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in un Mondo che Cambia

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REPLACING OLD FORESTS WITH YOUNG PLANTATIONS CAN IMPACT SUMMER CONVECTIVE RAINFALL

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KEY POINTS:

- A non-linear relation between Bowen ratio and soil moisture, together with free atmosphere conditions, regulates cloudy/cloudless regimes above land.
- Young trees regulate the persistence of convective conditions enhancing rainfall recycling mechanisms, old trees exert little control.
- Large scale plantation expansion can alter key aspects of the hydrological cycle by modifying land-atmosphere conditions.

1 INTRODUCTION

Forests worldwide represent a major carbon sink and, given that forest losses have strongly contributed to anthropogenic CO₂ emissions (Le Quere et al. 2013), carbon sequestration strategies support tree plantation expansion and afforestation projects (Jackson et al. 2005). As a consequence, over the last 50 years, some regions such as the Southeastern United States (SE-US) exhibited both forest losses and gains (Hansen et al., 2013) with old natural forests being replaced by young fast growing trees (Wear & Greis, 2012). Given the current climate policies and the increasing demand for wood (e.g. for biofuel production), plantation expansion in the SE-US is projected to increase in the coming years (Wear & Greis, 2012; Manoli et al., 2016) but the full environmental consequences of such large-scale land use changes are not fully understood. Jackson et al. (2005) demonstrated that afforestation can impact usable water, increasing soil salinization and decreasing stream flow, thus offsetting the benefits of climate mitigation. Here we use observations from four Loblolly pine (Pinus taeda) plantations in the SE-US together with a zero-order analytical model of the Soil-Plant-Atmosphere (SPA) system to assess whether the proliferation of young plantations replacing old forests can impact key aspects of the hydrological cycle, such as convective clouds formation and rainfall recycling mechanisms.

2 MATERIALS AND METHODS

2.1 Study sites

Observations from four Loblolly pine plantations located in North Carolina, USA, are considered here (see Figure 1 and Table 1). Two sites (C1 and C2) are located in the Coastal region and two sites (P1 and P2) in Piedmont region (Manoli et al., 2016). The first site C1 is a young plantation that was clear-cut in 2004 and replanted in 2005 with two-year-old loblolly pine seedlings, site C2 is a 15-year-old (at the time of monitoring) plantation situated in the lower coastal plain, site P1 is a 22-year-old stand situated within the Duke Forest, and site P2 is an old stand with 35-year-old pines (approximately 30 km northwest of site P1). The two coastal sites (C1-C2) and the old plantation (P2) are treated as a chronosequence (i.e. pine stands of the same species, with comparable hydro-meteorological conditions and soil characteristics but different ages) to investigate the impact of tree age on the partitioning of surface energy fluxes. Sites C2 and P1 have comparable stand age (mature 15-20 year-old pines) but different edaphic conditions and they are used to evaluate the role of soil type (predominantly Belhaven series histosol over coarse sand at site C2, mostly clay at site P1) on SPA interactions. All the sites were instrumented with Eddy covariance systems and soil moisture sensors. Further information on data collection and site characteristics can be found in Manoli et al. (2016).
Figure 1. Case studies: (a) geographic distribution of Loblolly pines in the Southeastern US, location of the study sites (red symbols), and (b) stands age. Conceptual model (modified from Bonetti et al., 2015 and Manoli et al. 2016): (c) predisposition to convective rainfall is defined by the crossing of the Atmospheric Boundary Layer (ABL) with the Lifting Condensation Level (LCL), (d) a surface energy balance is used to determine the partitioning of available energy into sensible ($H_s$) and latent ($LE$) heat and (e) simplified temperature and humidity profiles in the atmosphere are assumed (Porporato 2009).

