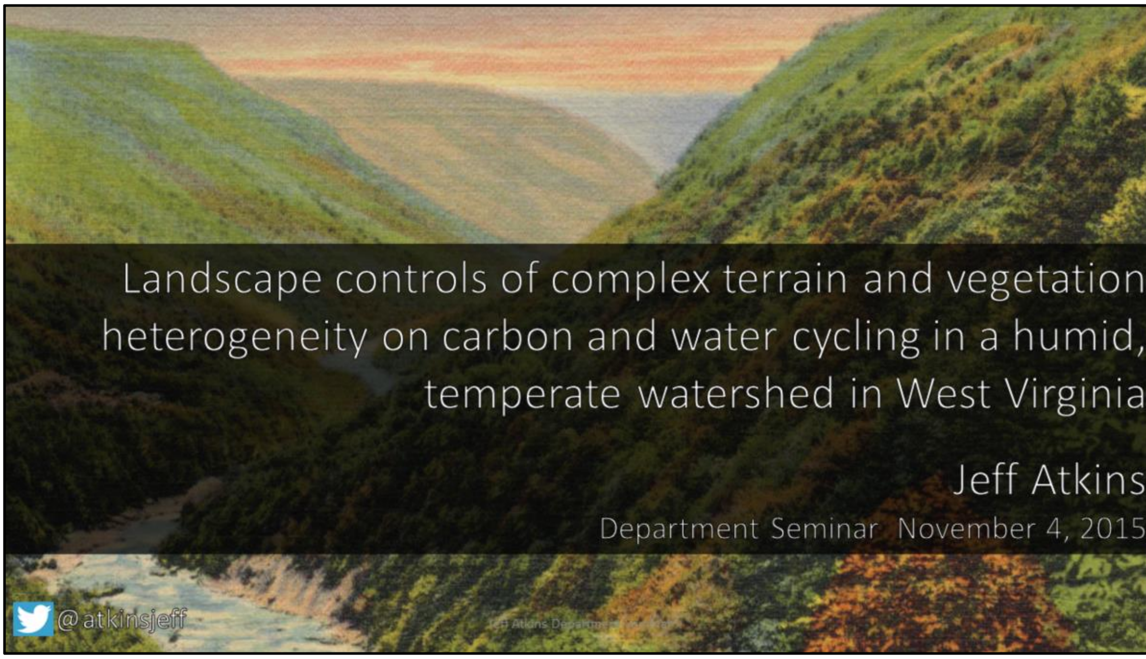
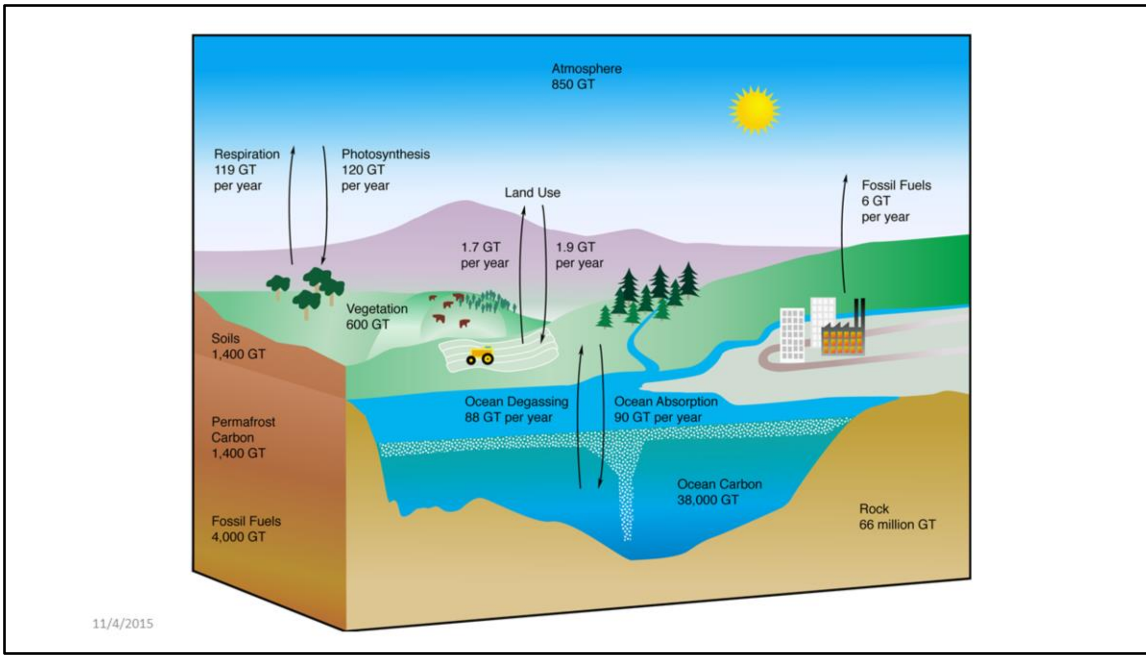

Landscape controls of complex terrain and vegetation heterogeneity on carbon and water cycling in a humid, temperate watershed in West Virginia
Jeff Atkins
Department Seminar November 4, 2015
@atkinsjeff



Every good talk about carbon begins with a carbon cycle diagram. Let's look at the terrestrial carbon cycle here to the upper left. Our units here are in gigatonnes of C or if you prefer, petagrams. Photosynthesis or GPP brings in 120 Pg of C a year, while ~ 120 is respired back to the atmosphere. Of this portion that is respired back to the atmosphere, half, about 60 Pg makes up soil respiration.

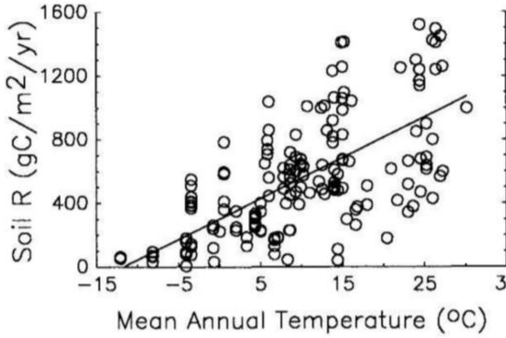


Fig. 2. Soil respiration and mean annual air temperature for sites listed in the Appendix. The line shows the least squares relationship between the two variables (Table 2).

from Raich & Schlesinger (1992)

The primary control on soil respiration is temperature. If we look at this plot of soil respiration values against MAT from various ecosystems across the globe from Raich and Schlesinger 1992, we see a strong positive correlation of soil respiration with MAT.

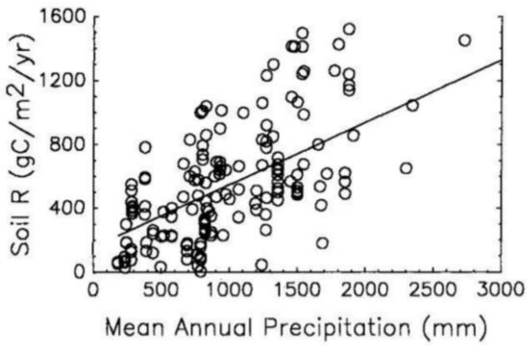
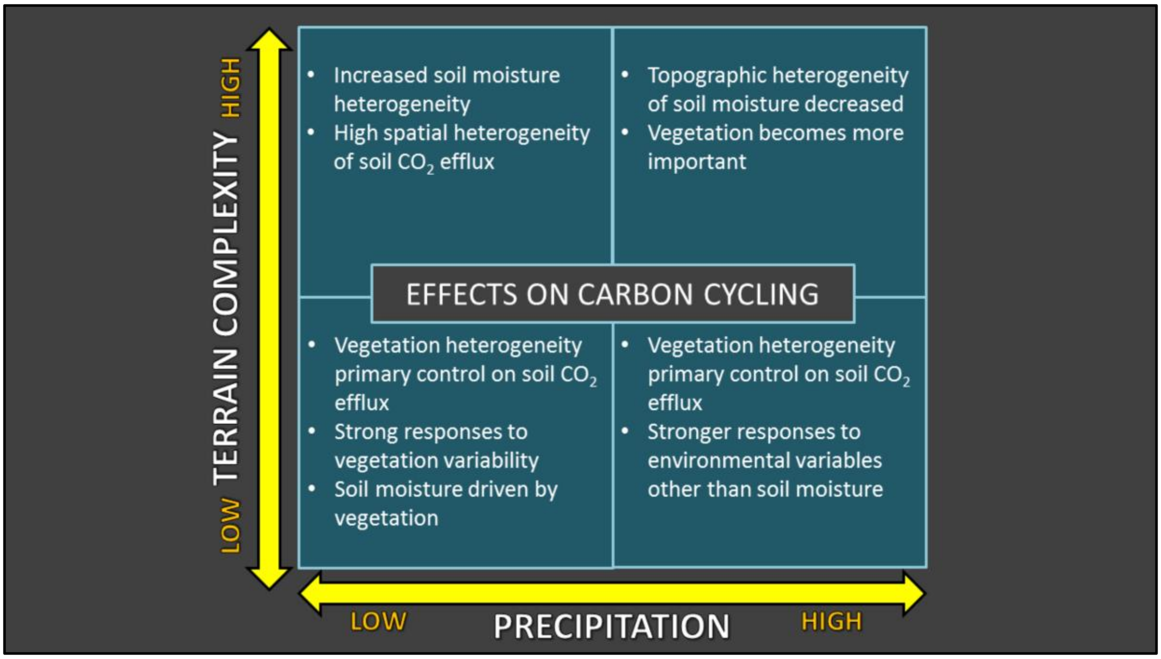


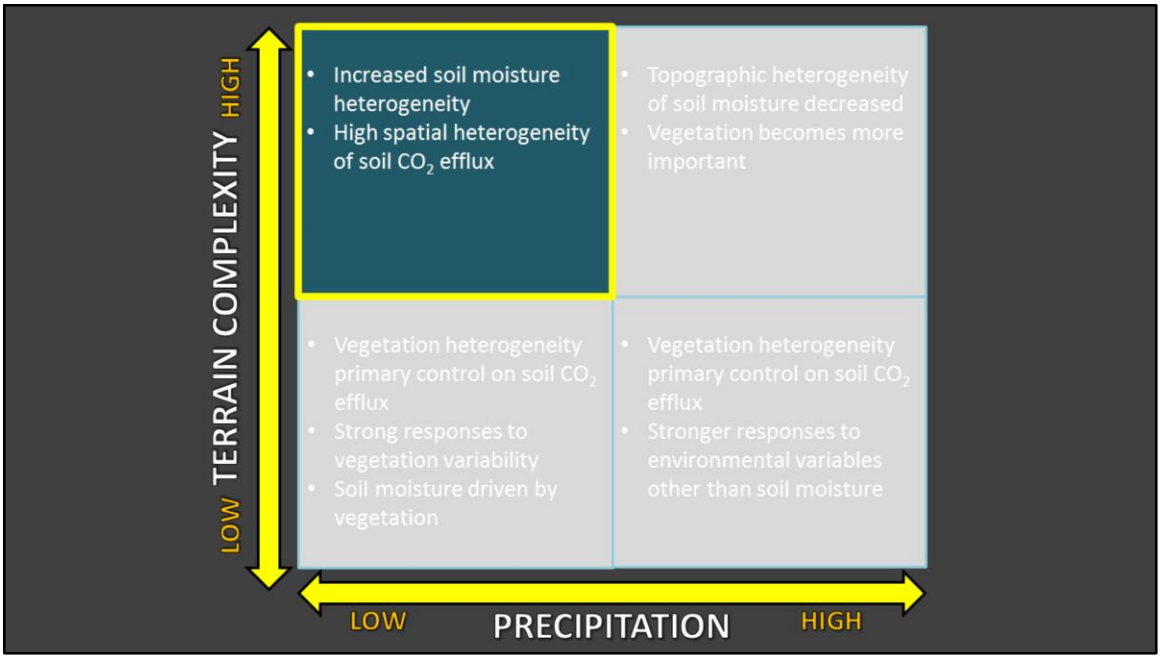
Fig. 3. Soil respiration and mean annual precipitation for sites listed in the Appendix. The line shows the least squares relationship between the two variables (Table 2). Two sites had >3000 mm precipitation and are not shown here.

from Raich & Schlesinger (1992)

