Plant vs. environmental influences on soil respiration in a mixed-grass prairie under cattle grazing: A path analysis

X. Dong[1], P.E. Nyren[2], B.D. Patton[2], M.A. Liebig[3],
A. Chatterjee[4], L.J. Cihacek[4]

1:Texas A&M AgriLife Research, Uvalde, TX (Email: xuejun.dong@ag.tamu.edu)
2:North Dakota State University, Central Grasslands Research Extension Center, Streeter, ND
3:USDA-ARS, Mandan, ND
4:North Dakota State University, Department of Soil Science, Fargo, ND

Introduction

Despite heavy study in past decades, soil respiration and its regulation in agricultural fields are not well understood. This is primarily due to the fact that soil respiration is influenced by multiple factors operating at different time/spatial scales in the soil-plant system. Novel methods combining field experimentation and statistical testing are needed for improved understanding. Using field-measured soil respiration rates and a path analysis-based permutation resampling, we wanted to clarify to what extent soil respiration in a grazing rangeland was influenced by plant growth and by environmental factors.

Materials and methods

The study was conducted at the Central Grasslands Research Extension Center, Streeter, ND. The site locates in a mixed-grass prairie under long-term moderate and heavy grazing by beef cattle. Within one moderate and one heavy grazing pasture, a land area of 15×15 m^2 in dimension was selected and fenced. Within the fenced area a rain-out-shelter 3×6 m^2 in dimension was constructed for drought treatment and soil trenching was done to a depth of 1 m to exclude the contribution of plant live roots to soil respiration (Figure 1). Sixteen permanent soil collars were installed in both the trenched and untrenched plots and soil respiration rates were measured weekly during the growing seasons from 2007 to 2011. Volumetric water content and soil temperatures at 2.5 cm and 10 cm soil depths were measured using a set of ECHO sensors and T-type thermocouples connected to a CR3000 and a CR10X datalogger in a moderate and heavy grazing site, respectively. Leaf area index (LAI) was measured multiple times using a LP-80 Ceptometer (Decagon Devices, Inc.) during the growing season and appropriate data interpolation methods were employed to estimate seasonal dynamics of LAI. Within the fenced area, vegetation was clipped to mimic cattle grazing. Soil respiration rates were linked to plant variable LAI and environmental variables (soil temperature and moisture) through a path model and the bootstrap resampling was used to test the plant vs. environmental influences on soil respiration.

Figure 1. Field plot in the heavy grazing site, showing two trenched sub-plots (with neutron probe tubes and respiration collars) and two untrenched ones in between under natural (control) conditions, as well as a partial view of the 3×6 m^2 rain-out-shelter.

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Seasonal dynamics of leaf area index

