Impacts of ozone air pollution and temperature extremes on vegetation density and ecosystem health

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1.Introduction

Ozone, a molecule making up of three oxygen atoms, is a phytotoxic greenhouse gas which has accumulated more than threefold from pre-industrial concentration at the Earth surface [*Lombardozzi et al.*, 2015]. It can be found in both the stratosphere (90%), a layer of the upper atmosphere, and in the troposphere (10%), the lowest layer of the atmosphere. Stratospheric ozone forms naturally under photodissociation of oxygen and shields the Earth surface from harmful ultraviolet radiation. Tropospheric ozone predominantly originates from photochemical reactions of methane (CH4), volatile organic compounds (VOCs) and nitrogen oxides (NOx), which are largely released to the atmosphere from anthropogenic emissions, such as combustion of fossil fuels in power plants and mobile vehicles [*Ainsworth et al.*, 2012]. Natural vegetation also produces biogenic VOCs [*Krupa andManning*, 1988].

Surface ozone, which is unstable and highly reactive, is a harmful air pollutant to human health and the environment [*Ainsworth et al.*, 2012]. Breathing in ozone can reduce lung function and trigger different health problems like coughing and chest pain. An estimated 0.7 million deaths annually are attributed to anthropogenic ozone pollution [*Anenberg et al.*, 2010]. On the other hand, surface ozone has significant negative impacts on crop yields [*Ashmore*, 2005] with an estimate of global economic loss from $14 billion to $26 billion [*VanDingenen et al.*, 2009].

Different effects of ozone on vegetation are summarised in Table 1. Arrows represent that individual variables changes due to ozone exposure increase or decrease. Black arrows indicate agreement among a wide range of studies while white arrows indicate less certain results. Many studies showed that ozone reduces photosynthesis, tree biomass and crop yield. The complicated ozone-mediated biogeochemical feedbacks on plants are not fully understood [*Ainsworth et al.*, 2012]. Plants may reduce their stomatal conductance to minimise the damage to internal tissues when ozone concentration is high, which will, in turn, lower photosynthetic activity [*Reich and Amundson*, 1985] and foliage density [*Ainsworth et al.*, 2012]. Thus, the deposition of ozone into plants through stomata is reduced. Closing stomata may protect plants from some ozone damage, but, as the ambient ozone concentration accumulates, such mechanism may not be sufficient to offset the damage and plant physiology will be affected.

Variable	O_3 Effect
Visible injury	⇧
Photosynthesis	⬇
Stomatal conductance	⇩
Dark respiration	⇧
Tree biomass	⬇
Crop yield	⬇
Root growth	⇩
Decomposition	⇩
Nitrogen uptake	⇩

Table 1 Summary of ecosystem-level ozone effects (extracted from Felzer et al [2007])

According to Sadiq *et al* [2017], both biogeochemical and biogeophysical feedbacks play an important role in controlling surface ozone concentration. In Figure 1, decreased LAI leads to lower transpiration rate, which may reduce latent heat flux. So, the surface temperature will increase and enhance ozone formation through increased isoprene emission from vegetation under high NOx abundance. On the other hand, rising temperature will increase LAI through promoting photosynthetic rate. We are interested in how temperature, ozone concentration and LAI are interrelated in these feedback mechanisms.

