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The Impact of Drought on the Sierra Nevada Range: Using Remote Sensing Data to Estimate Large-Scale Carbon Dioxide Flux

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Abstract

Remote sensing is a widely used technique for studying Earth systems, including ecosystem response to global warming. With the recent California drought, remote sensing gives an opportunity to study large-scale CO_2 flux changes over time due to insufficient water uptake by plant life. In this study three flux towers were used, to correlate Net Ecosystem Exchange (NEE = PRI * NDVI * PAR), gathered from remote sensing data, and measurements of CO_2 flux from *in-situ* flux towers over an area of 8,149 km^2 in the Sierra Nevada Range. To estimate CO_2 from NEE, two linear regressions were used which correlated with the temperature stress response of plants (>23.5 and <23.5 degrees C), with R^2 values of 0.81 and 0.83 respectively. Per-pixel CO_2 flux was estimated for flights between 2011 (pre drought) and 2015 (during drought). This study showed a 25% (4.8 g / min) decrease in net carbon fixation between September 2011 and October 2014 over 34 km^2. Also seen was a decrease in net carbon fixation over 7,737 km^2 of 90.2% (18,863 g / min) between June 2013 to June 2015. Of the 411.6 km^2 affected by the 2013 Rim Fire, this study showed a decrease in net carbon fixation of 85.5% (1,574 g / min) between June 2013 and June 2015. It is estimated that the entire Rim Fire (1,041 km^2) could have caused a total decrease in net carbon fixation totaling 3,982 grams per minute from 2013 to 2015.

Introduction

It is hard to be unaware of the current debate on global warming. Some people may just hear about it on the news, and some may be noticing the climate changing right at home. The big contributor to global warming is the accumulation of greenhouse gases. These chemicals trap some of the heat from the sun and allow Earth to be habitable, but an excess in these gasses will increase the global temperature, a process which has already begun. Since the 1880s, the Earth's temperature has risen by 1.6 degrees Fahrenheit, and it is expected to continue to increase at a faster rate. The ten hottest years in the last 134 have been since 2000, with the exception of 1998, and with 2015 being the hottest year yet (Shaftel). Although greenhouse gases, such as carbon dioxide (CO_2), occur naturally, this continued climb has been caused by many human-related processes. The biggest contributor is the burning of fossil fuels like oil, coal and natural gas. Alteration of land use, such as deforestation, and industrial processes like cement and steel production also add to the overload of carbon dioxide (Canadell et al. 304-305). The lifetime of CO_2 in the atmosphere has been estimated to be about 200 years, adding to the importance of

prevention and recovery (Sonnemann and Grygalashvyly, 1591). The main way to lessen the carbon dioxide in the atmosphere has been through the natural processes our forests provide.

It may be considered common knowledge that plant life provides the oxygen necessary for almost all other forms of life on Earth, but it might not be as well-known that our forests take in carbon dioxide. On average, they absorb (or "fix") almost 122 billion tons of carbon dioxide per year through photosynthesis (Beer et al., 834). In the process of photosynthesis plants take in CO_2, water, and energy from the sun, and convert them to sugars and oxygen following the chemical equation:

$$6\ CO_2 + 6\ H_2O \xrightarrow{+\text{ light}} C_6H_{12}O_6 + 6O_2$$

Where H_2O is water, $C_6H_{12}O_6$ is sugar, and O_2 is oxygen. If any one of the materials needed for photosynthesis are lacking, such as water, plants will decrease photosynthesis and may become dormant, therefore decreasing the rate they take in CO_2.

When plants become water-limited they will close their stomata, or the openings in their leaves in which gas exchange occurs, in order to reduce the evaporation of water. This was seen in a study by Sherrard and Maherali in which plants that were well-watered showed an increase of 303% in stomatal conductance when compared to those that weren't (Sherrard and Maherali, 2481). To insure survival, plants have to produce energy, so they begin the process of respiration. During respiration plants break down their stored sugars and combine them with oxygen to release carbon dioxide and energy. The plants then release this carbon dioxide into the atmosphere. One large concern is that this decrease in CO_2 uptake, as well as its release during respiration, means more carbon dioxide is in the atmosphere, therefore compounding the effects of global warming.