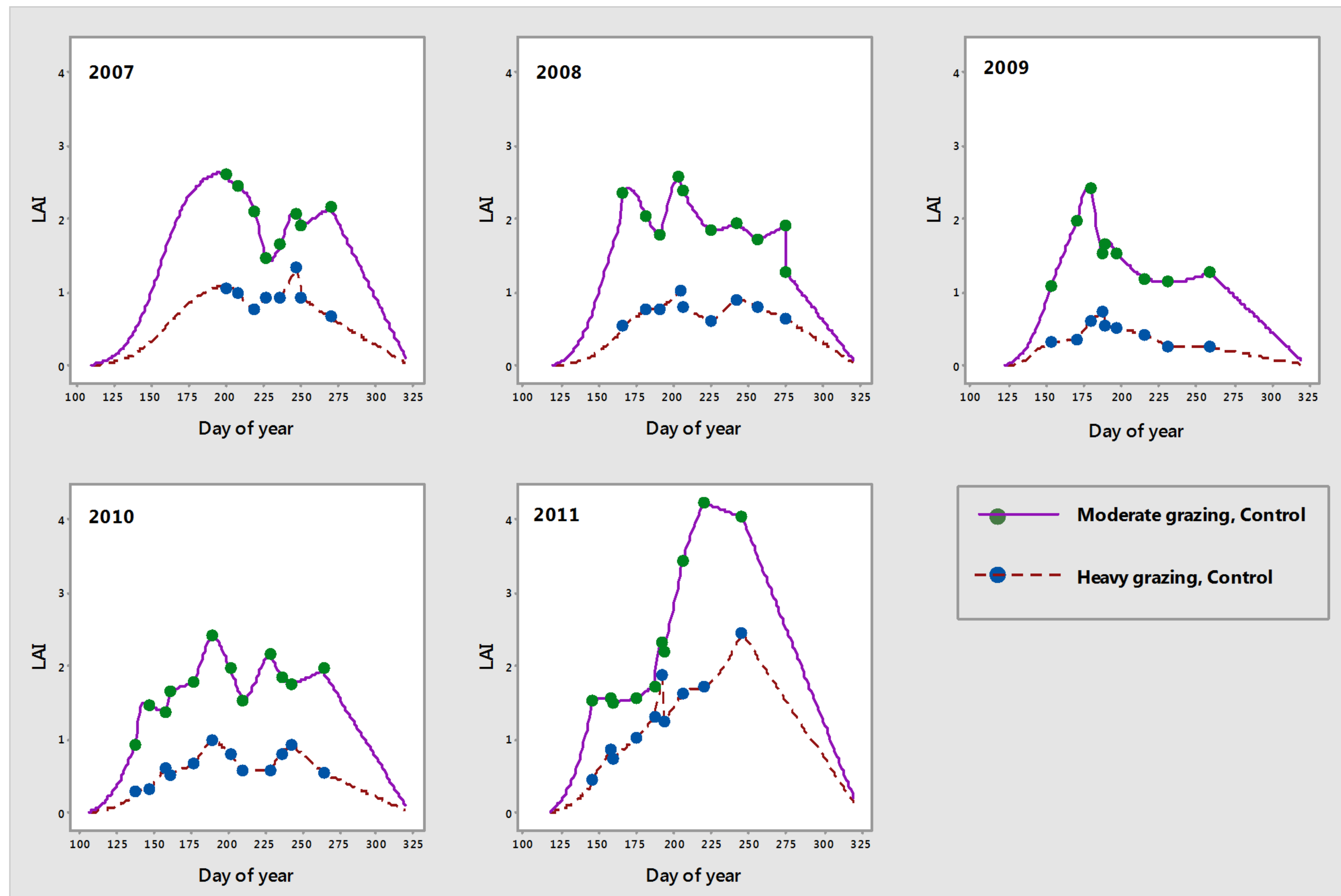

Figure 2. Measured and estimated daily values of leaf area index (LAI) under natural (control) conditions in a moderate and a heavy grazing sites from 2007 to 2011. LAI was assumed to present during days when the soil temperature at 5 cm depth was higher than 0 °C. Values prior to first measurement during a season was assumed to follow a sigmoidal growth curve and those after last day of measurement decrease linearly to zero on last day of above 0 °C soil temperature.