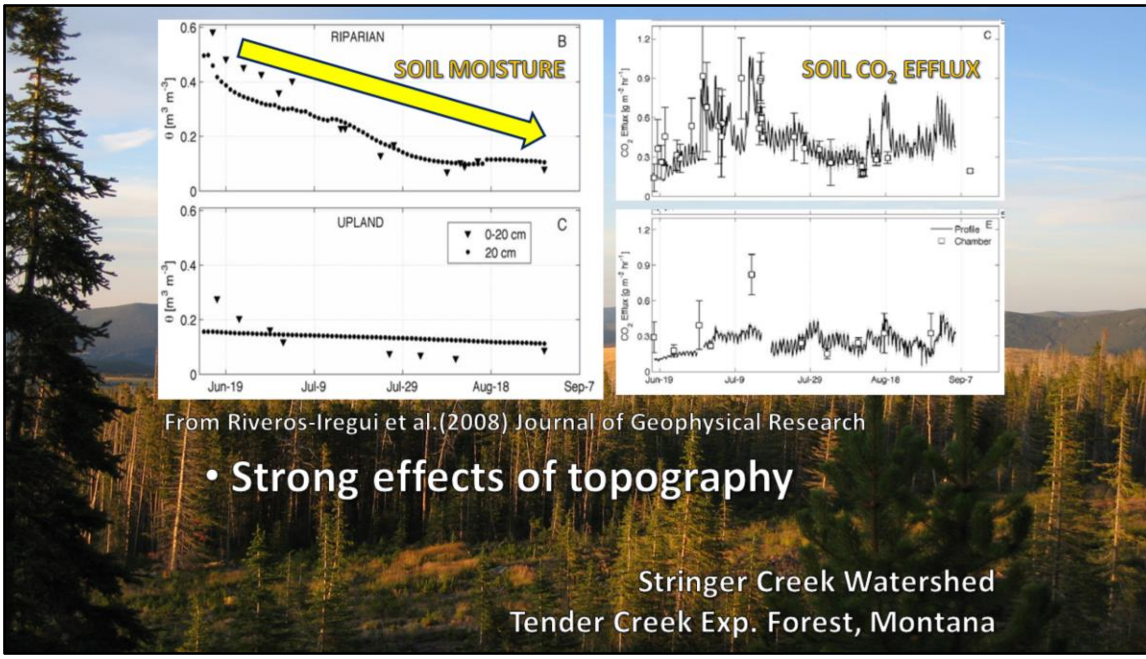
The secondary control on soil respiration is available moisture—displayed here as MAP—our input of moisture to the system. Again, this plot from Raich and Schlesinger shows that, globally, soil respiration values show a generally positive correlation with MAP. However, while these plots show the overall global, broad scale patterns of soil respiration with climate variables, landscape heterogeneities are not explicitly considered.



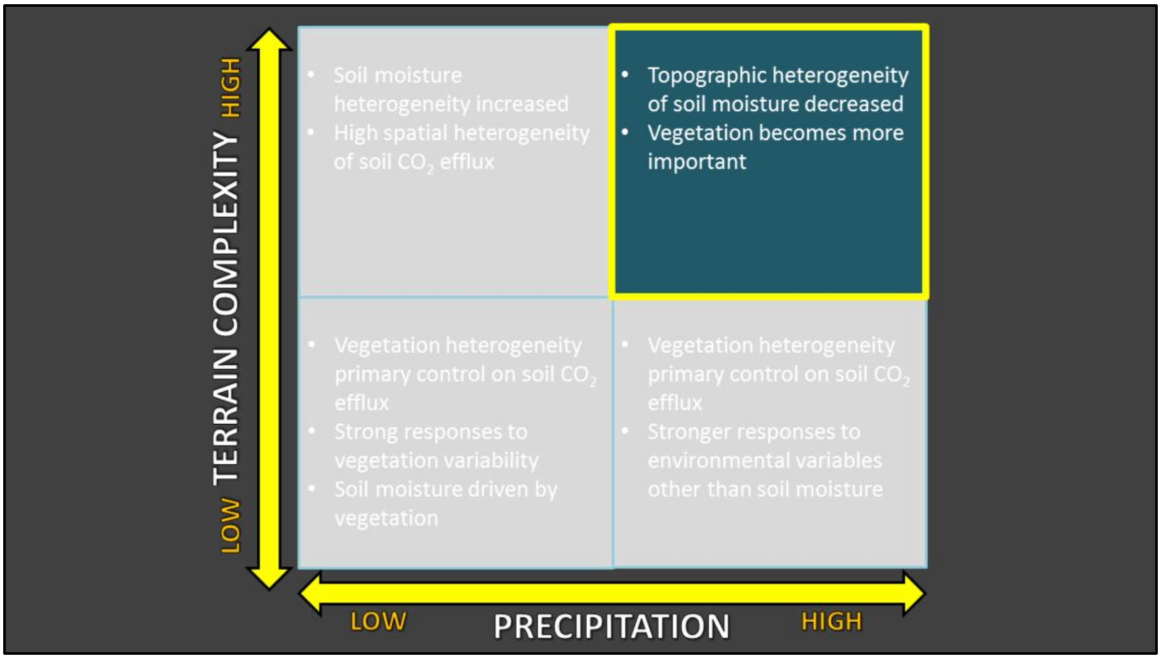
Our conceptual model of the interaction of terrain complexity and precipitation. Today we will only be talking about areas of high terrain complexity.



Increased soil moisture heterogeneity
High spatial heterogeneity of soil CO_2 efflux
Topographic heterogeneity of soil moisture decreased
Vegetation becomes more important
Vegetation heterogeneity primary control on soil CO_2 efflux
Strong responses to vegetation variability
Soil moisture driven by vegetation
Vegetation heterogeneity primary control on soil CO_2 efflux
Stronger responses to environmental variables other than soil moisture
LOW TERRAIN COMPLEXITY HIGH
LOW PRECIPITATION HIGH



An experiment in the Tender Creek Experimental Forest in Montana showed that for a low precipitation system, in this case one where the main input of moisture to the system comes in the form of early season snowmelt and vegetation has little variation, topography mediates the soil moisture regime and therefore affects the magnitude and timing of peak carbon fluxes, here represented as soil CO2 efflux on the right.



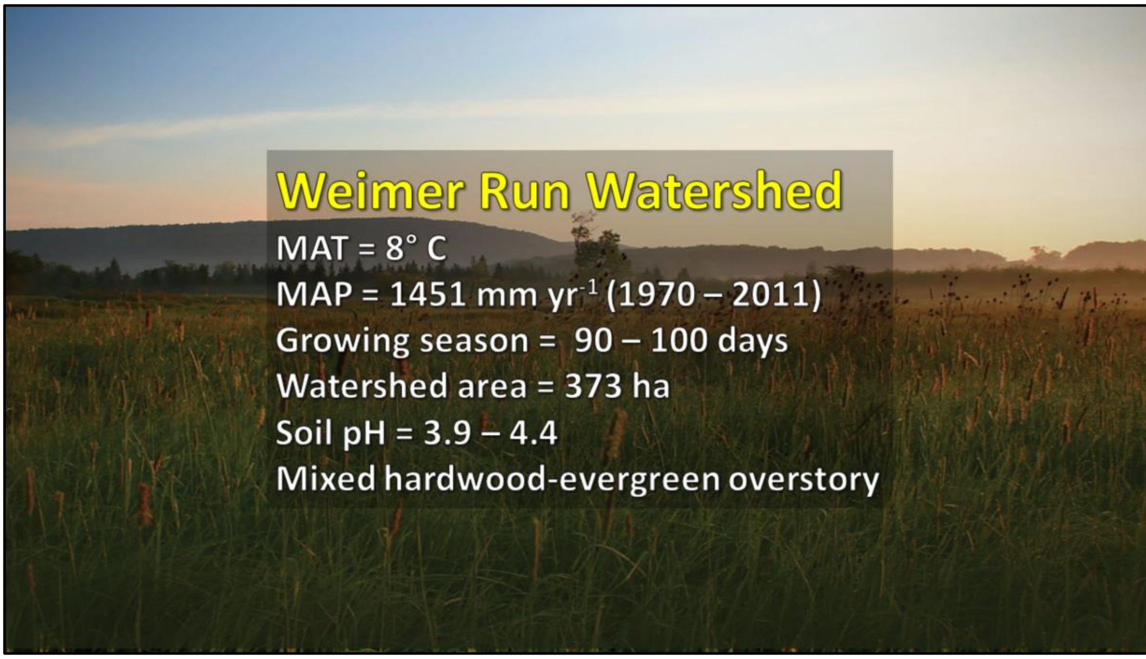
In areas of high terrain complexity with higher inputs of moisture, vegetation is expected to exert stronger controls on carbon and water cycling.

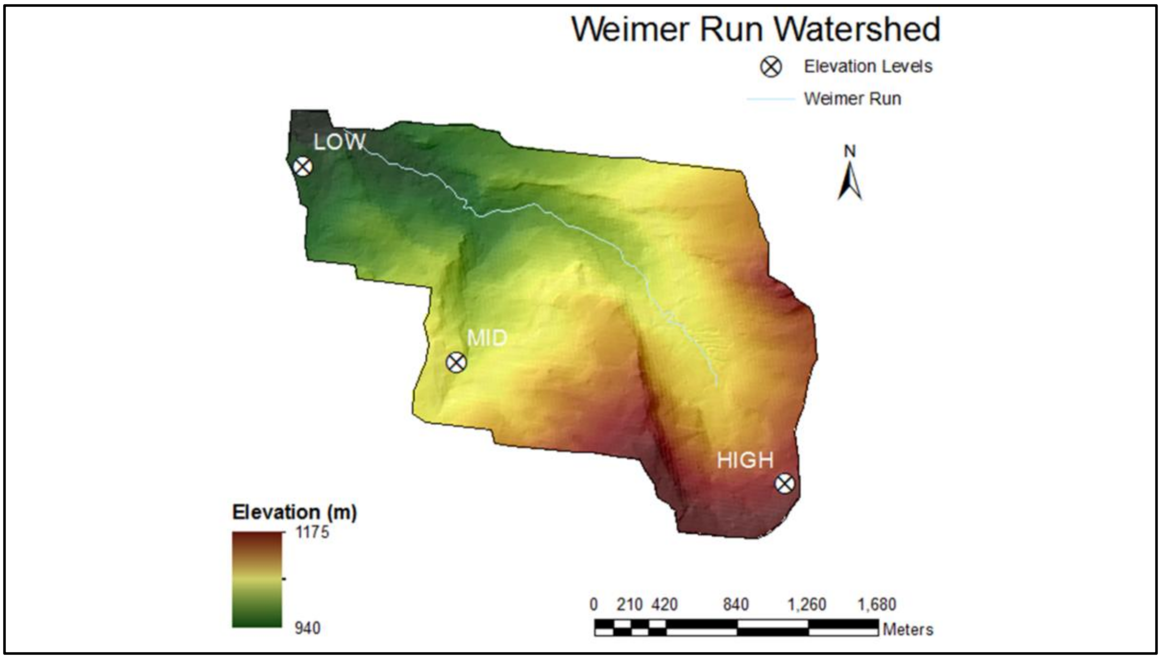
RESEARCH QUESTIONS

- How do landscape position and vegetation heterogeneity affect carbon cycling in a complex, humid watershed?
- What is the response of fluxes to inter-annual climate variability?
- Over the last several decades, how has vegetation cover changed in this watershed and what are the possible implications?

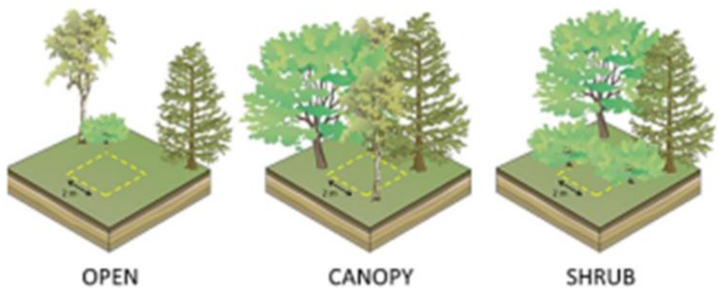
Questions.

Location of study site near Canaan Valley, WV.


