Deforestation effects on land surface energy coupling: a data-driven perspective

Y. Zhu, R. H. Zong, and T. Y. Zhang

***Abstract*—** Deforestation dramatically alters land surface properties and functions through multiple biogeophysical and biogeochemical pathways. However, a quantitative identification of how deforestation affects local energy-water-vegetation coupling is still challenging. In this study we employed information theory and transfer entropy framework to identify the overall feedback pattern of land surface water-energy-vegetation coupling, using high frequency eddy covariance measurements at forested versus deforested sites. We found that deforestation strengthened the directional influence of atmospheric demand on land surface water flux, and more importantly, deforestation broke the coupling between vegetation activities and local precipitation, which led to a less efficient ecosystem to recycle and maintain water within this system.

***Index Terms*—** deforestation, surface energy balance, water-energy coupling

I. Introduction

Deforestation is one of the major ecosystem disturbances that induced by anthropogenic activities such as agriculture expansion [1]. Through directly removing land surface forest cover and converting to grass or crops that have totally different biogeophysical and biogeochemical properties, deforestation alters land surface energy, water, and vegetation dynamics as well as their complicated interactions. Furthermore, the impacts could propagate through the coupled system, which affect environmental conditions and climate dynamics at regional and global scale through teleconnection [2]. In order to better evaluate the consequence of large-scale deforestation, and to build a reliable climate model, it is critically important to gain a deeper understanding of the interaction between land surface vegetation cover and the atmosphere.

The original idea that vegetation cover (such as forest) might exert a strong control on land surface energy coupling came from Plinky the Elder in the first century AD, who claimed that deforestation of Mount Himus led to both hydrological and meteorological changes. During the recent decades, considerable numbers of hydrologists, climatologists and biologists devoted to the research of coupling paradigm between the vegetation and the atmosphere, which generated a number of reviews and syntheses of these interactions [3]. Emergent patterns of these coupling have been studies via establishing relationship between land state/fluxes and atmospheric state/fluxes, however previous work mainly relied on either land surface models that potentially have large uncertainties or land surface flux/state measurements using simple linear regression [4].

The understanding of how deforestation affects land surface water, energy, and carbon cycle coupling is complicated by the fact that 1) lack of statically reliable approach to identify non-linearly system feedback for a vegetation-atmosphere coupling; 2) difficulties to differentiate coupling paradigms between forested and deforested sites at a systematic perspective with low frequency and non-continuous measurements of surface fluxes. We overcame those difficulties by first employing high-frequency (half-hourly), continuous, and high-precision eddy covariance measurements at paired forested and deforested sites and then applying well-developed information theory that is appropriate for non-linear feedback identification.

II. Methodology

A. Data

In this study we employed high frequency eddy covariance (EC) [5] measurements of ecosystem carbon, water and energy fluxes. As a matter of fact, many other alternative approaches, such as gradient method have been proposed and applied to observe the high frequency turbulence fluxes within a vegetated land surface during the last decades. However, the intense but intermittent characteristics of the fluxes, together with the complex system dynamics, make them inapplicable. EC is a direct method that measures the vertical turbulent momentum with a minimal influence on the environment. Here we considered EC measures of 1) latent and sensible heat (Fig. 1a, 1f), 2) plant photosynthesis (Fig. 1b), 3) shortwave radiation, precipitation, temperature and vapor pressure deficit (Fig 1c, d, e, g) as background environmental conditions. In addition, an integrated variable, evaporative fraction (EF, Fig 1h) [6] is calculated as:

$$EF = \frac{LE}{LE + SH} \tag{1}$$

where LE and SH are observed latent and sensible heat fluxes, and resultant EF represents the partitioning of surface energy fluxes into water pathway and heat pathway [7].

In order to study the deforestation effects on land surface energy and water coupling, we selected paired EC sites that experience the same background climate (temperature, precipitation, solar radiation) while have completely different water and energy effluxes as well as vegetation activities. Site IT-CA1 (E 12.02, N 42.380, blue line in Figure 1) and

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site IT-CA2 (E 12.02, N 42.377, red line in Figure 1) are deciduous broadleaf forest and grassland site, respectively. We first integrated the half-hour flux data into a daily temporal resolution from 2011 to 2014, and fed them into our causality identification framework (see Section 2.2)

B. *Modeling*

The statistical framework we used to analyze the coupling strength and direction within the vegetated land surface is called transfer entropy [8], which is an advanced methodology for time series analysis. Previous work also demonstrated this approach worked much better than Granger causality framework under non-linear condition. Based on information theory, the amount of information (H) encoded in a specific time series could be calculated as:

$$H(x) = \sum_{i=1}^{n} p(x_i)\log_2 p(x_i) \tag{2}$$

where x, y are two different time series of interest, xi and yi represent instance within each time series. The physical meaning of entropy is uncertainty. Further, the information entropy of variable X, given another variable Y, called the conditional information entropy could be calculated as:

$$H(X|Y) = -\sum_{y_i}\sum_{x_i} p(x_i,y_i)\log_2 \frac{p(x_i,y_i)}{p(y_i)} \tag{3}$$

where p(x,y) denote joint probability distribution of X and Y. Given conditional information entropy, we can readily derive the joint information entropy of X and Y as:

$$H(X,Y) = H(Y) + H(X|Y) = -\sum_{y_i}\sum_{x_i} p(x_i,y_i)\log_2 p(x_i,y_i) \tag{4}$$