Path models of soil respiration rates

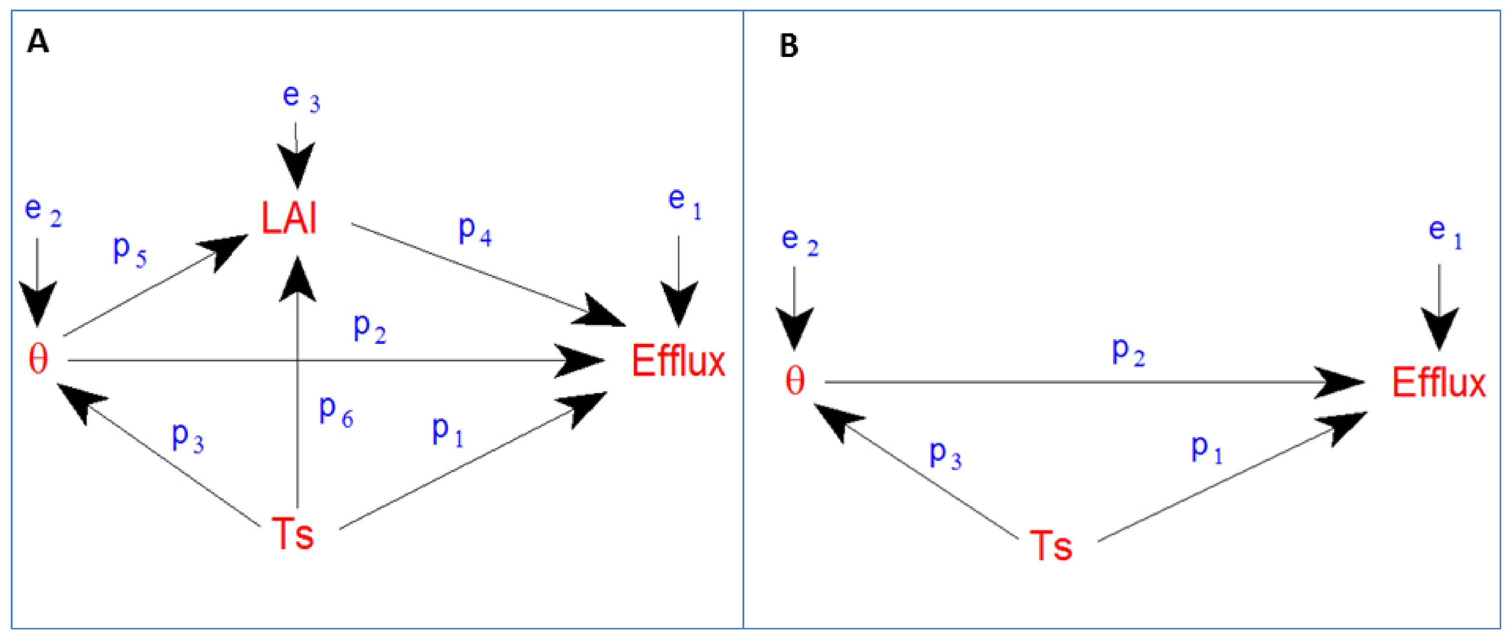

*Figure 3. The relationship between soil respiration and two environmental (soil temperature, Ts, and moisture, θ) and one physiological variable (LAI) was formulated as a path regression model, as shown in (**A**) for the untreched plots and (**B**) trenched plots (maintained vegetation-free by frequent clippings). In the untrenched plots (**A**), there were three structural equations to be solved:*

$E = p_1T + p_2\theta + p_4L + e_1$
$L = p_6T + p_5\theta + e_3$
$\theta = p_3T + e_2$

*In the trenched plots (**B**), there were two equations to be solved:*

$E = p_1T + p_2\theta + e_1$
$\theta = p_3T + e_2$

In the above, abbreviations 'E', 'L' and 'T' represent 'Efflux', 'LAI' and 'Ts', respectively. All the error terms (e_1, e_2, e_3) represent influences from other unknown sources on the dependent variables. In order for the path coefficients to be directly comparable, all the variables (dependent and independent) must be standardized before being used in the path models.

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Results: Path and effect coefficients

Table 1: Path coefficients obtained by fitting the path models in Figure 3 to the measured sol respiration data from 2007 to 2011. Also shown are the effect coefficients, which include both the direct and indirect effects of a variable on soil respiration rate (**bold**).

Trenching	Water.	Grazing	p_1	p_2	p_3	p_4	p_5	p_6	e_1	e_2	e_3	**LAI**	θ	**Ts**
U†	Drt.	Hea.	0.269	0.572	-0.069	0.408	0.054	0.352	0.699	0.997	0.912	**0.408**	**0.594**	**0.371**
		Mod.	0.227	0.404	-0.075	0.346	0.244	0.178	0.702	0.998	0.930	**0.346**	**0.488**	**0.252**
	Ctr.	Hea.	0.589	0.487	-0.212	0.258	-0.161	0.231	0.647	0.975	0.919	**0.258**	**0.446**	**0.554**
		Mod.	0.348	0.389	-0.159	0.419	-0.132	0.314	0.786	0.992	0.914	**0.419**	**0.333**	**0.427**
T	Drt.	Hea.	0.214	0.358	-0.024	-	-	-	0.881	0.999	-	-	**0.358**	**0.205**
		Mod.	0.395	0.446	-0.179	-	-	-	0.791	0.988	-	-	**0.446**	**0.315**
	Ctr.	Hea.	0.619	0.216	-0.217	-	-	-	0.789	0.984	-	-	**0.216**	**0.573**
		Mod.	0.402	0.085	-0.184	-	-	-	0.878	0.988	-	-	**0.085**	**0.386**

†Abbreviations: 'U' - 'Untrenched'; 'T' - 'Trenched'; 'Drt.' - 'Drought'; 'Ctr.' - 'Control'; 'Hea.' - 'Heavy grazing'; 'Mod.'- 'Moderate grazing'.

Hypotheses motivated by path coefficients

- *Hypothesis 1: Is physiological control of efflux more prominent under moderate grazing than under heavy grazing?*
  - Result: We tested this hypothesis separately for control and drought conditions. In each case, the fraction of 'effect' coefficient for LAI out of the total effect coefficients of LAI, θ and Ts was considered as observed critical value, k. Then we ran the path model 2000 times, each based on one resample (without replacement) from the pooled data of control ($k = 0.355 - 0.205 = 0.15$) and drought ($k = 0.319 - 0.297 = 0.022$) treatments under particular grazing regimes. This was to see if the observed k values could have happened purely by chance. The answer for Hypothesis 1 was **YES** for natural (control) condition ($p = 0.0005$), but **NO** for drought treatment ($p = 0.316$).
- *Hypothesis 2: Does the effect of Ts dominate that of theta under natural condition but reverse holds under drought condition?*
  - Result: We tested this hypothesis under moderate and heavy grazing treatments with trenched and untrenched conditions. The test statistic was $k = P_{\theta,ctrl}/P_{Ts,ctrl} \times P_{Ts,drt}/P_{\theta,drt}$. Under trenched conditions, k for moderate site was $0.22 \times 0.71 = 0.156$, and the like value for heavy site was $0.377 \times 0.573 = 0.216$. Based on 2000 resamples drawn from the original pooled datasets, the answer for Hypothesis 2 was found to be **YES** for both moderate ($p < 0.0001$) and heavy ($p = 0.002$) sites. The answer was also **YES** for untrenched conditions with moderate ($k = 0.78 \times 0.516 = 0.403, p = 0.0075$) and heavy ($k = 0.625 \times 0.805 = 0.503, p = 0.0045$) grazing.
- Implications: Soil moisture strongly dictates which factor(s), physiological or environmental, dominate the regulation of soil carbon efflux in the mixed-grass prairie, even though plants maintained higher vigor under moderate grazing than under heavy grazing. Under drought situation, soil moisture was a dominant factor influencing soil respiration (Figure 4).