A process that can cause significant changes in large-scale carbon dioxide uptake is severe, long-term drought. An example of the detrimental effects drought can have on plant life can be seen in the paper by Huggins et al. in which the species *Astragalus jaegerianus* was studied from 1999-2010. During this time period the Mojave Desert in Southeastern California was experiencing a severe drought in which the population of *A. jaegerianus* saw a large decline, and in some areas was almost forced into extinction (Huggins et al. 120). Another study done by Ozolincius, et al. looked at the effect of an artificial drought on a population of a 60-year-old Scots Pine stand in central Lithuania. The authors did this by analyzing indicators such as needle

age, litterfall, and crown defoliation (Ozolincius et al. 299). Ozolincius et al. noticed a large decrease in plant structure, in which they saw changes in crown defoliation where needles fell faster and there was a weaker formation of shoots and needles (Ozolincius et al. 305). This method of data acquisition is termed field data collection, and can be highly accurate. One downside to this direct form of data collection is that individuals must spend days at a time in the field gathering data, and must return at regular intervals to repeat the process.

Other methods of field data collection have been developed in which there is less need for a research team to spend time out in the field. One technique that has been in use for many years is data collection from *in-situ* flux towers. These towers assess the amount of a certain variable (water, carbon dioxide, nitrogen, light, etc.) that flows through a unit of area (usually m^2) per unit time (seconds). These are often very accurate and once in place are relatively inexpensive to operate, but the data is not always readily available and the towers are only useful on a small scale.

The issue with collecting field data is it can be very expensive and time consuming, so more advanced techniques have been developed in order to assess forest / ecosystem health. One such technique is airborne and satellite remote sensing, which records wavelengths of light that are reflected off of a surface. Remote sensing data will also contain factors such as latitude / longitude, time, slope of the ground, elevation, and angle of the sun. Many indices have been created to attempt to analyze plant health using ratios between these wavelengths, the efficacy has been heavily studied, and new indices are constantly being developed and improved. One such index is the Normalized Difference Vegetation Index (NDVI), which assesses plant greenness, a representation of plant biodensity. Another important index is PRI, or the Photochemical Reflectance Index. PRI is an indicator of plant stress, and uses the ratio between two wavelengths of light that indicate the presence of the pigment xanthophyll, and lack of chlorophyll, which is degraded when the leaf becomes senescent. Xanthophyll is also seen in leaves with certain nutrient deficiencies ("Xanthophylls"). These indices have been important in the assessment of ecosystem health on both the small and large scale.

The recent California drought has been one of the most severe on record, with 62% of the state considered to be in the "extreme" to "exceptional" category (Heim). The drought began in 2012 and has already cost billions of dollars in both agricultural losses and funding for the creation of policies for water conservation. Californians continue to decrease their water

consumption (23.9% between June 1st 2015 and February 29th 2016), but the effects of the drought will be seen for many years after it has ended (Alexander). The area hit the hardest is the Sierra Nevada Range, which covers 39,612 mi^2 of the eastern edge of California. There is a strong need to develop techniques to assess such ecosystems on a large scale in order to determine to what extent their health has declined, as well as what implications that may have for the entire globe.

In order to analyze forests on a scale such as that of the Sierra Nevada Range, a combination of previous techniques should be used to insure accuracy, but allow for large-scale analysis. Combining flux tower data with remote sensing allows for such a study, and one of the variables that best determines an ecosystems health is CO_2 flux. CO_2 flux is the amount of carbon dioxide being taken into, or released from, an ecosystem, and is an indicator of plant photosynthesis and respiration, respectively. CO_2 flux is commonly seen in units of micromols of CO_2 per m^2 per second. Being able to quantify this CO_2 flux using remote sensing would allow an individual to assess how an entire ecosystem may be changing due to a factor such as severe drought. This technique could also determine change over many years with much less cost, time, and effort when compared to the process of collecting field data. In order to estimate CO_2 flux with remote sensing, a variable must be compared to a known flux, such as that from a flux tower. This is the technique used for this study, and is similar to the technique Zang et al. used in their research, where they compared the variable NEE (Net Ecosystem Exchange) from remote sensing to flux tower readings to assess seasonal changes in the CO_2 flux of crops (Zang et al. 40).