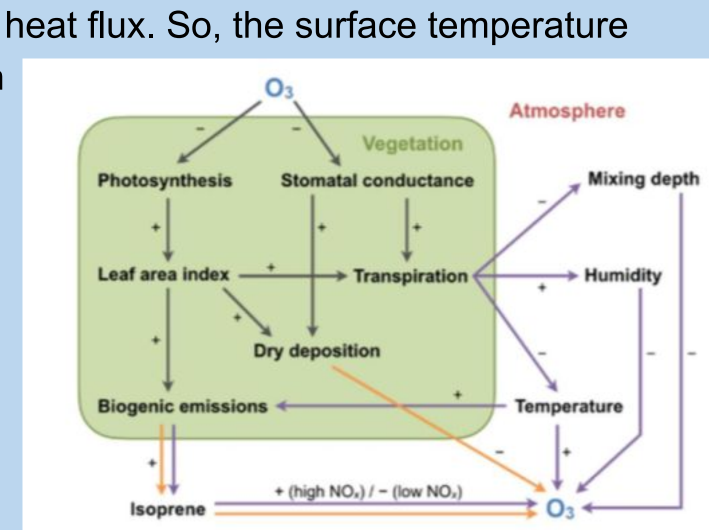
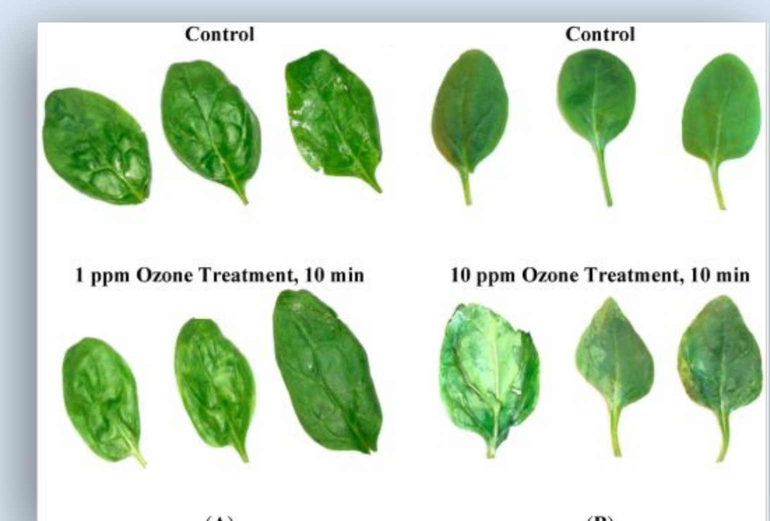


Figure 1 Ozone-vegetation coupling and feedbacks (extracted from Sadiq *et al* [2017])

(A) Impact of ozone exposure levels on visual quality of spinach when treated at 1 ppm ozone concentration for 10 min
(B) Ozone injury / visual damage on spinach when exposed to 10 ppm ozone concentration for 10 min



2. Methodology

We developed a Partial Derivative Linear Regression model to extract the true sensitivity of Ozone on LAI, which is defined as the response of vegetation to ozone after removing temperature as the dominate confounding variable.

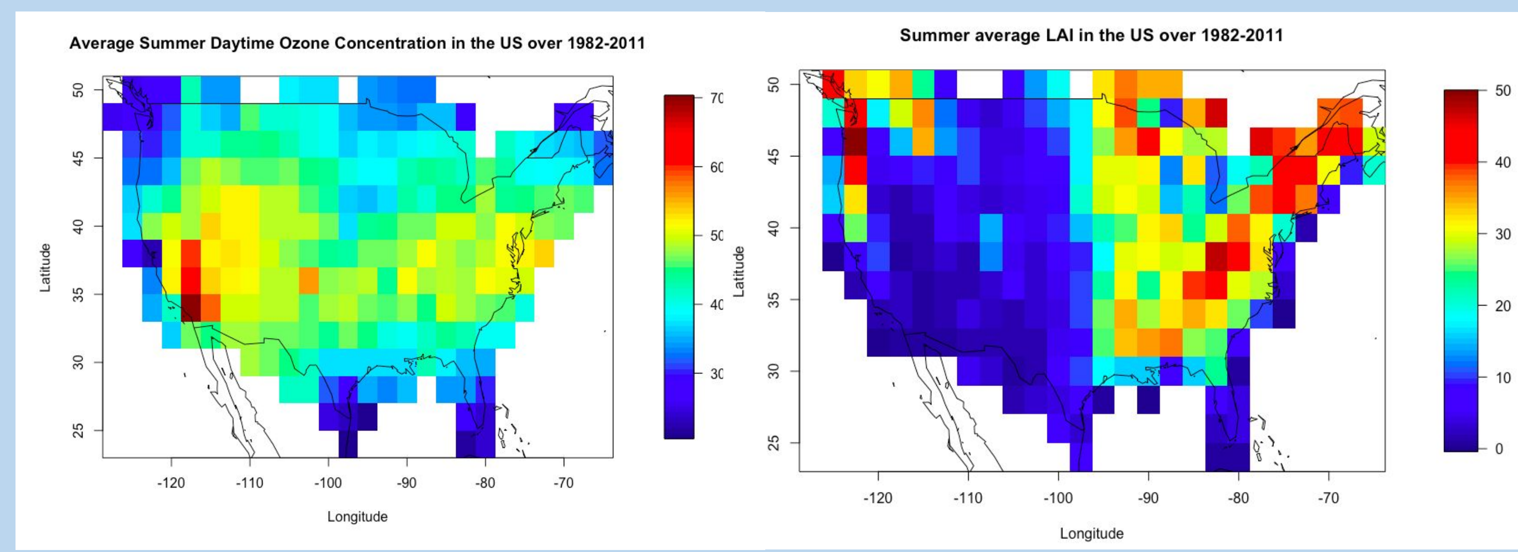
$$\frac{d\ln L}{d[O_3]} = \frac{\partial \ln L}{\partial [O_3]} + \frac{\partial \ln L}{\partial T}\cdot\frac{dT}{d[O_3]}$$