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Stand Age [yr]</th>
<th>Soil Type</th>
<th>LAI$_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 - Young plantation</td>
<td>Coastal region, NC (USA)</td>
<td>2-5</td>
<td>Ultisol/Sandy-loam</td>
<td>4.1</td>
</tr>
<tr>
<td>C2 - Coastal plantation</td>
<td>Coastal region, NC (USA)</td>
<td>15</td>
<td>Histosol/Sandy-loam</td>
<td>5.6</td>
</tr>
<tr>
<td>P1 - Duke Forest</td>
<td>Piedmont region, NC (USA)</td>
<td>22</td>
<td>Clay</td>
<td>5.8</td>
</tr>
<tr>
<td>P2 - Old plantation</td>
<td>Piedmont region, NC (USA)</td>
<td>35</td>
<td>Sandy-loam</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 1. Study sites: location, tree age, soil type, and maximum leaf area index (LAI$_{max}$). Additional information can be found in Manoli et al. (2016).

2.2 Model description

The main precipitation mechanism likely to be impacted by large-scale land cover changes in the SE-US is convective rainfall, i.e. rainfall generally occurring during summer as a result of ecosystem level heat and moisture fluxes (Juang et al. 2007; Bonetti et al., 2015) when they occur on spatial scales much larger than the Atmospheric Boundary Layer (ABL) height (ca. 1000-2000 m). In order to develop a simple analytical criterion for convective clouds/rainfall generation, the following assumptions are made: (i) general circulation is neglected, only vertical exchanges are considered, (ii) the ABL is well-mixed, (iii) the Bowen ratio $Bo = H_s / LE$ (where $H_s$ and $LE$ are the sensible and latent heat fluxes, respectively) is constant during the day (Porporato, 2009), and (iv) cloud formation is approximated by the crossing between the ABL height and the Lifting Condensation Level (LCL). Such a crossing is a necessary (but not sufficient) condition for convective rainfall initiation (Juang et al., 2007; Bonetti et al., 2015). Under these assumptions and using a prescribed parabolic function of time $t$ to describe the diurnal evolution of net radiation, an analytical solution for the daily dynamics of the ABL height $h$ can be derived (Porporato, 2009):
where \( t_0 \) is the time at sunrise (being \( t_0 < t < 2t_0 \) the time of day), \( \beta \) is the fraction of sensible heat flux entrained from the top of the ABL, \( R_{n,\text{max}} \) is the daily maximum net radiation, \( \gamma_\theta \) is the potential temperature lapse rate, \( \rho \) is the mean density of air and \( \varepsilon_p \) is the specific heat capacity of dry air at constant pressure.

Using simplified temperature and humidity profiles (Figure 1e), Eq. (1) can be used to derive analytical expressions for the evolution of both ABL potential temperature \( \theta = \theta(h, \gamma_\theta, \gamma_\phi, h) \) and specific humidity \( q = q(h, \gamma_\theta, \gamma_\phi) \), where \( \gamma_\phi \) is the humidity lapse rate and \( \gamma_\phi \) and \( q_\phi \) the intercepts of the potential temperature and humidity linear vertical profiles, respectively (Porporato, 2009). The dynamics of the LCL height \( (L) \) is thus estimated as (Stull, 1988):

\[
L(t) = \frac{R \theta}{g M_a} \ln \left[ \frac{P_s}{P_L(\theta, q)} \right]
\]

where \( R \) is the universal gas constant, \( g \) is the gravitational acceleration, \( M_a \) is the molecular weight of air, \( P_s \) is the atmospheric pressure at the canopy surface, and \( P_L \) is the atmospheric pressure at height \( L \), estimated from ABL conditions \((\theta \text{ and } q)\). A cloud formation criterion can now be defined as (Manoli et al., 2016):

\[
\delta = \text{sgn}(\Delta)
\]

being \( \Delta = h-L \) a cloud formation function defining whether the ABL-LCL cross or not. Equations (1)-(3) provide a fully coupled description of the SPA system and convective clouds/rainfall occur when \( \delta = 1 \) (\( \Delta > 0 \)). Clear sky is expected otherwise \( (\delta = -1, \Delta < 0) \).