Estimating the carbon dioxide exchange between the atmosphere and our forests gives us the opportunity to monitor climate change on a large scale. Assessing how drought affects the ability of plants to take in CO_2 can provide knowledge on what to expect for future droughts, or how plants may respond if a drought continues. It would be expected that the Sierra Nevada Range has experienced a decrease in photosynthetic CO_2 uptake due to the recent California drought, and this decrease can be measured large-scale using remote sensing.

Methods

Figure 1. Footprint (8,149 km^2) of mosaicked June flight lines for dates after 2011. Located in the Sierra Nevada Range in California, USA.

The study area was 8,149 km^2 of the Sierra Nevada Range in California, USA (Figure 1). The temperature range during the times studied was between 4.3 and 32.2 degrees C (Mazzi). Typical soils in this area are Ahwahnee, Auburn, Whiterock, and Auberry ("Sierra Series"). The main tree species in the lower elevation are *Pinus sabiniana* and *Quercus douglasii*, while the mid to upper elevation has mainly *Pinus ponderosa* and *Pinus jeffreyi* ("Sierra Nevada Forests").

Remote sensing data were used from the NEON flight on September 24th 2011, as well as the AVIRIS flights from June 13th 2013, June 3rd 2014, October 3rd 2014, and June 1st 2015. ENVI classic 5.3 was used for analyzing remote sensing data. June flight lines were mosaicked with a total area of 8,149 km^2 for June flights, and 34 km^2 mosaics were made for September / October flights. Each mosaic was subsetted based off of a range of elevation only including 300 m to 3000 m to exclude ranges far above or below those covered by flux towers. Regions of interest (ROIs) were made for the 2013 Rim Fire covering 411.6 km^2.

Three flux towers at various elevations were used in this study. They were located in the San Joaquin Experimental Range (SJER) at 405 m, Ponderosa Pine forest (SOAP) at 1,160 m, and a Sierran Mixed Conifer forest (P301) at 2,015 m in elevation. Each flux tower had a footprint of 150 m x 50 m running West to East. Readings were done at 30 minute intervals starting in 2012. Soil moisture probes, temperature, PAR (photosynthetically active radiation) and CO_2 flux readings were sampled at 30 minute intervals at each tower. Annual soil moisture readings were averaged for three soil probes at each flux tower.

NEE (net ecosystem exchange) was calculated using remote sensing data for the footprint around each flux tower using the variables NDVI (normalized difference vegetation index), PRI (photochemical reflectance index), and PAR (photosynthetically active radiation), and the following equation:

$$NEE = NDVI * (1/PRI) * PAR$$

NDVI and PRI were gathered through remote sensing data, while PAR was gathered from flux tower data. Linear regressions were made between the flux tower reading of CO_2 at the moment the flight took place and NEE. For NEE values close in time and space, CO_2 and temperature readings were extrapolated for more discrete readings. PAR was further estimated based on flux tower readings, and was adjusted via remote sensing data containing the angle of the sun and slope of the ground (cosine), as well as the elevation at each pixel. A polynomial regression line between PAR and elevation was found using PAR at each flux tower during the flights and elevation gathered from remote sensing. The final linear regression equations were used to calculate CO_2 flux per pixel for each mosaic over the entire area. CO_2 flux for the 2013 Rim Fire was estimated separately for June 2013, 2014 and 2015 flights.

Results

Linear Regressions

It was seen that two linear regressions existed between NEE vs. CO_2 separated by temperature induced stress. After distinguishing between periods of high and low heat-stress, data taken when temperatures were above 23.5 degrees C (high stress) had an R^2 value of 0.81, while temperatures below 23.5 degrees C (low stress) had an R^2 value of 0.83 (Figure 2). Temperatures above 23.5 degrees C took place during the following flight lines: September 24th 2011, October 3rd 2014, and June 1st 2015. Temperatures below 23.5 degrees C took place during the June 13th 2013 and June 3rd 2014 flight lines.