$$\frac{\partial \ln L}{\partial [O_3]} = \frac{d\ln L}{d[O_3]} - \frac{\partial \ln L}{\partial T}\cdot\frac{dT}{d[O_3]}$$

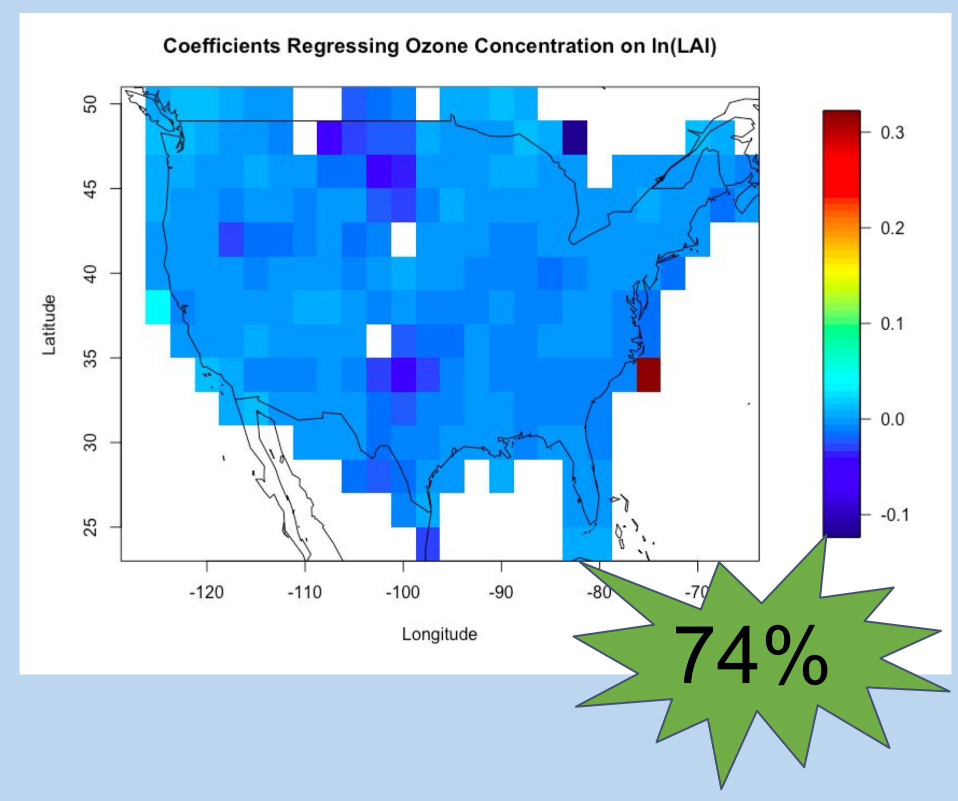
3. Data Analysis

Ozone

Comparing the Ozone and LAI plots in the United States, we observed that areas where ozone concentration were high, LAI index were below average in general and vice versa.