In this study, the most essential statistical quantity is the Transfer Entropy (TE) that quantifies the reduction in the Shannon entropy of time series Y by knowledge of X at time lag t, which is additional to the reduction of entropy because of knowledge of the previous history of time series Y. The transfer entropy can be obtained as the following by combining Eqn. 2-4:

$$T(X>Y,\tau) = H(X_{t-\tau},Y_{t-\omega}) + H(Y_t,Y_{t-\omega}) - H(Y_{t-\omega}) - H(X_{t-\tau},Y_t,Y_{t-\omega})$$
$$= \sum_{x_\tau,y,y_\omega} p(x_\tau,y,y_\omega)\log_2 \frac{p(y|x_\tau,y_\omega)}{p(y|y_\omega)} \tag{5}$$

where w is set to one to represent one time step previous history of time series Y. With this transfer entropy statistical framework, we analyzed EC measurements of LE (latent heat), GPP (photosynthesis), FSDS (solar radiation), Prcp (precipitation), T (Temperature), SH (sensible heat), VPD (vapor pressure deficit) and EF (evaporative fraction) to reveal the direction and magnitude of systematic coupling and feedbacks, at grassland site versus forest site.

III. RESULTS

We focused on the feedback patterns among latent heat, Gross Primary Production (GPP or photosynthesis rate), short wave radiation, precipitation, temperature, sensible heat, atmospheric vapor pressure deficit, and evaporative fraction. Pairwise correlation analysis showed a significant correlation between latent heat and GPP (Figure 2, R2 at grass site is 0.87, forest site is 0.65), although correlation doesn't necessarily be equal to causality. Also shortwave radiation was positively correlated with sensible heat flux (Figure 2, R2 at grass site is 0.75, forest site is 0.83). Sensible heat flux also negative correlated with evaporative fraction (R2 at grass site is -0.82, forest site is -0.93)

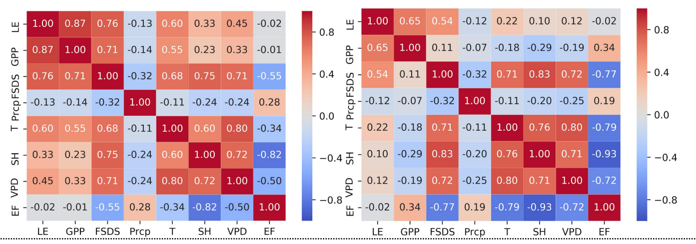

Figure 2. Pairwise linear correlation among observed variables at grass site (left panel), and forest sites (right panel).

Correlation analysis revealed straightforward pairwise linear interactions, however did not imply the direction of the interactions (or feedbacks). To this end, our transfer entropy analysis further showed that overall land surface energy-water-vegetation coupling was generally consistent at forested and deforested sites (Figure 3). Specifically, shortwave radiation (FSDS) exerted a first order control on the system coupling (largest green node means highest gross information production that affect the coupled system), while precipitation (Prcp) was somehow less important in determining the magnitude and direction of the system feedbacks (smallest node).

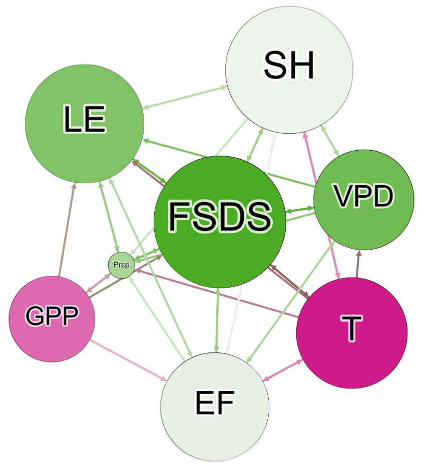

Figure 3. System interaction map of land energy-water-carbon coupling (coupling direction and magnitude).

However, deforestation indeed modified some sub-components of the coupled system, although not the overall structure. For example, deforestation imposed a strong directional impact from atmospheric VPD on latent heat flux, which meant after deforestation the land surface was directly exposed to atmosphere and the water flux likely more controlled by atmospheric dryness. Such a small change of coupling paradigm could lead to a deforested land surface that was much more vulnerable to the change of atmospheric moisture condition than forested land surface. Another identified significant impact of deforestation on land surface water-energy-vegetation coupling was that grass site showed little impact of vegetation activity (GPP and LE) on local precipitation compared with forested site. It implied that without forest cover, the water movement pathway from soil through vegetation into atmosphere is dramatically suppressed.

IV. Conclusions

As one of the major anthropogenic disturbance, deforestation is expected to dramatically affect land surface properties, biogeophysical and biogeochemical processes. However, quantitatively identification of such changes is challenging. In this study we employed advanced statistical framework based on information theory and successfully identified the overall feedback pattern of land surface water-energy-vegetation coupling paradigm by applying this framework to eddy covariance high frequency measurements at paired forested and deforested sites. Furthermore, we were able to differentiate the coupling paradigms between forested and deforested sites. We found that deforestation imposed a stronger impact of atmospheric moisture demand on land surface latent heat flux, also deforestation broke the close linkage between vegetation activities and local precipitation, which potentially made the land surface be less efficient in recycling water and maintaining the moist climate.

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