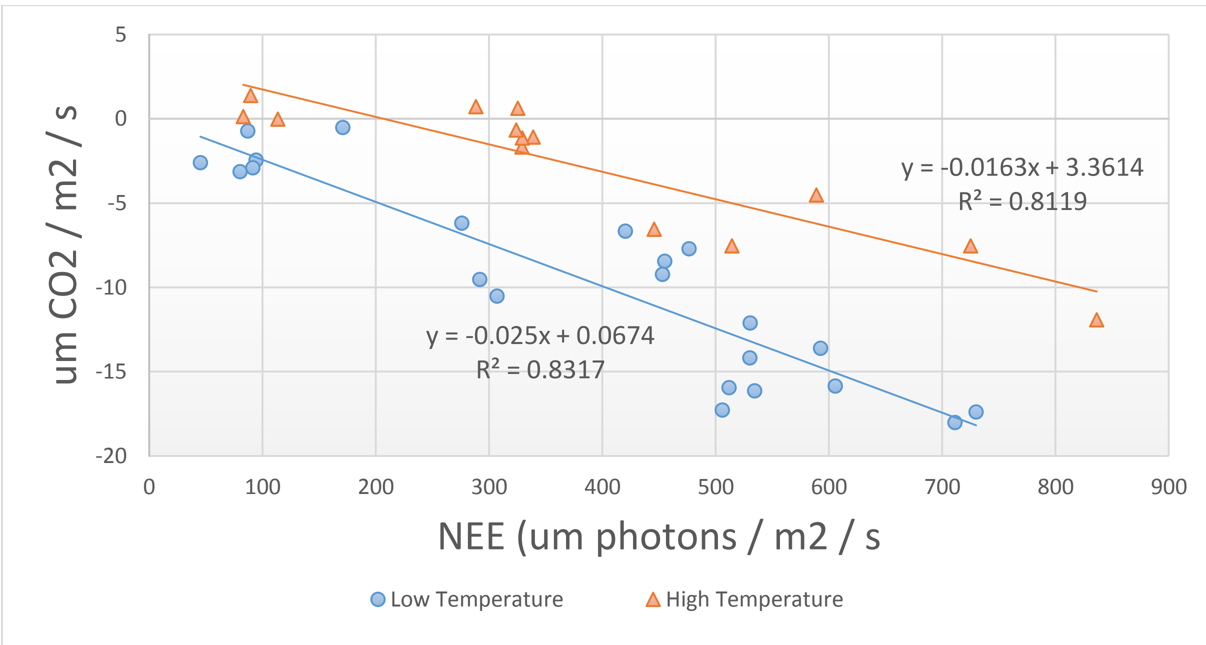

Figure 2. Remote sensing NEE (um photons / m^2 / s) vs. flux tower CO_2 flux (um of CO_2 / m^2 / s) for high (>23.5 degrees C) and low (<23.5 degrees C) temperatures in the Sierra Nevada Range.

CO_2 Flux Estimates

There was a 25% decrease (4.8 g of CO_2 / min) in net carbon fixation over an area of 34 km^2 between September 24th 2011 and October 6th 2014 (Figure 3). There was also a decrease in net carbon fixation over 7,737 km^2 of 3,397 g / min (16%) (June 2013 to June 2014), and a decrease of 15,466 (88%) between June 2014 and June 2015. The 2013 Rim Fire region showed a decrease in net carbon fixation of 1,290 g / min (70%) from June 2013 to June 2014. As well as a decrease of 284 g / min (51.5%) between June 2014 and June 2015 (Figure 4).