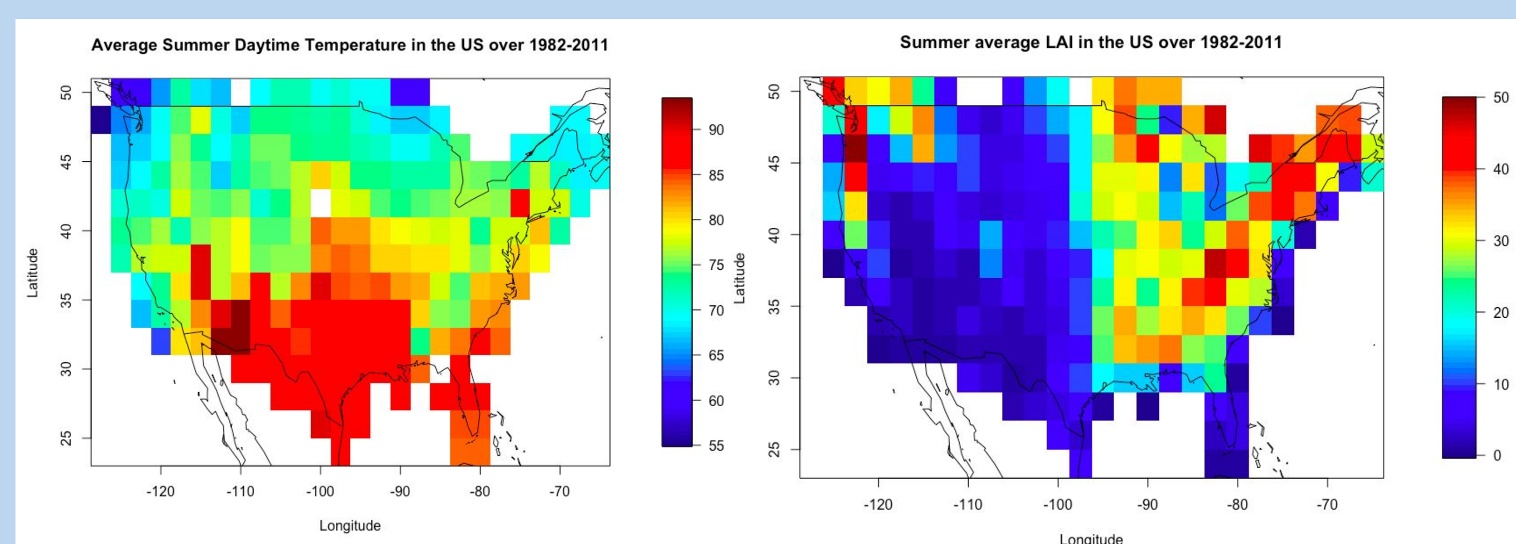


In addition, we regressed ozone concentration on ln(LAI) using orthogonal regression. The result were significant because over 70% of the United States have negative coefficients, meaning that when ozone concentration increases in these areas, LAI decreases as consequence. However, this relationship included hidden confounding variables and cannot explain the true response of vegetation density on ozone.