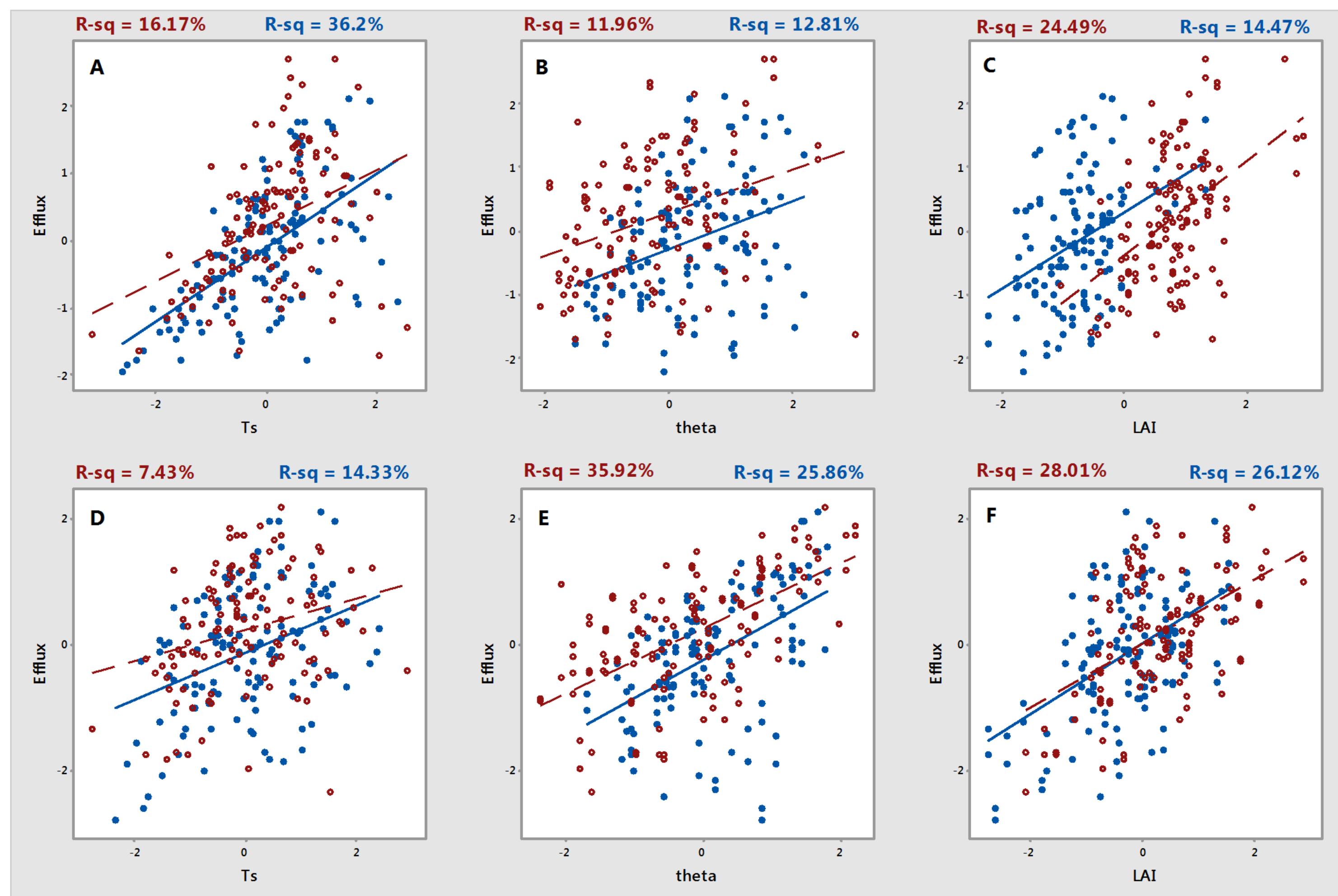

*Figure 4. Scatter plots of soil respiration rate against soil temperature (Ts), moisture (θ) and leaf area index (LAI) under untrenched natural (**A**, **B**, **C**) and drought (**D**, **E**, **F**) plots, based on data measured from 2007 to 2011. Blue dots and brown circles indicate data values for heavy grazing and moderate grazing, respectively. Also shown are the R-square values from the individual linear regressions. All data were standardized.*