GEOG:4470 Ecological Climatology
Lab 7: Light-Use Efficiency
Due: 5:00 p.m. on Friday April 24, 2020
10 points

Goals:

- Continue practicing programming in R.
- Calculate gross primary production of Duke Forest using a light-use efficiency model based on remote sensing and meteorological data.
- Think about assumptions and uncertainties in modeling gross primary production.

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:

- Meteorological: Total daily photosynthetically active radiation (PAR; MJ m^{-2} day^{-1}), minimum daily air temperature (Tmin; °C), and mean daily vapor pressure deficit (VPD; hPa)
- Remote sensing: Daily red and near infrared (NIR) reflectance of the forest canopy from MODIS

Theory:

In this lab we will use a light-use efficiency model, based on satellite remote sensing, to estimate total net photosynthesis (gross primary production, or GPP) of Duke Forest. Compared to the models we have been using in previous labs, this is a very simple model that estimates GPP based on the total absorbed PAR by the canopy (APAR) and an efficiency of the canopy at converting APAR to carbohydrates (ε, in grams of carbon per MJ of absorbed PAR):
$GPP = APAR \times \varepsilon$.

To estimate APAR, we multiply the measured PAR at the top of the canopy (given in the data file) by the fraction of that PAR that is absorbed by the canopy (FPAR):
$APAR = PAR \times FPAR$.
PAR at the top of the canopy is easy to measure or estimate from meteorological data, and FPAR is linearly related to the normalized difference vegetation index (NDVI) measured by satellites:
$NDVI = \frac{NIR - Red}{NIR + Red}$.
NDVI (unitless) can theoretically range from −1 to 1, but usually does not fall below −0.2. Healthy plant leaves reflect a lot of NIR (~80%) but absorb a lot of Red radiation to drive photosynthesis, so NDVI increases with increasing density of vegetation: a healthy, dense forest will often have NDVI>0.9. To convert NDVI to FPAR, we will use a simple, empirical linear model:
$FPAR = 1.24 \times NDVI - 0.168$.

Estimating the "light-use efficiency" (ε) of the canopy is a little trickier since it varies for different types of plants, and it is also reduced by "environmental stress" (nonoptimal temperatures and moisture deficits). Most models therefore estimate "light-use efficiency" (ε) based on a biome-specific maximum light-use efficiency (ε_{max}) that is reduced based on a set of functions ($f(E)$) of temperature, VPD, and other environmental stresses:

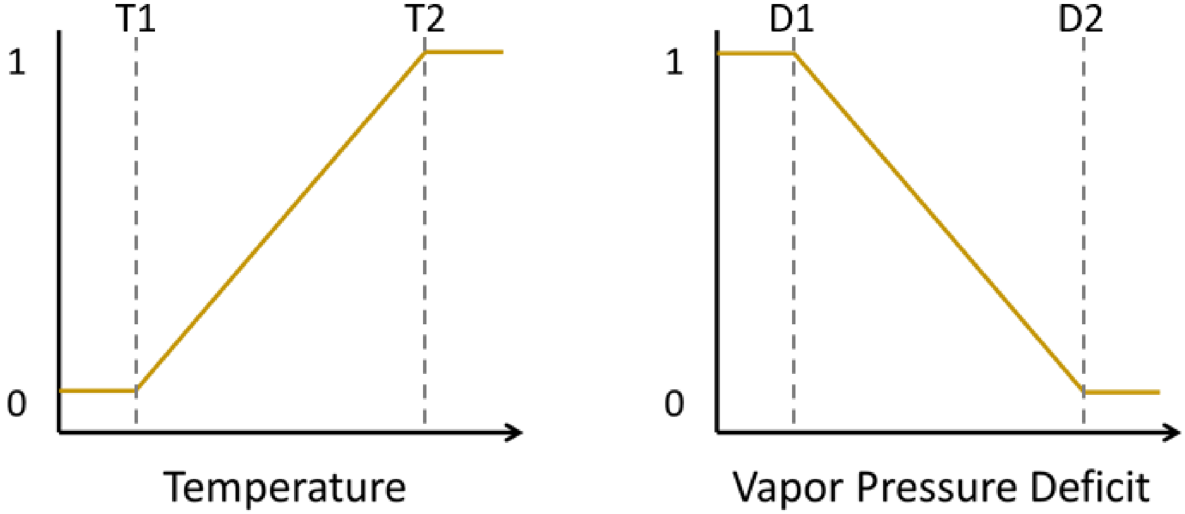
$\varepsilon = \varepsilon_{max} \times f(E) = \varepsilon_{max} \times \min\,(f(T), f(D))$.