Weimer Run Watershed
MAT = 8° C
MAP = 1451 mm yr^{-1} (1970 – 2011)
Growing season = 90 – 100 days
Watershed area = 373 ha
Soil pH = 3.9 – 4.4
Mixed hardwood-evergreen overstory



Our experimental design used three elevation classes.



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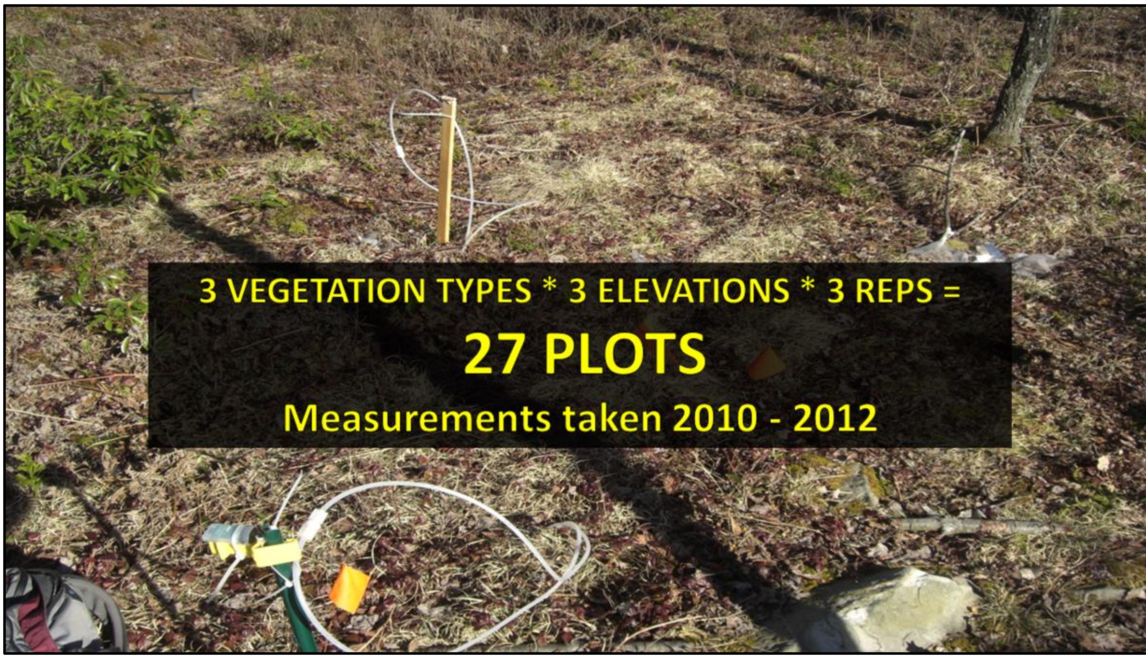
And three vegetation classes depicted here. OPEN – is an interior forest gap, CANOPY – is closed forest, and SHRUB – is interior, forest with shrub cover, usually rhododendron maximum.



Replicates. We measured weekly from May through October.

Soil CO_2 efflux
Measured with an
Infrared Gas Analyzer
(IRGA)

To approximate soil respiration, I used a portable infrared gas analyzer that measures soil CO2 efflux.

Soil Respiration (R_{SOIL}) – the sum of autotrophic (root) and heterotrophic respiration

Soil CO_2 Efflux (F_{SOIL})– the instantaneous transport of soil CO_2 from below- to above-ground

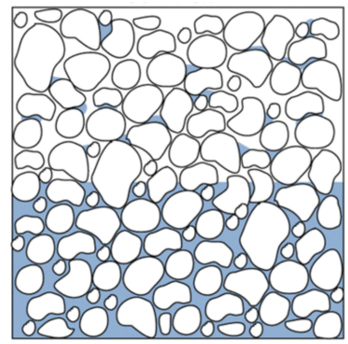
Differences. Respiration is all of the production in the system. Efflux is an instantaneous measurement and is influenced by transport which is related to present moisture in the system.

Soil temperature (°C) and volumetric water content ($m^3\ m^{-3}$)

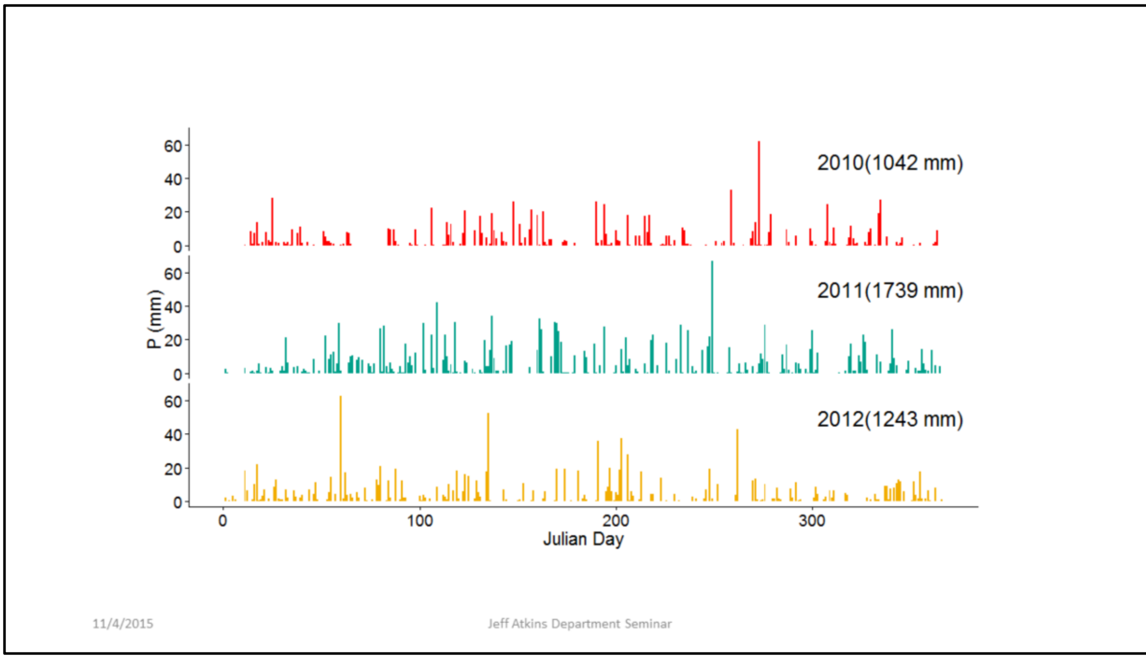
Both measured at 12 cm.

Water-filled pore space (m^3 m^{-3})

- Correct TDR VWC measurements based on soil permittivity
- Adjust corrected VWC by soil porosity (Φ)



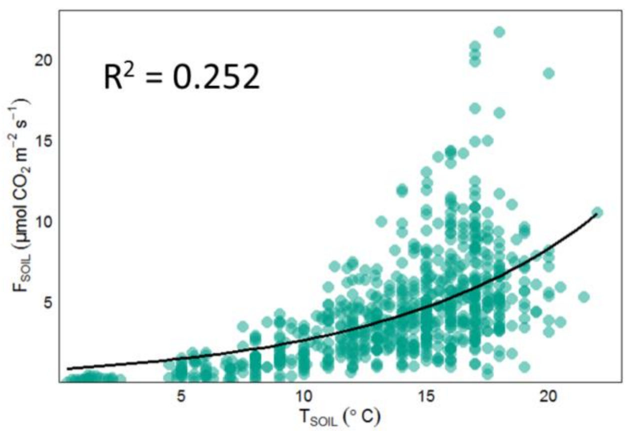
VWC measures corrected to WFPS as WFPS serves as a more mechanistic variable.



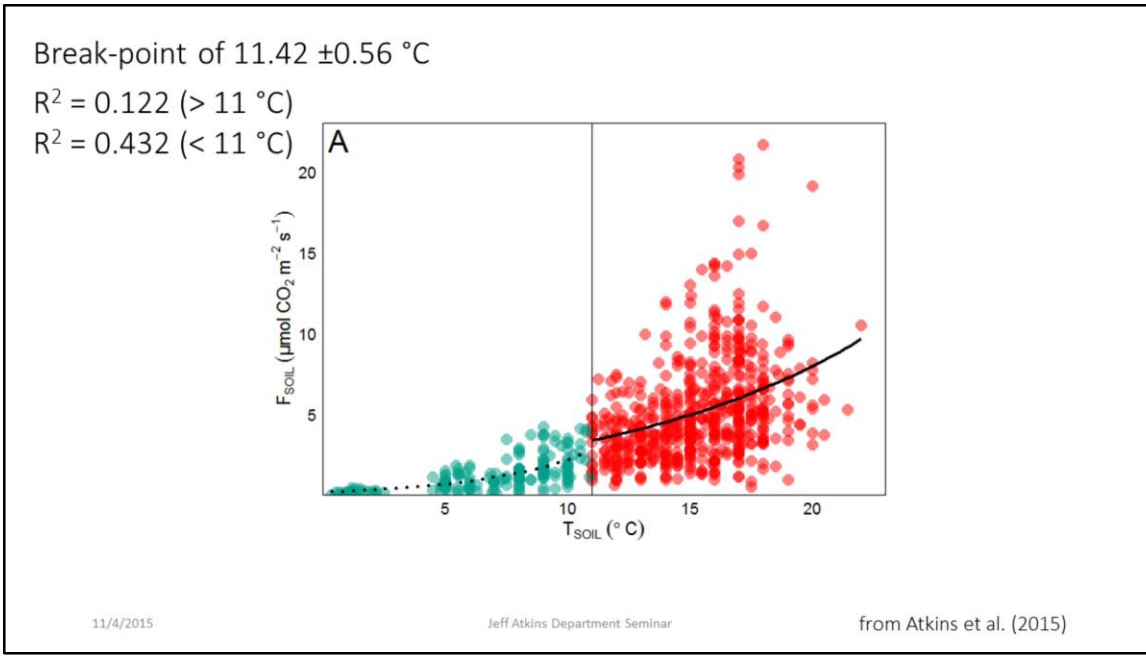
During the study, rainfall varied dramatically. Remember, our mean rainfall was 1450 mm per year. During 2010, our driest year, rainfall was 1042 mm while 2011 was much higher than the average, at 1739 mm. 2012 was closer to the average 1243 mm. Rainfall in this watershed is fairly well-distributed across the year.

How do landscape position and vegetation heterogeneity affect carbon cycling?

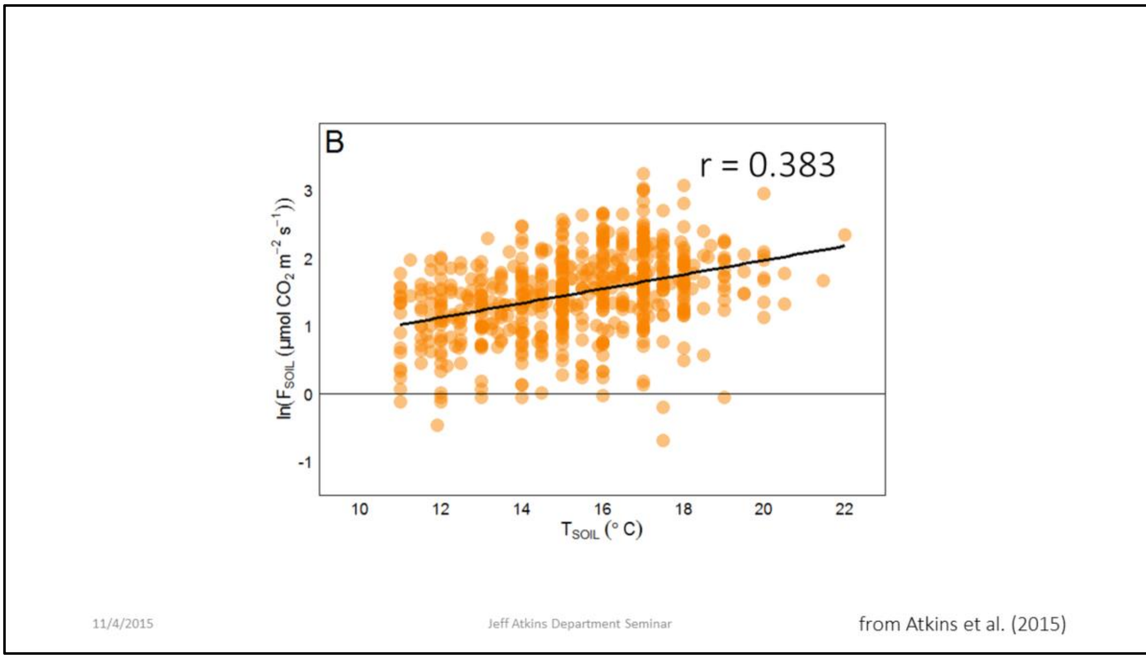
Research question one.