Two main parameters, controlling the amount of water vapor in the ABL available for clouds formation, can be identified: (1) the Bowen ratio \( Bo \), encoding the flux of water from soil to the atmosphere as regulated by land surface processes and (2) the free atmosphere (FA) conditions (encoded in the humidity lapse rate \( \gamma_\phi \)), determining the amount of water vapor entering at the top of the ABL by entrainment. The solution of \( \Delta(Bo, \gamma_\phi) = 0 \) (for \( t=2t_0 \) as illustrated in Manoli et al., 2016) thus provide the transition between cloudy/cloudless regimes as a function of biotic (land fluxes) and abiotic (FA) conditions.

3 RESULTS AND DISCUSSION

In Figure 2a-d the Bowen ratio measured at the sites (summer convective conditions only, see Manoli et al., 2016 for details) is plotted against observed root zone soil water content (SWC). The results provide a neat power law relation (black lines in Figure 2a-d) that encodes the role of root water uptake, stomatal regulation and photosynthetic processes on the partitioning of surface energy fluxes:

\[
Bo(SWC) = aSWCr^b + Bo_w
\]

where \( a \) and \( b \) are parameters that depend on soil and vegetation characteristics and \( Bo_w \) is the Bowen ratio under well-watered conditions. Eq. (4) can be used together with Eq. (3) to define the cloud formation criterion as a function of SWC, i.e. \( \Delta = \Delta(SWC, \gamma_\phi) \), and disentangle the role of soil vs FA conditions in triggering convective rainfall. The results (Figure 2e-h) show that under wet soil conditions, cloud formation can occur over a wide range of FA conditions due to the large amount of water vapor transpired by vegetation. When the soil becomes dry water stress can reduce pine transpiration and drive the ecosystem to a suppression of convective clouds (i.e. shallow cumuli can form only if there is enough moisture in the FA).

The threshold for water stress (represented by the SWC causing a steep increase in Bo, as observed in Figure 2a-c) provides a threshold for convective cloud formation (Figure 2e-g) and a lack of subsequent precipitation might enhance a positive feedback with water stress (i.e. less transpiration-less precipitation, Manoli et al., 2016). This threshold depends on both soil characteristics (Figure 2b-c) and stand age (Figure 2a,b,d), suggesting that pine’s development stage can influence rainfall recycling mechanisms. While soil characteristics defines the “operational” SWC (and the threshold for water stress), tree age affects the
ecosystem response to SWC changes. As the pines grow, stress conditions occur at lower SWC values (e.g. due to root growth) and by age 5, the young plantation (C1) starts exhibiting $Bo$-SWC patterns similar to the mature sites C2 and P1 (Figure 2a). However, the Bowen ratio at the old stand P2 (Figure 2d) shows little variations with SWC and a much higher $Bo_w$ compared to the young and mature stands.

These results suggest that young and mature pines are more sensitive to soil conditions than old stands: they operate at the verge of hydraulic failure, but regional hydrology and site-level water recirculation provide sufficient moisture to sustain convective precipitation. On the contrary, old pines appears to be insensitive to soil moisture variations, implying higher tolerance to drought but limited ability to recirculate available water. Therefore, large scale plantation forestry expansion such as the one projected in the SE-US, can impact key aspects of the hydrological cycle by modifying land surface fluxes and subsurface water availability and need to be accounted for in future water resources planning.

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**Figure 2.** Results: (a-d) observed relation between Bowen ratio and soil water content (circles) and fitted power law relation (lines); (e-h) cloud formation threshold $\Delta = 0$ (lines) compared with observed SWC and FA conditions (circles). The predisposition to triggering convective rainfall is illustrated by the cloud formation criterion (cloudy/rainy for $\delta > 1$, cloudless/no-rain for $\delta = 1$). Observations from the site C1 are divided into three sub-sets: year 2006 (2 yr old trees, red circles/line), year 2007 (3 yr old trees, blue circles/line) and years 2008-2009 (4-5 yr old trees, grey circles/black line).