In this lab we will use two environmental stress functions: a piecewise linear function of minimum temperature ($f(T)$) that simulates dormancy of plants during the winter, and a piecewise linear function of VPD ($f(D)$) that simulates stomatal closure when VPD is high (see graphs below):

$$f(T) = \begin{cases} 0, & T_{min} < T_1 \\ \dfrac{T_{min} - T_1}{T_2 - T_1}, & T_1 \le T_{min} < T_2 \\ 1, & T_{min} \ge T_2 \end{cases}$$

$$f(D) = \begin{cases} 0, & D \ge D_2 \\ \dfrac{D_2 - D}{D_2 - D_1}, & D_1 \le D < D_2 \\ 1, & D < D_1 \end{cases}$$

These functions say that when Tmin is below a lower threshold (T1) (or when VPD is above an upper threshold, D2), then the light-use efficiency of the canopy is 0. In other words, environmental conditions are so bad (temperatures are too low or VPD is too high) that the plants aren't photosynthesizing at all. Conversely, when Tmin is greater than an upper threshold (T2) (or when VPD is below a lower threshold, D1), then conditions for photosynthesis are optimal and light-use efficiency will occur at 100% of its maximum possible value (ε_{max}).



Putting this all together, our final light-use efficiency model for GPP is:

$$GPP = PAR \times FPAR \times \varepsilon_{max} \times \min\,(f(T), f(D))$$

In this lab, we will use model parameters for a deciduous broadleaf forest (DBF), which is the type of biome present at the Duke Forest flux site. However, if you want to do the optional extra credit question at the end of the lab, I have also provided the parameters for evergreen needleleaf forest (ENF), shrubland (SHB), and grassland (GRS):

	DBF	ENF	SHB	GRS
ε_{max} (g C MJ^{-1})	1.165	0.962	0.841	0.860
T1 (°C)	-6.0	-8.0	-8.0	-8.0
T2 (°C)	10.0	8.0	9.0	12.0
D1 (Pa)	650.0	650.0	650.0	650.0
D2 (Pa)	1650.0	4600.0	4800.0	5300.0

0. Load the data

Download Lab7_Dannenberg.R and from ICON, and save it to your Labs folder, replacing my last name with your last name. Save the data file (GppParTminVpdRedNir-daily.csv) to your data folder.

Double-click your Labs.Rproj file to open RStudio, and then open Lab7_<your lastname>.R in RStudio. Load the data, calculate the date, and convert VPD from hPa to Pa by running lines 4-9.

1. Calculate NDVI and fraction of PAR absorbed by the canopy.

Calculate NDVI using line 12. Now, try using this NDVI to calculate the fraction of PAR absorbed by the canopy using the equation above, and assign it to a new column of the `dat` data frame (`dat$FPAR`). Use your calculated FPAR to calculate total absorbed PAR by the canopy (APAR; in MJ m^{-2}) using the equation above, and assign it to a new column of the `dat` data frame (`dat$APAR`).

Make a time series of NDVI and FPAR on the same graph (both unitless), and time series of PAR and APAR on the same graph (both in MJ m^{-2}). Describe the patterns you observe.

2. Estimate "environmental stress" from low temperatures and high VPD.

Calculate the "environmental stress" terms ($f(T)$ and $f(D)$) using lines 16-30 (everything after the "Question 2" section and before the "Question 3" section).

Make a time series of $f(T)$ (dat$fT) and $f(D)$ (dat$fD) on the same graph. Describe the patterns you observe. When are plants usually temperature-stressed? When are they usually water-stressed? How often does the ecosystem operate under "optimal" conditions? How often are conditions so bad that plants aren't able to photosynthesize at all?

3. Estimate GPP.

Using the maximum light-use efficiency of deciduous broadleaf forests (1.165 g C MJ^{-1}), estimate the GPP using the light-use efficiency model described in the theory above (see the highlighted equation).

Make a time series with both observed GPP (dat$GPP) and estimated GPP (dat$GPP_est) on the same graph. Also make a scatterplot comparing observed GPP (x-axis) to estimated GPP (yaxis). Describe the seasonal patterns that you observe in the time series. How well did our light-use efficiency model do at estimating the observed GPP of Duke Forest? (If you want to, you can also use lines 36-38 to calculate the R^2, mean absolute error, and mean bias of our light-use efficiency model.)

4. EXTRA CREDIT: Do something fun, land cover change edition! (4 bonus points)

Let's say that you replaced the deciduous broadleaf forest with some other kind of ecosystem of your choice (evergreen needleleaf forest, shrubland, or grassland), but kept the same NDVI and FPAR. Based on the biome-specific parameters listed in the table above (in the Theory section), what do you think would happen to GPP? (In other words, how would optimal light-use efficiency change? How would sensitivity to temperature and VPD change?)

Update the parameters in the code for questions 2 and 3 and recreate the time series. What happened to GPP? How does this compare to your expectations? Did the ecosystem become more or less able to take up carbon?

Submit your answers as a PDF document (Lab7_<your lastname>.pdf) on the Assignments page of ICON. Also submit your final R script (Lab7_<your lastname>.R) with your assignment.