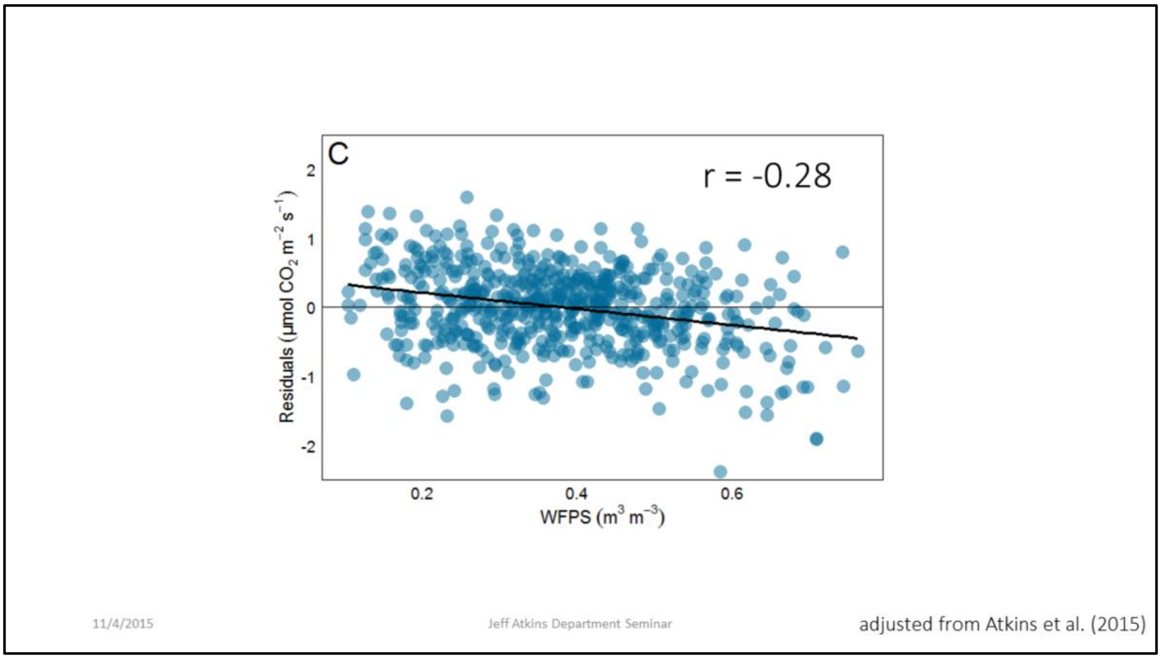
First, let's look at all of our measured fluxes. Carbon Fluxes, measured again as soil CO2 efflux, are presented here on the y-axis, with soil temperature at 12 cm on x-axis. If you recall the Raich and Schlesinger plot from early where soil respiration was plotted against MAT, you can see that this plot mirrors that relationship. However, with increasing temperature, the variance and of fluxes to temperature increases and we have an overall poor model fit represented by the R-squared of 0.252. To investigate this, we chose to use a change-point analysis technique called piecewise regression.



Piecewise regression identifies a statistically significant breakpoint in the data. Piecewise regression gives us a break point of 11.42. We chose to be a bit conservative and identified 11 degrees C as our breakpoint. We then analyzed the exponential relationships of temperature to fluxes above and below 11 degrees. For the remained of the analysis, I chose to focus on fluxes only above 11 degrees. Below this threshold, it is fairly evident that temperature is the primary control on fluxes. I am more interested in what is going on in the system when temperature is no longer limiting.



Since an exponential relationships exists between temperature and carbon fluxes, I first linearized that relationship by taking the natural log of F soil, our soil CO2 efflux term, and then putting that against temperature. Here we find a strong positive correlation of 0.38 with temperature.



Next, I extracted the residuals from the temperature/flux relationship and put that against our WFPS values. An analysis of this relationship shows a strong negative correlation of fluxes to WFPS within the Weimer Run watershed.

Soil CO_2 Efflux (F_{SOIL})

- Above 11° C, temperature no longer primary driver
- Negative correlation with WFPS

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Conclusions from our broad-scale first assessment of the data. This meets our expectation.


Elevation effects
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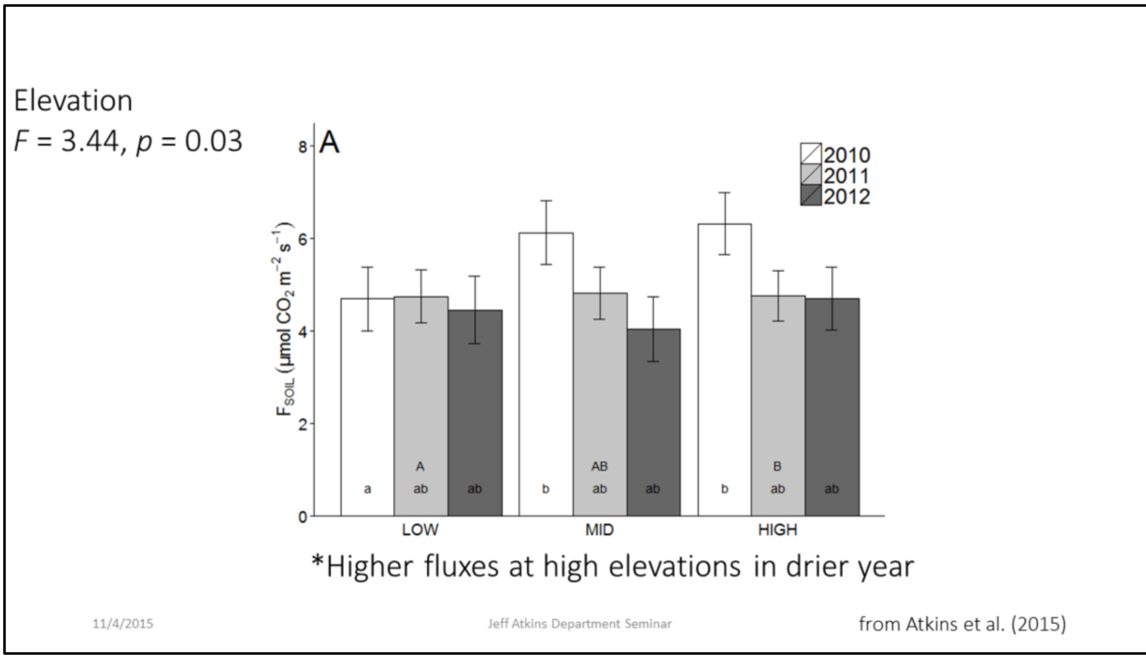
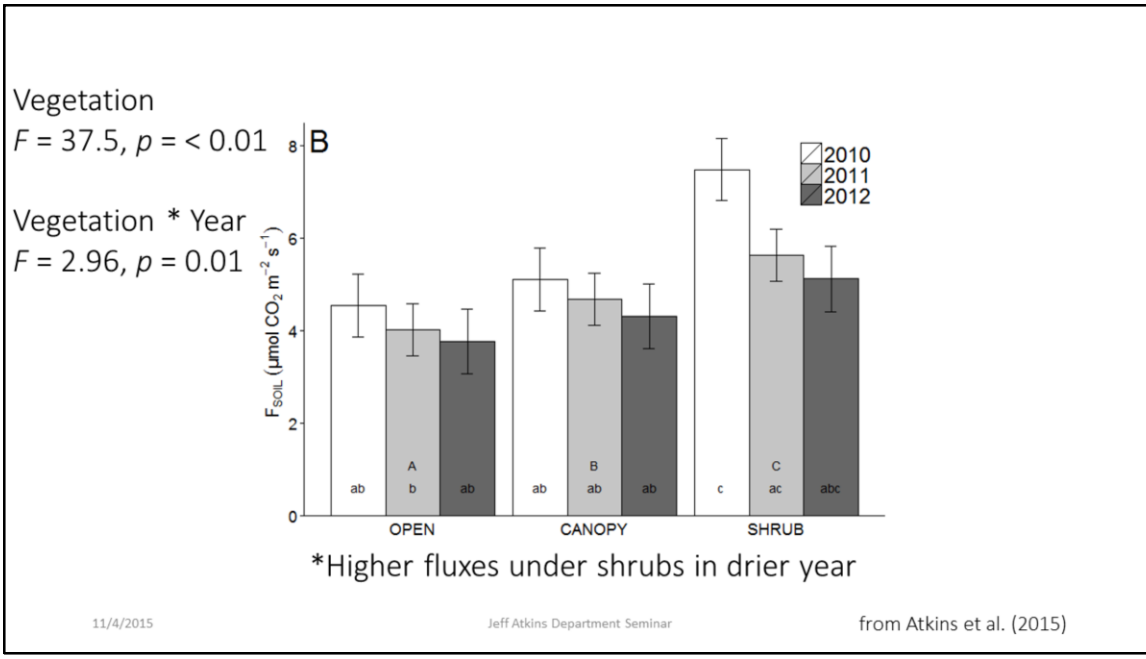
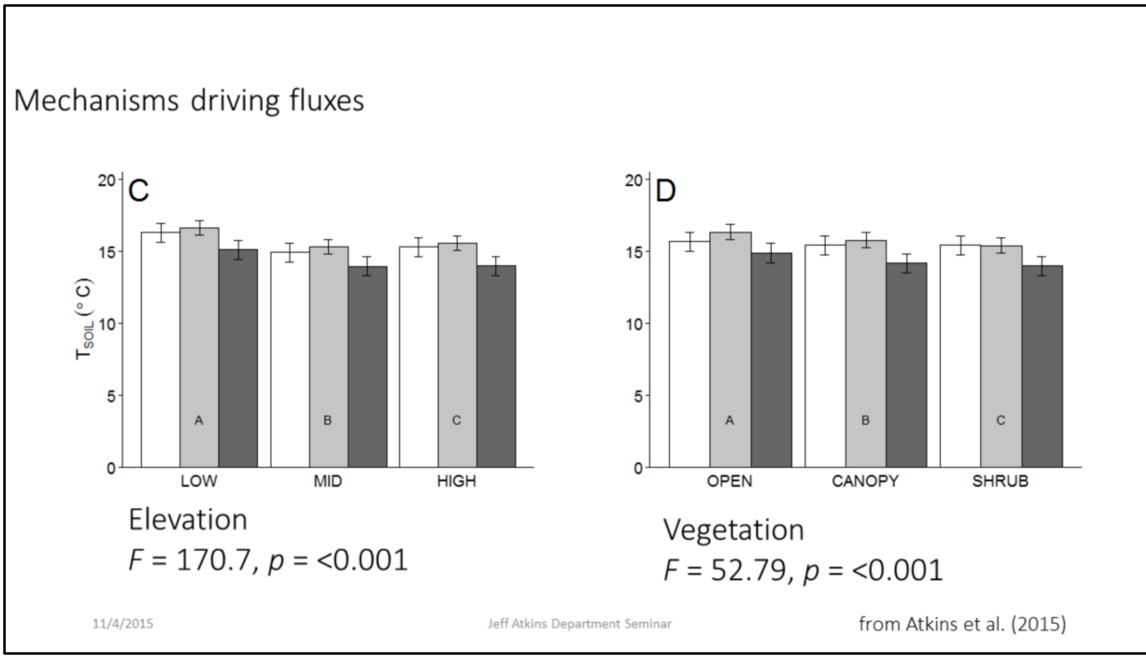


Here we have least squares means of F soil broken up by year and by elevation class. During 2010, our drier year, there are higher fluxes higher in the watershed. During 2011, our wet year, these elevation effects are muted. Results of a repeated measures mixed-model ANOVA contrasting elevation levels gives us overall significant differences in fluxes among elevation classes for the data set as whole—regardless of year. That is driven primarily by 2010 our dry year.