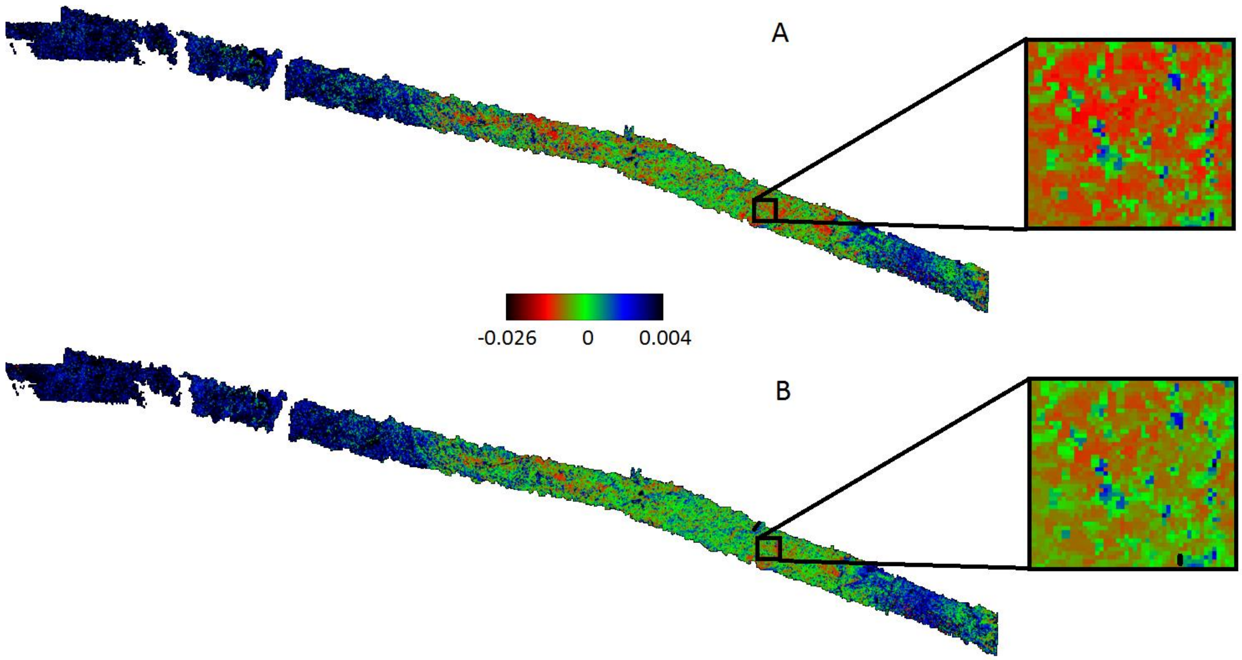

Figure 3. Remote sensing CO_2 flux estimate images from ENVI Classic 5.3 on September 24th 2011 (A) and October 6th 2014 (B). Negative values represent carbon fixation while positive values represent carbon release.