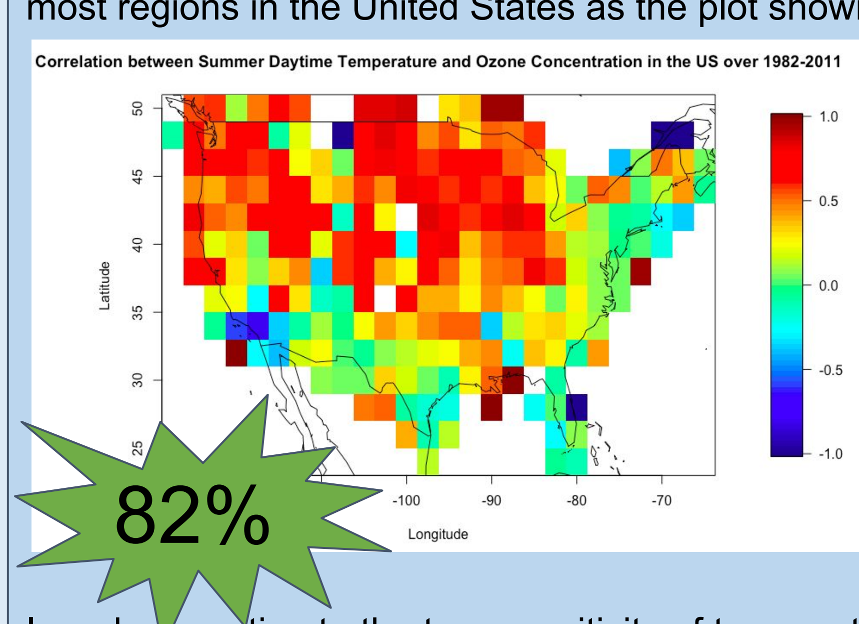


Temperature

Comparing the Temperature and LAI plots in the United States, we observed similar patterns of ozone and LAI. Areas where temperature were over 80°F, LAI index were among the lowest in the United States.