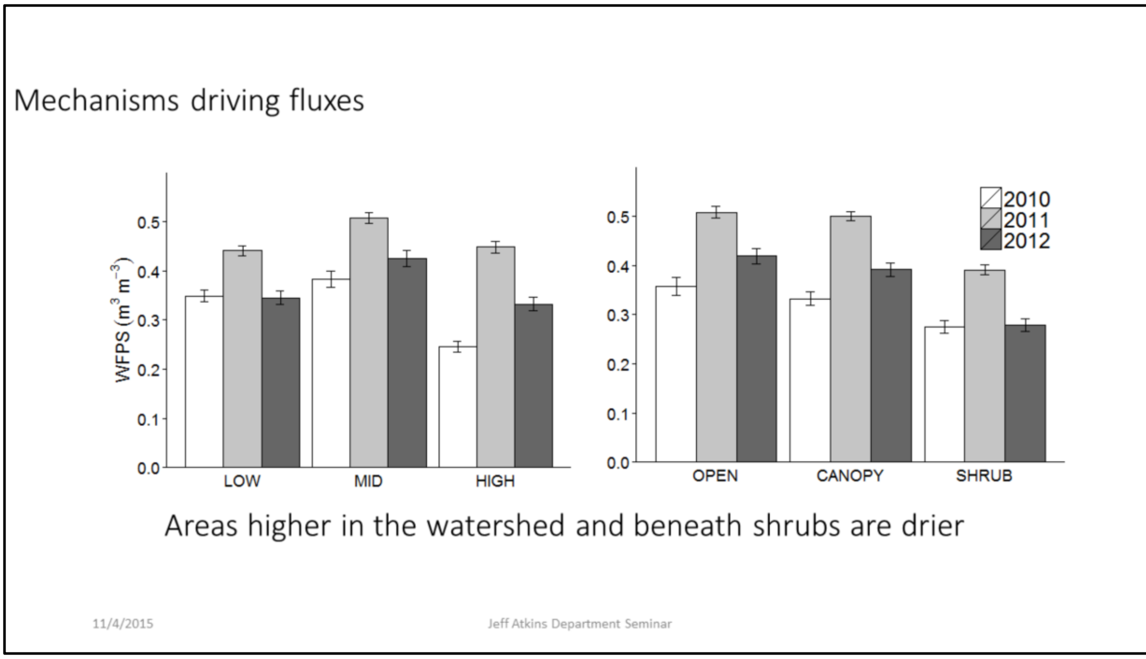

Vegetation effects



Plots beneath our shrubs have the highest fluxes overall, but this effect is notably pronounced during our drier year. Higher moisture levels in the system in 2011 and 2012 mute this effect, but fluxes from shrub plots are still higher and significantly different among years. Let's look at mechanisms.



First, let's look at soil temperature. Similar style plots, with temperature on the y-axis. At left is our soil temperature by elevation class and at right by vegetation class. For both elevation and vegetation there are differences in soil temperature. Temperatures cool moving upwards with elevation and are warmer in open areas and cooler beneath shrubs. Our shrub plots at the higher elevation level are the coolest plots, yet have the highest rates of soil CO_2 efflux.



In a sense, we have controlled for temperature by looking only at fluxes above 11 degrees C. So let's look at WFPS. 2010 was our dry year and that is reflected here in the data, as is 2011, our wet year. Overall, higher elevations and plots beneath shrubs are drier. Differences among elevation are more evident in our drier year, while differences among vegetation classes is more evident in our wet year.

Elevation

- Higher fluxes at mid and high elevations in 2010
- Soil temperatures lower at higher elevations
- Topographic effect on moisture

We see higher fluxes higher in the watershed, an effect exacerbated during 2010 when there is a more pronounced effect of topography on soil moisture.

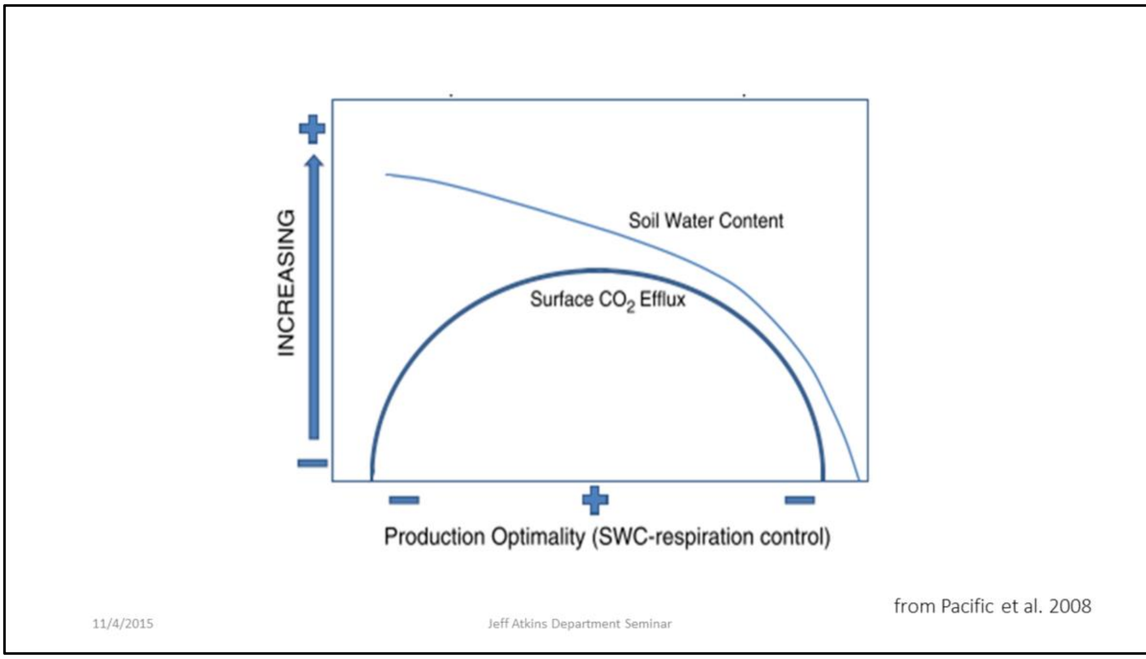
Vegetation

- Higher fluxes beneath shrubs—increase w/ drier conditions
- Beneath shrubs is colder and drier
- Open areas are warmer and wetter

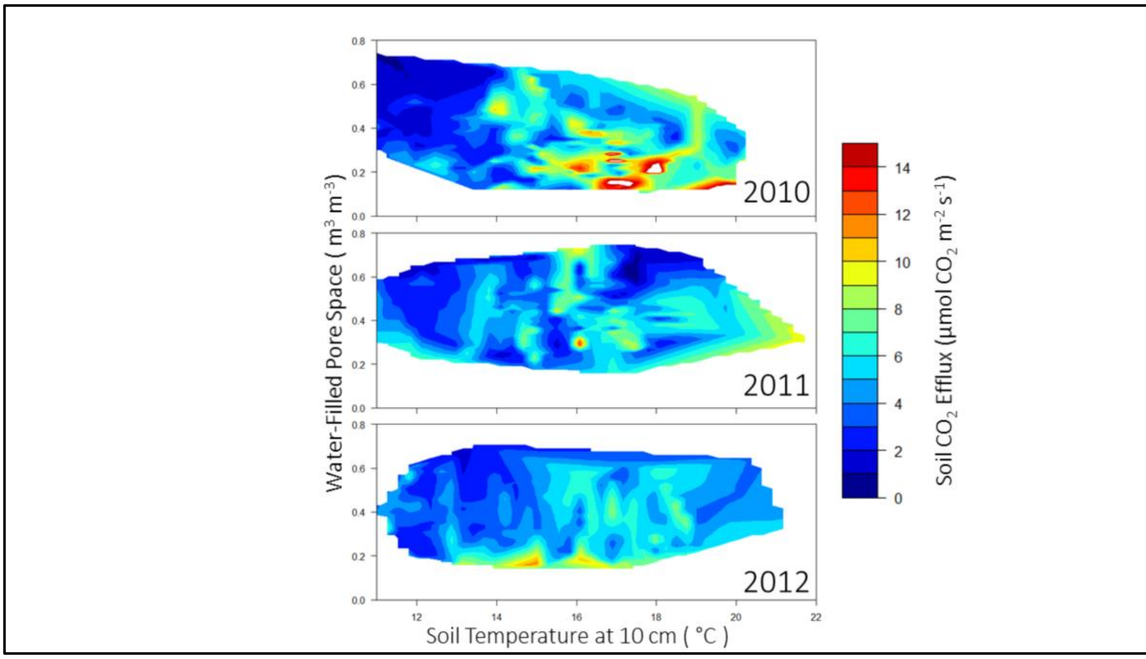
Areas beneath shrubs are drier and cooler, but also have the highest fluxes. This effect is also exacerbated during our drier year.

Given the response seen during just a three year period, I became interested in investigating the role of climate variability and how it has changed.

What is the response of fluxes to inter-annual climate variability?



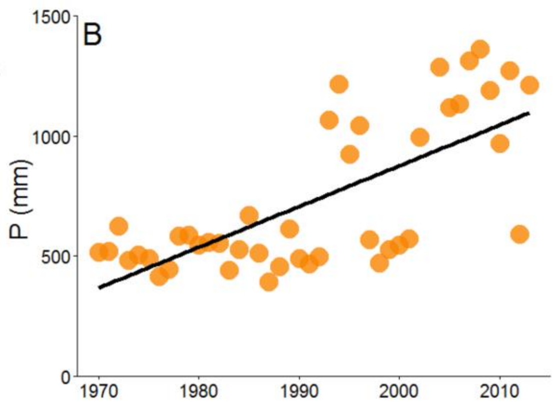
This conceptual diagram pulled form Pacific et al. 2008 shows the hypothesized relationship of soil CO2 efflux with changes in soil water content. A production optimality exists at medial values of soil moisture. At high values of soil water, we see decreased transport of soil CO2 through the soil matrix, at low values, there is desiccation and decreases in soil CO2 production.



Now, let’s take combine all of our information. We have a heatmap of soil fluxes with soil moisture on the y-axis, soil temperature on the x-axis and color indicating the magnitude of fluxes. We also have it broken up by year. At top, in 2010, we see evidence of this optimality—peak fluxes occurring when the watershed is drying, not necessarily at peak soil temperature. During 2011 and 2012 we see similar albeit altered patterns.

Annual precipitation

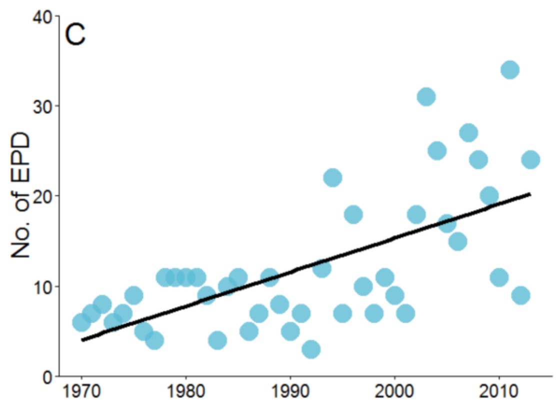
*Significant increases in the mean and the variance



While we have considered the spatial variance, let’s take a deeper look at the temporal variation. Here we have precipitation totals from 1970 to 2012. We see an overall increase in precipitation and more interestingly an increase in year to year variance. A Breusch-Pagan test shows there is significant heteroscedasticity over this climate period. This has potentially important ecological ramifications.

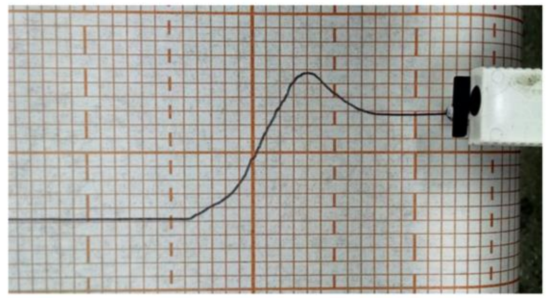
*Significant increases in the mean and the variance

EPD = Extreme Precipitation Days



One of the contributing factors is the increase in what I have termed extreme precipitation days, defined here periods when more than 1 inch of rainfall falls in a 24 hour period. Again, a similar pattern to overall rainfall with increasing variance and evidence of heteroscedasticity.