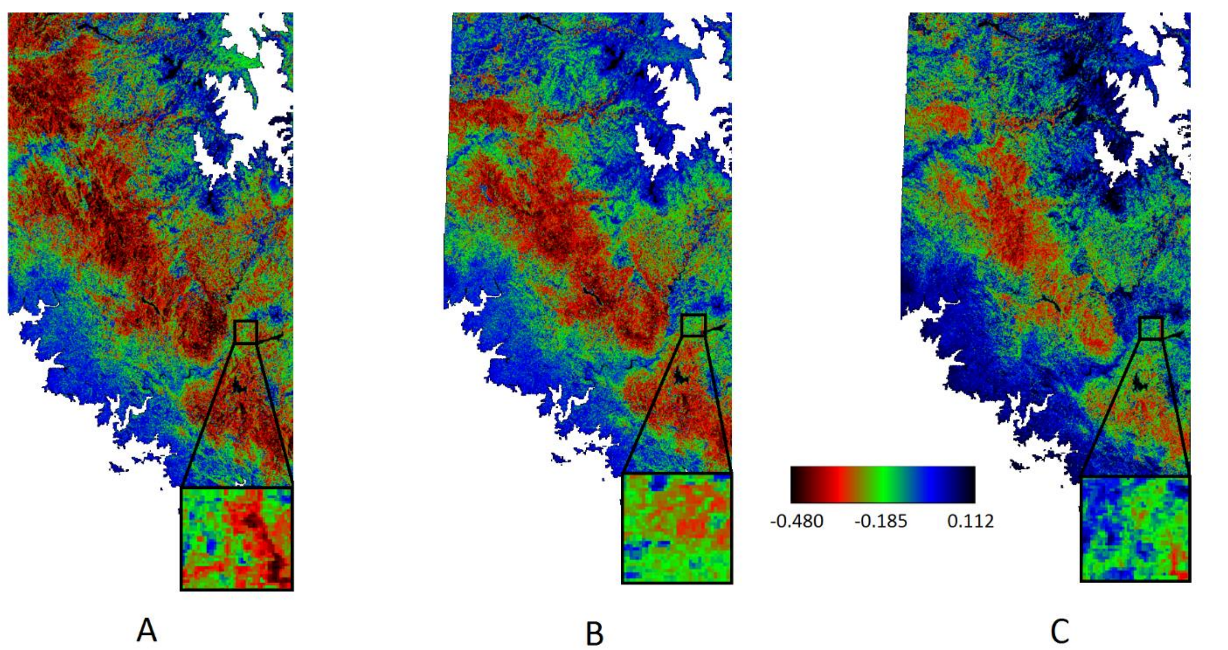

Figure 4. Remote sensing CO_2 flux estimate images from ENVI Classic 5.3 for June 2013 (A), June 2014 (B), and June 2015 (C). Negative values represent carbon fixation while positive values represent carbon release.

Soil Moisture

Average annual soil moisture (m^3 water / m^3 soil) around the SJER flux tower decreased from 2012-2015 from 588.6 to 433.7. Soil moisture at P301 increased from 645.9 to 654.3 from 2012 to 2013, but dropped to 367.2 by 2015. Soil moisture at SOAP decreased from 2012-2014 from 1,102.2 to 757.4, and then increased in 2015 to 962.2 (Figure 5).

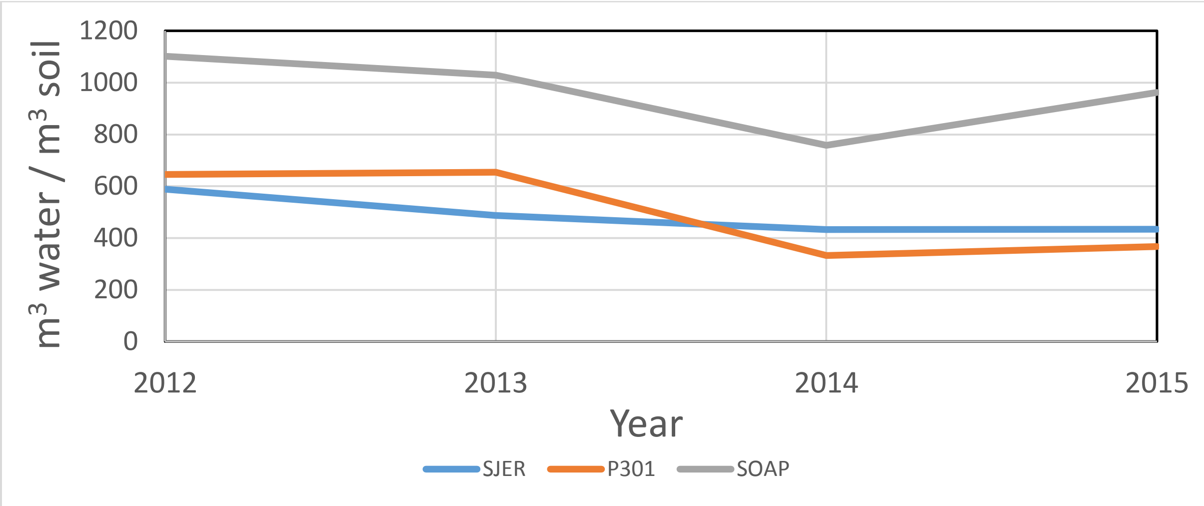

Figure 5. Average annual soil moisture in m^3 water / m^3 soil for each flux tower (SJER, P301, and SOAP) from 2012-2015.

Average Temperature

The average annual temperature for the SJER was 19.8 degrees C in 2012, increasing to 20.8 degrees C in 2013, followed by a decrease to 20.0 degrees C in 2014, and 19.2 degrees C in 2015. At the SOAP flux tower average annual temperature was shown to increase from 11.2 degrees C in 2012, to 15.4 in 2013, and 16.5 degrees C in 2014, with a decrease to 19.2 degrees C in 2015 (Figure 6).

