + L_{net,canopy}$$

$$R_{net,shaded} = R_{shaded\_par} + R_{shaded\_nir} + L_{net,canopy}$$

The total canopy net radiation by both sunlit and shaded leaves is

$$R_{net,canopy} = L_{sunlit} R_{net,sunlit} + L_{shaded} R_{net,shaded}$$

For the forest floor, it receives longwave radiation from the air through the gaps and from the canopy that is not gap. In the meantime, it emit longwave radiation. Thus, the net long wave radiation for the forest floor is

$$L_{net,floor} = \varepsilon_{air} \sigma T_{air}^4 \exp(-K_d L) + \varepsilon_{canopy} \sigma T_{canopy}^4 (1 - \exp(-K_d L) - \varepsilon_{floor} \sigma T_{floor}^4$$

The net radiation for the forest floor considering both shortwave and longwave radiation is

$$R_{net,floor} = R_{floor} + L_{net,floor}$$