Climate
- Effects on fluxes
- IPCC projections
- Increased variance (heteroscedasticity)
- Ecosystem effects



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Year to year impacts on fluxes are potentially important consideration. There is further evidence of changes in snowfall and snow pack which has other impacts on decomposition and nitrogen movement.


Environmental Controls
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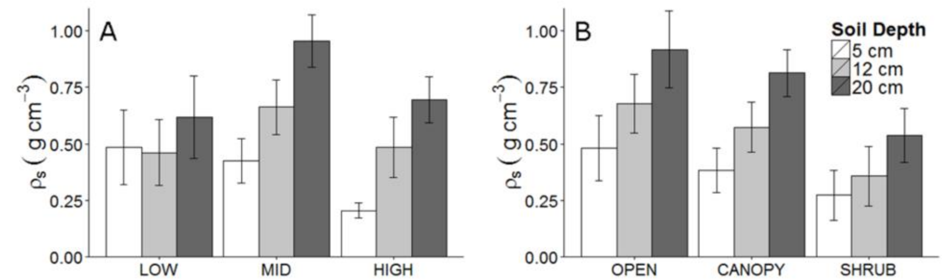
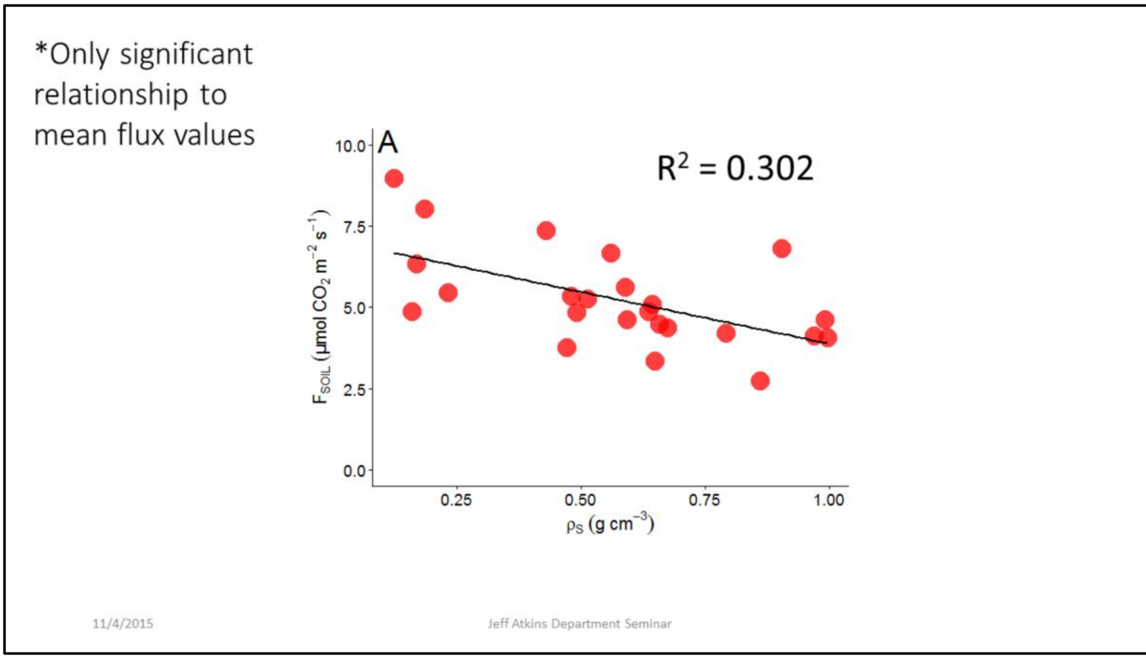


Plots beneath shrubs have lower soil bulk density and similar amounts of SOM—this means that SOM is potentially more exposed to oxidation and decomposition, contributing to greater carbon fluxes



Soil bulk density is the only environmental variable I measured with significant correlation to mean soil CO2 efflux.

"Shrub Effect"
- Higher soil porosity
- Higher soil nitrogen
- Higher soil carbon
- Lower soil bulk density

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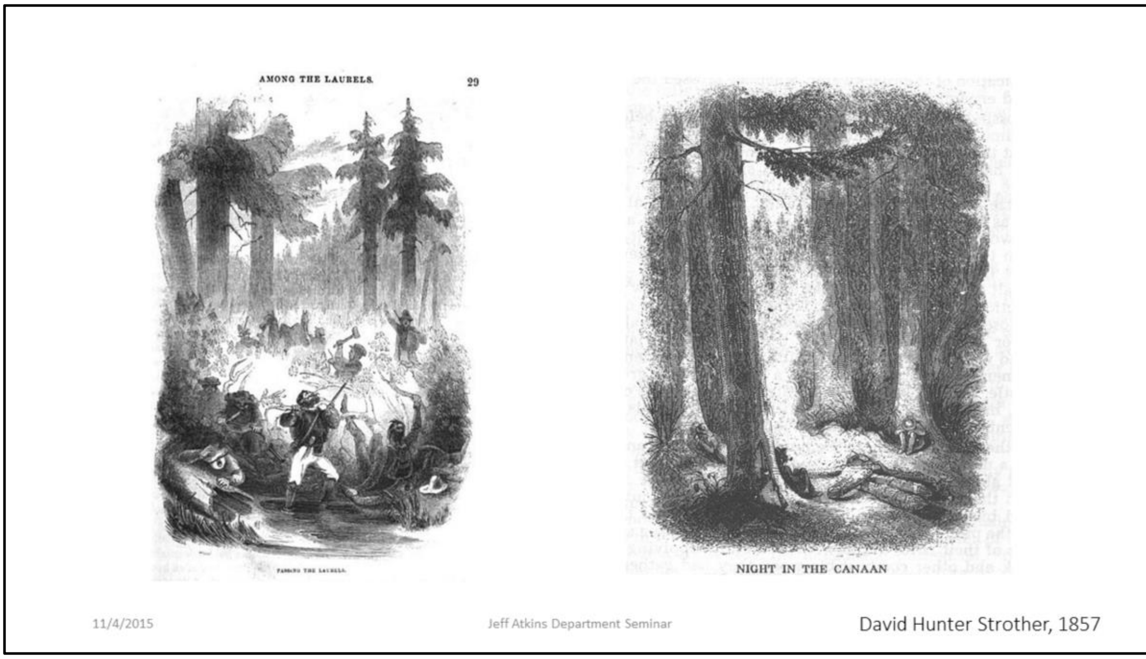
Which brings us to the question of how the vegetation is changing in the watershed through time.


Vegetation Change

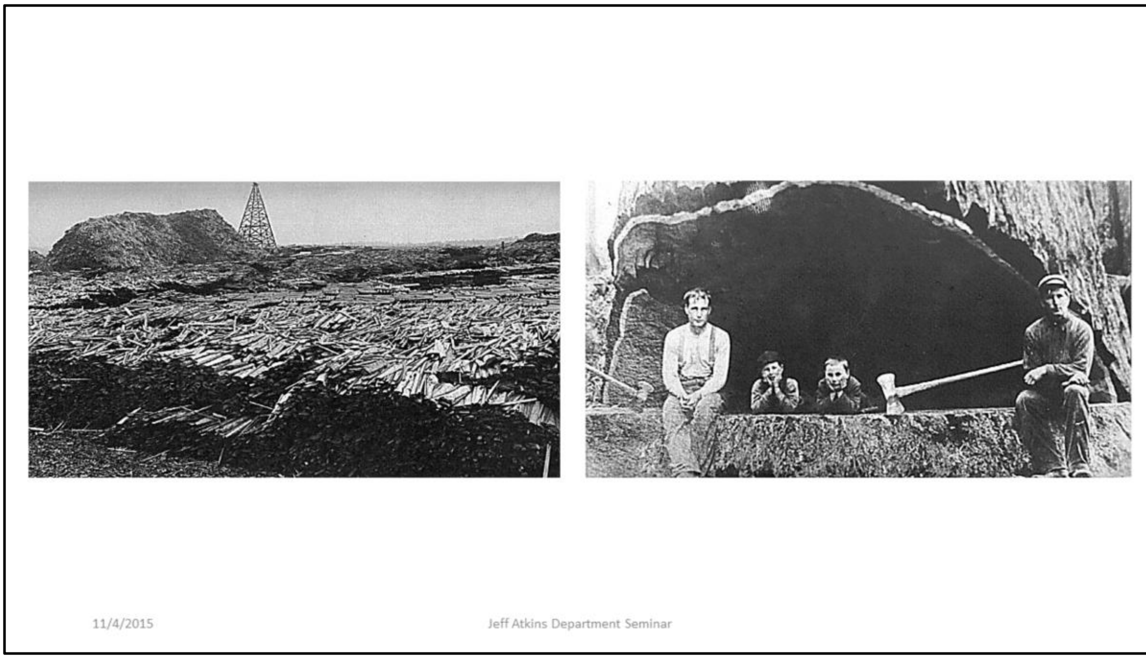
Has vegetation cover changed over the period of available satellite data (1986-2011)?



The earliest descriptions we have of the forests of the Canaan Valley come from early adventure texts detailing journeys of European settlers to discover the headwaters of the Potomac in the 1850's. These texts not only described a tremendous canopy of hemlock and red spruce, but also dense thickets of rhododendron, termed laurel-brakes.

"The hunters had been dodging the laurel-brakes all day. They seemed to dread the passage, and would frequently go miles around to avoid it. They had stories of men who had spent days in them, wandering in circles, and who had finally perished from starvation . . ."

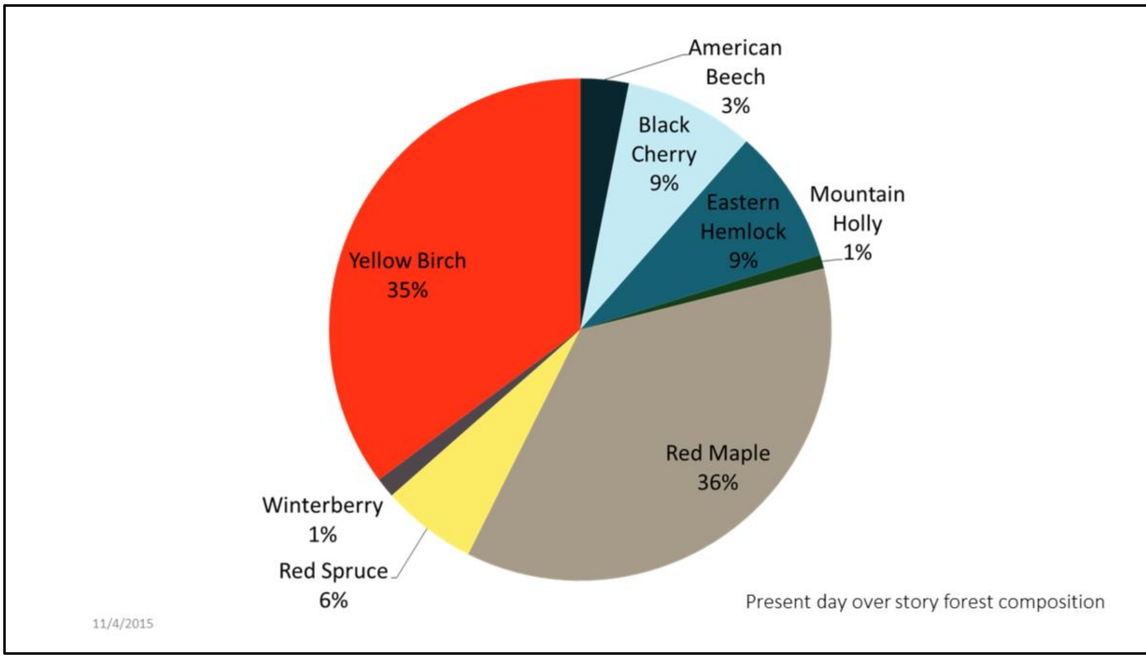
- David Hunter Strother, 1851



By the 1880’s Europeans had permanently settled near Canaan Valley and the railroad soon followed. Timber was quickly felled. Over 30 billion board-feet of lumber were felled in less than 50 years.