Rain

Cumulative rainfall was gathered from flux tower data for SOAP and SJER flux towers between 2012 and 2015 from January 1st to July 1st. Rainfall was 806.9 mm for 2012, decreased to 294.6 mm in 2013, increased to 336.3 mm in 2014, and then decreased again slightly to 309.9 mm in 2015 at the SOAP flux tower. Rainfall at the SJER flux tower was 273.8 mm in 2012, decreased drastically to 37.1 mm in 2013, increased to 149.8 mm in 2014, and decreased again to 41.6 mm in 2015. (Figure 6).

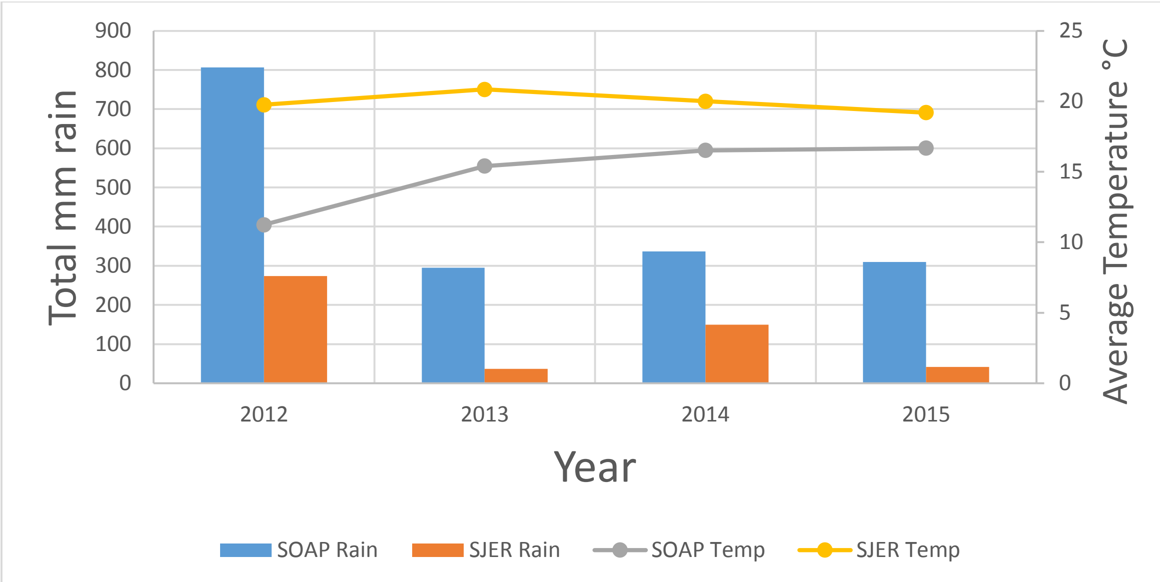

Figure 6. Total rain in mm and average temperature in degrees C, from January 1st and July 1st between 2012 to 2015 at flux towers SJER and SOAP (missing data for P301).

Field Images

Figures 7 and 8 show the partial to complete die-off of plant life at the differing elevations during June 2015 field data collection. Figure 8 shows the mid-upper elevation forest (SOAP and P301), while Figure 7 shows the lower elevation in the San Joaquin Experimental Range (SJER).

Figure 8. Lower elevation (approximately 300 m). Image taken June 22nd 2015.

Figure 8. Mid to upper elevation (approximately 7,000m). Image taken June 24th 2015.

Discussion

Of the two linear regressions found in this experiment, the high temperature stress (>23.5 degrees C) research flights had a slope (-0.0163) that was less negative than the low stress (<23.5 degrees C) research flights (slope of -0.025). This indicates that as the amount of energy from the sun increases (PAR), plants are not increasing their rate of photosynthesis as quickly (Figure 2). One possible explanation for this difference in slope is that as temperatures increase, less water is available to react with CO_2 to produce O_2 and sugars. The high stress regression also had a higher y-intercept (3.3614) when compared to the low stress regression (0.0674). Positive values on the y-axis (CO_2 flux) represent respiration, or CO_2 release, while negative values represent photosynthesis, or carbon fixation. This indicates that during high temperatures plants are respiring more and photosynthesizing less, releasing more CO_2 into the atmosphere. This may be due to plants actively closing their stomata in order to reduce the amount of evaporative water loss that occurs at high temperatures.