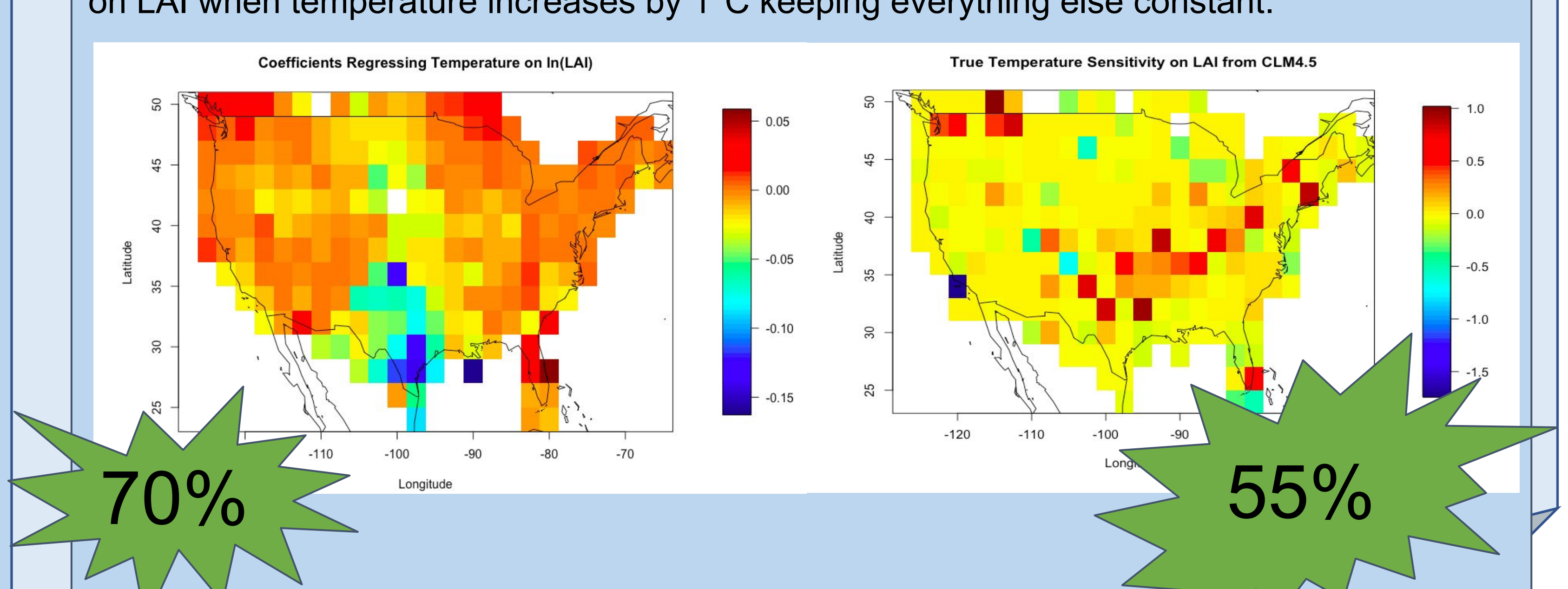


In order to prove and validate our observations, we calculate the correlation between average temperature and ozone concentration in the United States during summer time from 1982-2011. As expected, temperature and ozone concentration were highly correlated in most regions in the United States as the plot shown below:

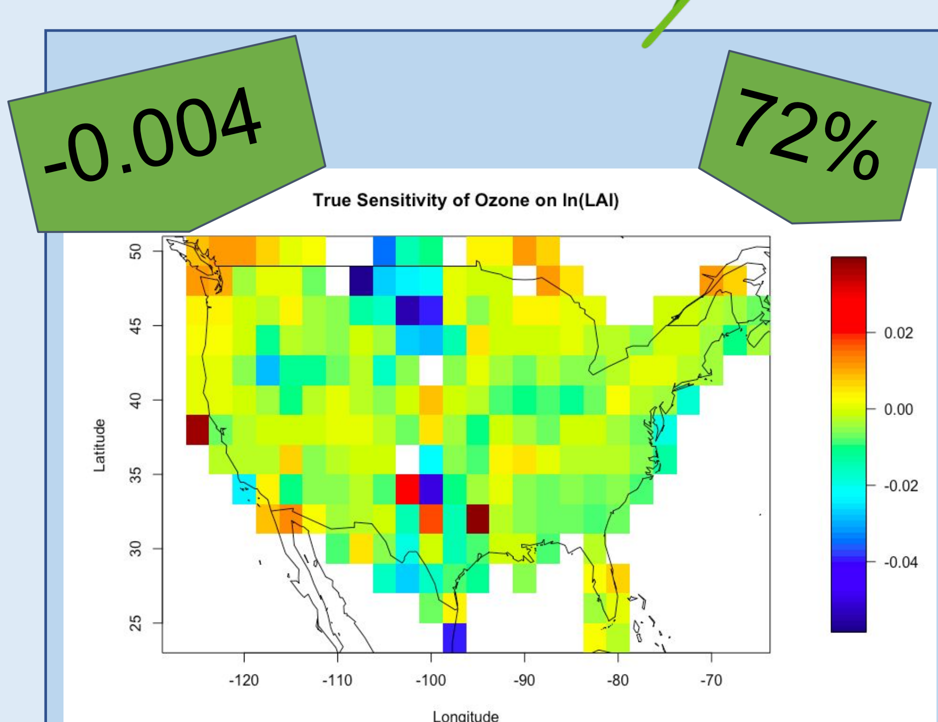


In addition, we regressed temperature on ln(LAI) using orthogonal regression. 70% of the regions in the United States have negative coefficients suggesting that when temperature increases in these regions, LAI decreases as a result. In fact, this relationship also included confounding variables.

In order to estimate the true sensitivity of temperature on LAI for our partial derivative model, we ran an experiment through the Community Land Model (CLM4.5) to simulate the effect on LAI when temperature increases by 1°C keeping everything else constant.



4. Result



Result shows that ozone reduced vegetation density after removing temperature effect in most regions in the United States. Some regions in Texas and northern US have extreme positive relationships between ozone and ln(LAI) but those are rare cases. This research provides a new perspective of how ozone impacts vegetation density during summer daytime in the United States.