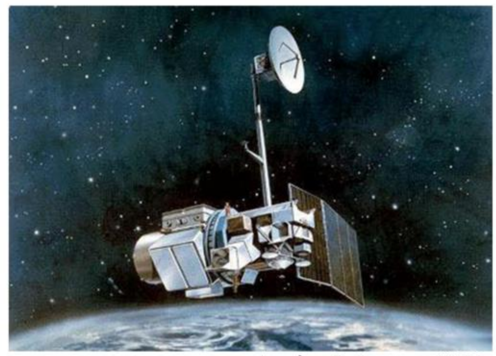
The ecological impacts of human disturbance were severe and profound.

Most of what wasn’t cut, was burned in subsequent forest fires. The dense, organic soils of the area in places burned to bedrock and mineral soil.



Today, the forests look much differently.

Remote Sensing
- Landsat 5 TM
- 30 m resolution, 25 years of available data
- Derived vegetation indices



Landsat 5. Courtesy NASA

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One method to examine change is to use remote sensing.

Normalized Difference Vegetation Index

- Relationships of the NIR to Red bands
- Index of plant “greenness”
- Correlates well to biomass and photosynthetic activity

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Tasseled Cap Transformations
- Brightness
- Greenness
- Wetness

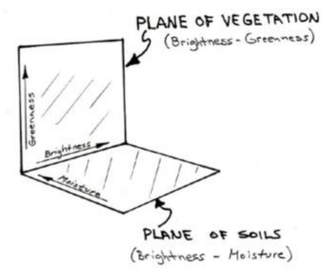


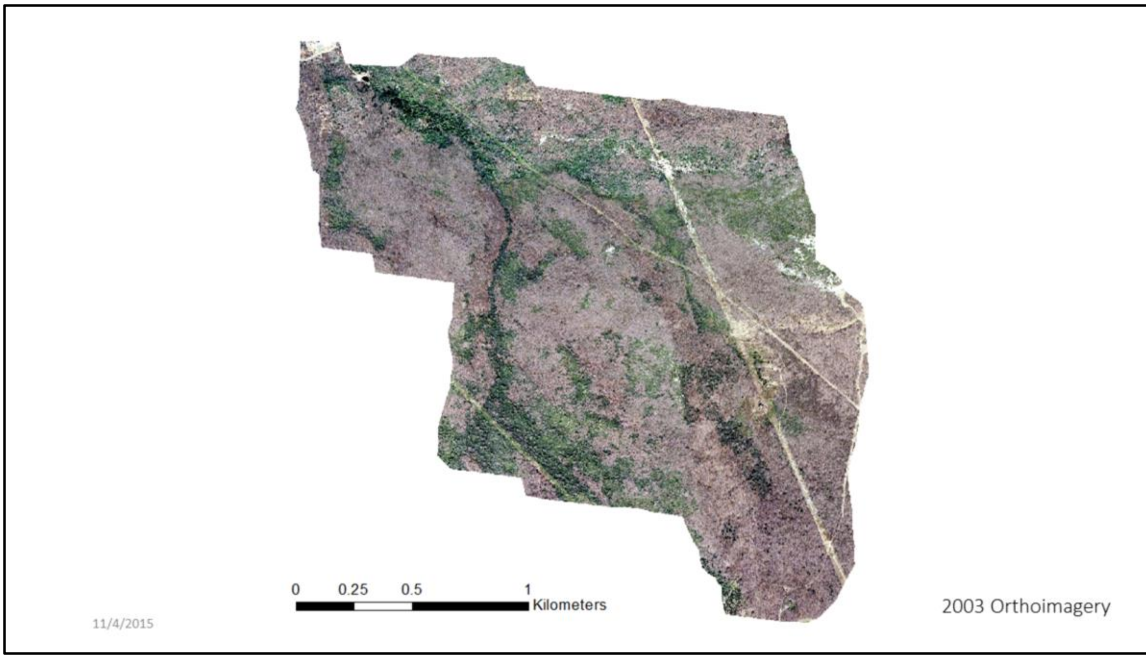
Image courtesy Liz Marcello

Disturbance Index (DI)
- Uses Tasseled Cap Transformations
- Corrected for mean and SD
- Detects change

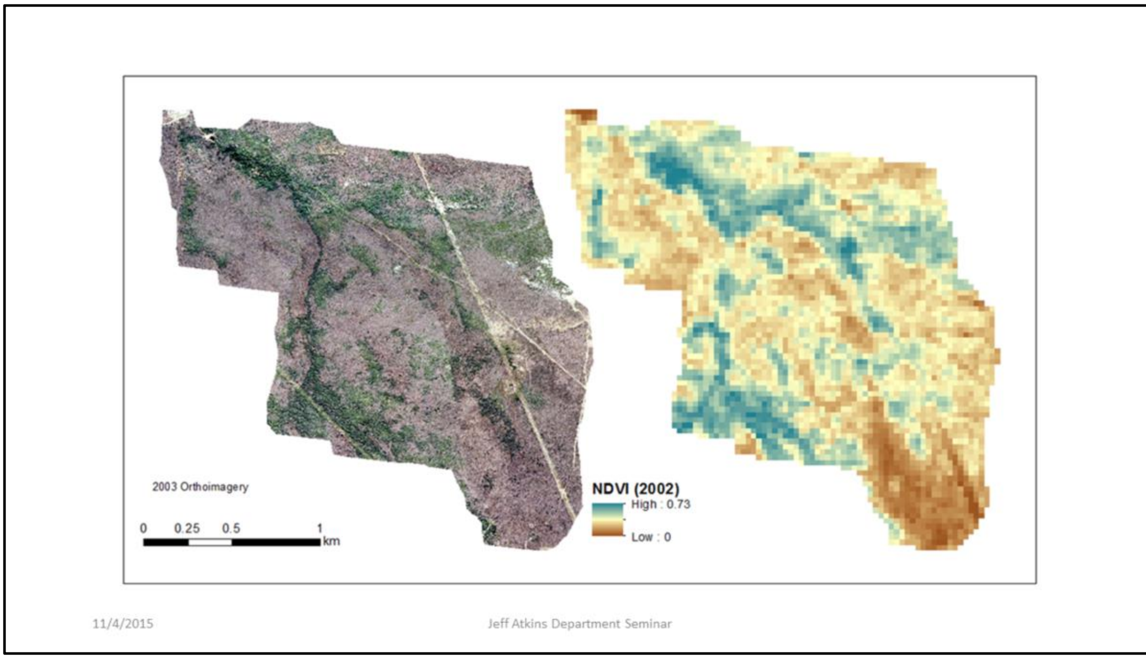
$$X_r = \left(X - X_\mu\right)/X_\sigma$$

$$DI = B_r - (G_r + W_r)$$

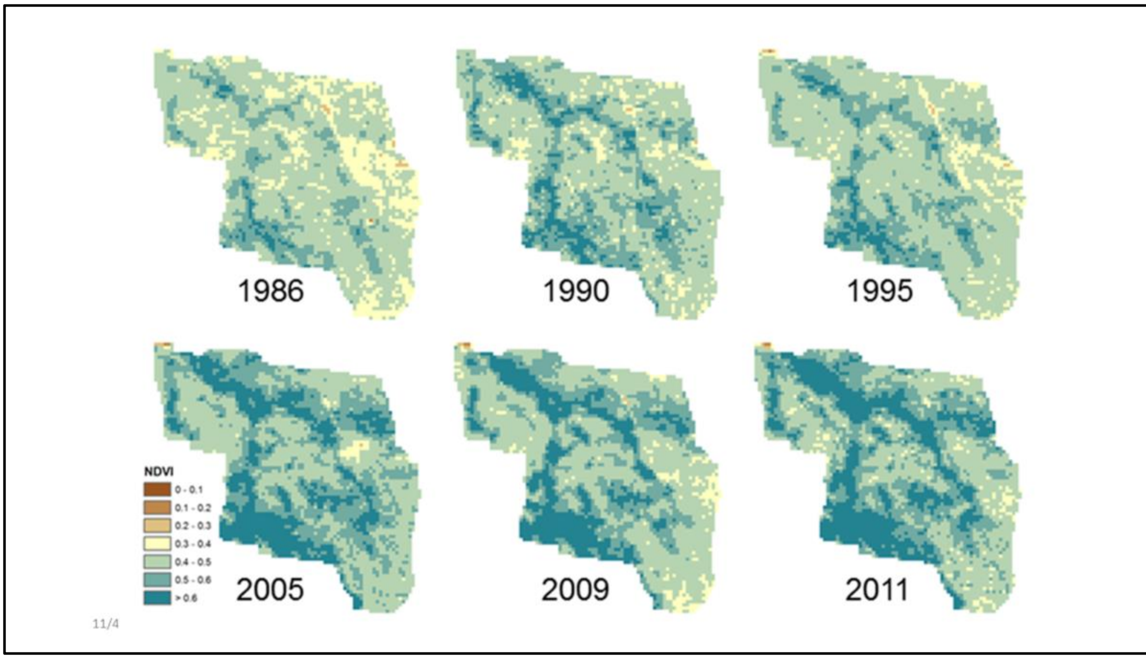
Our primary interest is in examining the understory, the evergreen shrub component of the watershed.



To do this, we chose to use snow-free winter scenes, Note the dense evergreen component in the watershed.



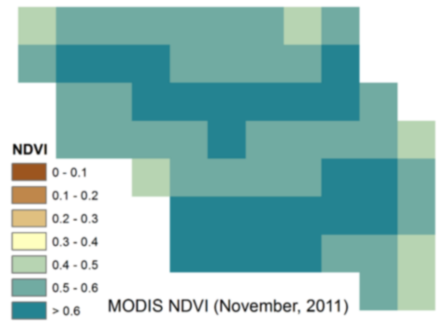
A comparison of the nearest scene we have to the orthoimagery. The NDVI signal tracks. 2002 has snow in the high area of the watershed, and was not used in the analysis.



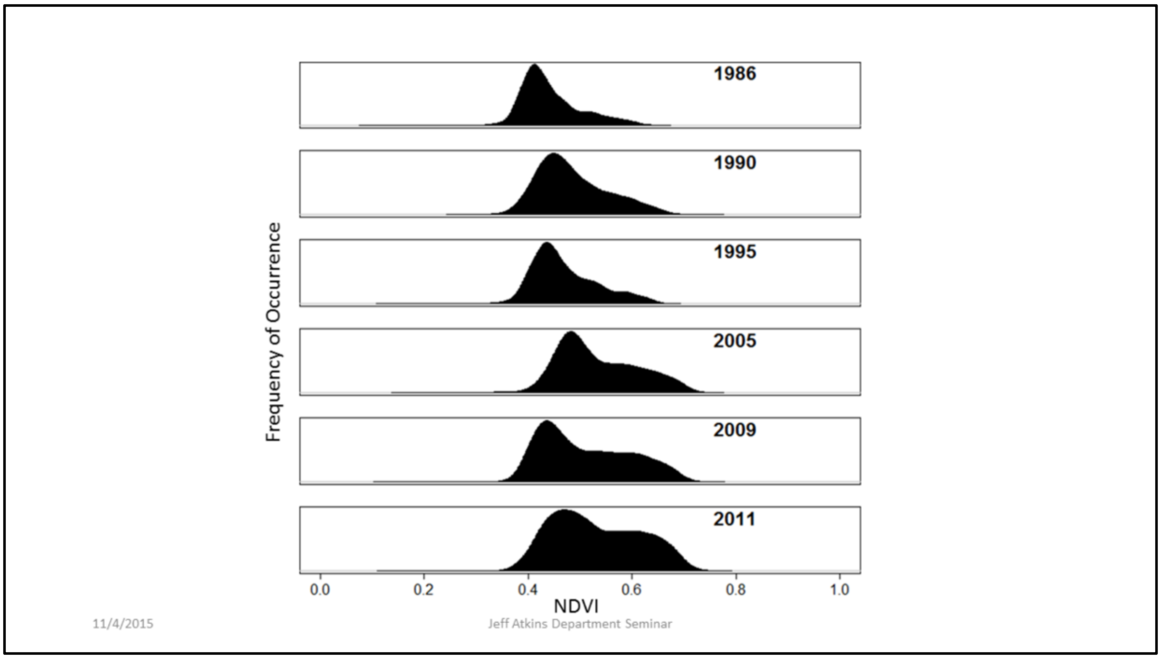
NDVI increases through time.