High temperatures were seen during the September 26th 2011 and October 6th 2014 flights covering 34 km^2. Using the high-temperature linear regression, it was seen that between these two dates there was a decrease in net carbon fixation of 25.3%. Although a variety of factors can affect CO_2 flux, such as cloud cover and wind velocity, these variables are not always consistent, and therefore have less of an impact over the timespan of these individual flights (approximately 4 hours). This large decrease is likely due large-scale decrease in photosynthesis caused by severe long-term drought.

Low temperatures were seen during the June 13th 2013 and June 3rd 2014 flight lines that covered 7,737 km^2. A decrease in net carbon fixation of 16% was noted between these two dates (Figure 4). Research flights on June 1st 2015 occurred during high temperatures, and therefore a decrease of 88% in net carbon fixation between June 2014 and June 2015 was seen. This drastic decrease is most likely due to the heat stress experienced during the time when the data was collected, and may not be representative of average change in carbon flux between these two years. Approximately 412 km^2 of the 2013 Rim Fire was visualized in the June flight lines, and CO_2 flux estimates were measured separately from the remaining 7,737 km^2 of the mosaics. A decrease in net carbon fixation of 70% was seen between June 2013 and June 2014, as well as a decrease of 51.5% between June 2014 and June 2015. This continued decrease after the initial die-off from the

fire is most likely due to the continued lack of water preventing the recovery of plant life in this area.

Soil moisture probes showed that the average annual soil moisture was the highest at the mid-elevation flux tower (SOAP) (Figure5). This is most likely due to cloud condensation caused by increased elevation and denser, taller forests (Figure 7). Images taken in the field showed forests much less affected by the drought in the mid-upper elevation when compared to the lower elevation (Figures 7 and 8). This is supported by Figure 5, in which SJER shows a decrease of approximately 30% in soil moisture from 2012 to 2013 which continues to decrease until 2015. In contrast, the mid-elevation flux tower (SOAP) shows a gradual decrease in soil moisture, with a sharp decline in 2014, followed by a mild recovery in 2015 (Figure 5). Also in support of the low-elevation being more affected is Figure 6, in which a large decrease in annual rain is seen between 2012 and 2013 at both flux towers, with SOAP having greater than 50% more total rain than SJER, which continued through 2015. The SOAP flux tower slowed a steady increase in temperature from 2012 to 2015, which could have caused plants in this area to close their stomata more frequently, decreasing their evaporative water loss, and prolonging the effects of severe drought (Figure 6). SJER saw a higher average annual temperature of 5 – 10 degrees C when compared to SOAP, which could account for a larger loss of water due to evaporation from both plants and soil, as well as a decreased rate in photosynthesis from high-temperature stress. These combined data support the visualization of the low-elevation being more severely affected by the California drought.

Conclusion

These data show that the recent severe California drought has had a negative effect on the ability of the plant life in Sierra Nevada Range to undergo photosynthesis. The large decrease in water availability not only causes a short-term drop in carbon fixation through a decrease in photosynthesis, but the prolonged water-stress may have serious effects on the health of the plant life, and may cause mass plant die-offs. It is important to study carbon dioxide flux during times of drought to assess the extent to which the event may be affecting the regions photosynthetic processes. It is also important to continue to study these areas to determine how quickly, if at all, an ecosystem may rebound after regular rainfall has returned. The fact that these drought-stricken forests are taking in less carbon dioxide, and in some cases releasing it into the atmosphere during respiration, may have significant effects on our global carbon budget.

The ability to analyze ecosystem health on a large scale such as the Sierra Nevada Range is important in furthering our understanding of Earth systems. The pressing issue of global climate change is calling for more advanced technologies to better predict what effects increased global temperature may have on this planet. Estimating carbon dioxide flux on these ecosystem scales may lead to more accurate assessments of carbon sinks and sources, and what effect these have on the global carbon budget. Further studies in which CO_2 flux is estimated in Earth's forests are necessary in order to obtain an understanding of the impact these systems have on the carbon cycle.

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