Comparisons to MODIS

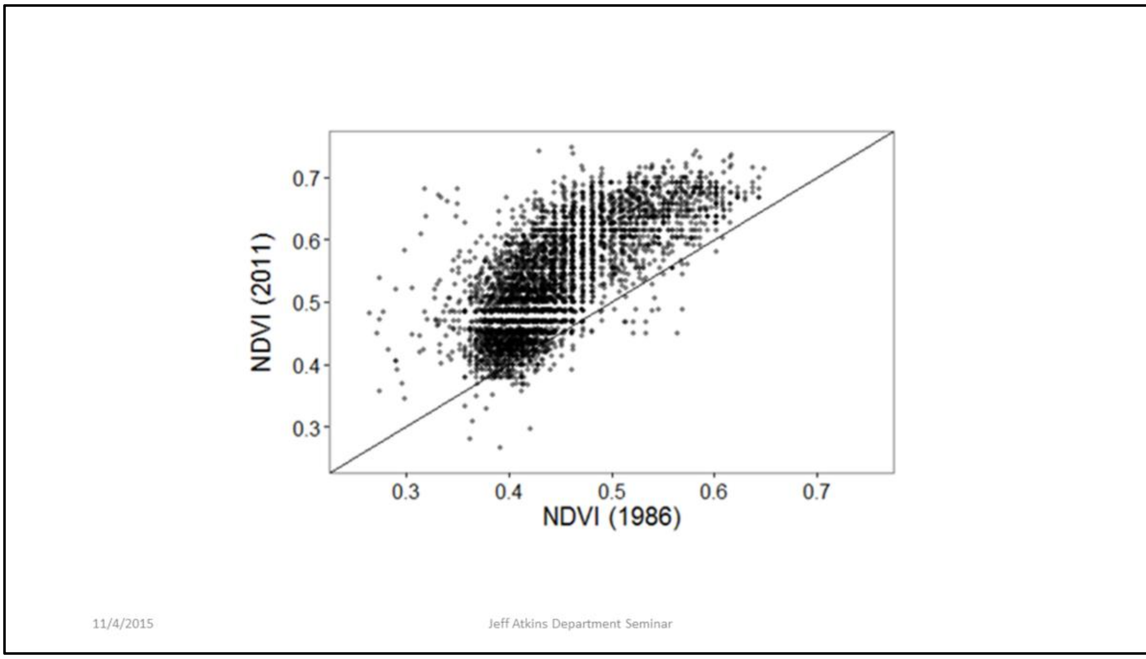
- Coarser resolution (250 m)
- Same time period
- Lowest scene NDVI 0.46



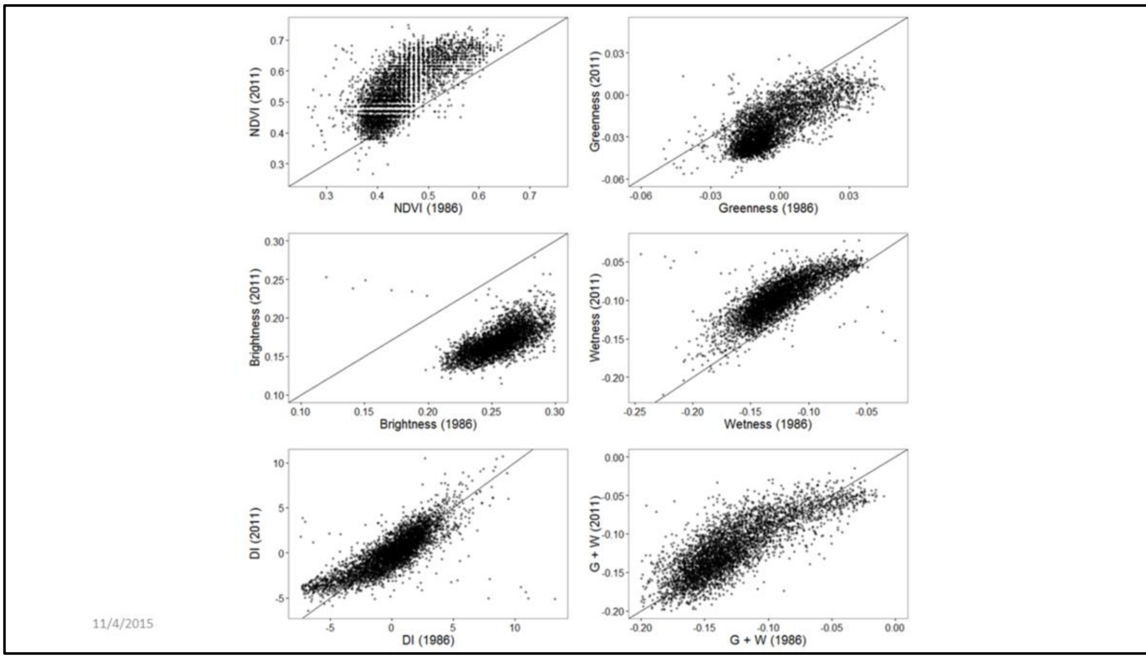
MODIS shows us that our low values, which are quite high, are reasonable.



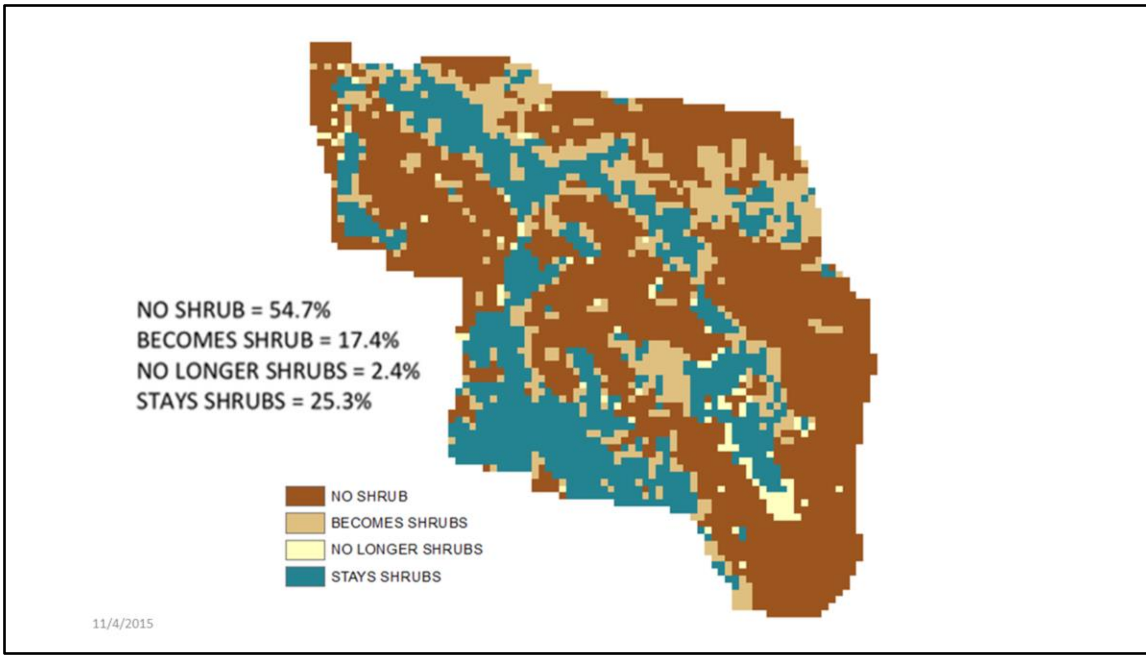
If we look at the distribution of NDVI through time, we can see evidence of this shift as well.



Another way to do this is to look at the 1986 and 2011 endmembers. Here we have 2011 on the y and 1986 on the x. Above the 1:1 line shows an increase.



Now, same things for the other models that we used. Note that Brightness decreases means that we have less bare soil. DI decreases in the lower values, that means we have denser cover. Greenness likely lacks the signal that we are interested in as it was adapted for agricultural uses.



Now if we look at what this means functionally in the system, when use cluster analysis on our 1986 and 2011 NDVI endmembers, we can see the areas that change classification.

Vegetation Change

- Significant winter “greening”
- NDVI as reasonable metric
- Multiple stable states
- Ecological, silvicultural, and societal impacts


Spatial Controls
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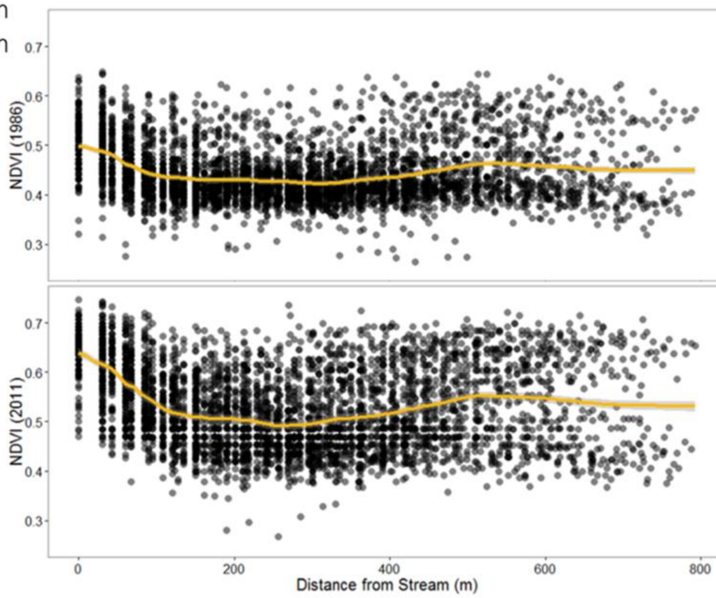
1986 - 133 ±5.7 m
2011 - 142 ±4.5 m



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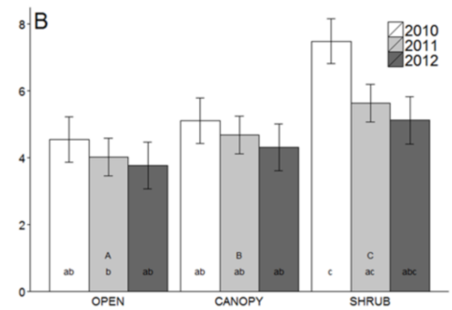
Shrubs are moving and radiating out from the riparian areas.

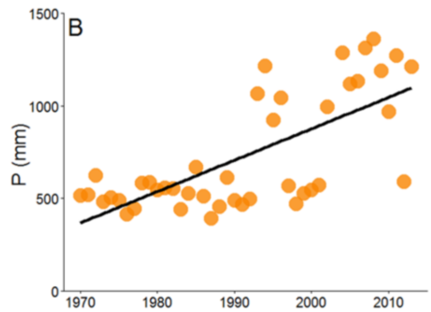
Spatial controls on shrubs
- Expanding from riparian areas
- More greening at lower elevations


Conclusions
11/4/2015
Jeff Atkins Department Seminar

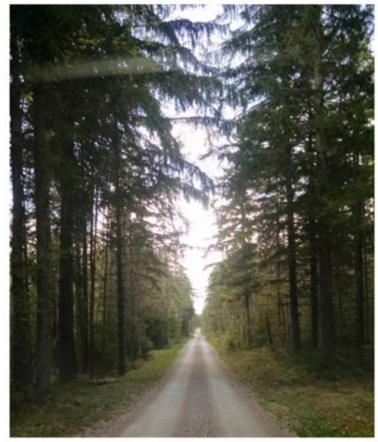
Effects of vegetation heterogeneity and the "shrub" effect



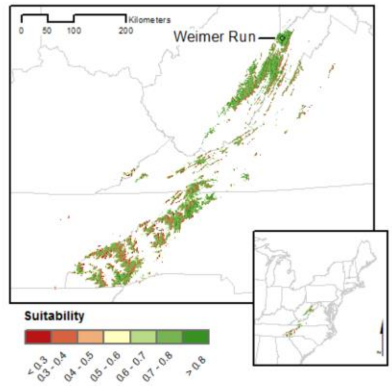
Responses to inter-annual climate variability



Shrub expansion and possible implications



Informing management decisions and further understanding



from Neblett et al. (In Prep)

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DEPARTMENT of ENVIRONMENTAL SCIENCES AT THE UNIVERSITY OF VIRGINIA

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Questions?