Does surface temperature decrease with ecosystem development? Testing the maximum entropy hypothesis

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Summary

It has been argued from thermodynamic principles that a more 'developed' ecosystem should have relatively lower surface temperature (T_s) than a less developed counterpart, all else being equal, if entropy production is maximized as ecosystems develop (Schneider and Kay, 1994). The logic behind this argument follows from the maximum entropy production (MEP) principle (Dewar, 2003). For open, non-equilibrium systems subject to external constraints (e.g. conservation laws and external forcing), such as ecosystems, the most probable macroscopic state, namely the state that follows from more microscopic pathways than any other (Jaynes, 1957), has a higher probability of being selected. In other words, the realization of ecosystem structures that dissipate energy for the production of entropy is a highly probable ecosystem state (Dewar, 2005). This ecosystem state is one that degrades energy (i.e. produces entropy) most efficiently, with a macroscopic characteristic being cooler T_s. It stands to reason that a highly dissipative state is not realized immediately by ecosystems; rather the chance of this structure occurring increases over time (Kay et al., 2001; Schneider and Kay, 1994).

The MEP outcome that more complex ecosystems have lower T_s has been found in isolated examples using thermal remote sensing (Allen et al., 2001; Kay et al., 2001; Luvall and Holbo, 1991), and thermal characteristics have been used to quantify ecosystem

restoration success (Aerts et al., 2004). It is difficult to quantify what "ecosystem dissipative structures" mean in practice (Ulanowicz, 1986), but divergence of surface temperature has been observed in ecosystem complexity gradients under conditions of environmental stress (Lin et al., 2009), with the more developed intact tropical forest exhibiting thermal characteristics indicative of self-organization with respect to artificial rainforest and degraded ecosystems. The implications of MEP have not been explored across global ecosystems to date (Stoy, in press) despite the logical consequences for ecosystem and energy management in an era of global change (Chaisson, 2008; IPCC, 2007).

We propose to investigate the predictions of the MEP hypothesis by comparing T_s variability, and its response to environmental stress, across the globe using examples of paired ecosystems of varying ecosystem-level complexity from the FLUXNET database. Specifically, we seek to address two coupled objectives: (i) quantify the effects of ecosystem complexity on surface temperature across global plant functional types (PFTs), and (ii) contribute to ecological theory by characterizing what 'ecosystem functional complexity' means for the purposes of quantifying entropy, noting that species diversity and functional diversity (including diversity of water and energy flow paths) may be intertwined. In other words, within the context of the second objective we will explore the role of ecosystem hydrology and the biosphere-atmosphere flux of water in conferring thermal characteristics to ecosystems of varying complexity.

This FLUXNET data access proposal is intended to contribute to the postdoctoral fellowship of the project co-coordinator, whose task it is in part to build upon the successes of her Ph.D. research (Lin et al., 2009).

Example and Proof of Concept

In can be shown for the case of the Duke Forest AmeriFlux chronosequence that the ecosystem with arguably lowest hydrological complexity, the old field ecosystem [OF, (Lai and Katul, 2000)] has higher T_s under conditions of hydrologic stress (quantified here by the soil moisture, θ) than adjacent forested ecosystems (Juang et al., 2007), resulting in greater sensible heat flux (Stoy et al., 2006). This effect is demonstrated in Figure 1, assuming to a first order that longwave upwelling radiation ('outgoing', LW_{out}) is an effective surrogate for cross-site T_s comparison [i.e. that inter-ecosystem differences in emissivity are small (Chen and Blong, 2002), but also noting that emissivity is related to albedo following Kirchoff's Law of thermal radiation, and that these albedos differ spatially and temporally in Duke Forest (Stoy et al., 2006)]. LW_{out} is greatest at OF, particularly during drought, compared to the planted pine (PP) and hardwood forest (HW) ecosystems, indicative of reduced evaporative cooling (Juang et al., 2007; Stoy et al., 2006) that is likely due to some combined effect of ecosystem water storage capacity, rooting depth and distribution, and inherent drought sensitivity (Lai and Katul, 2000), all of which are ecosystem characteristics that may be formally related to entropy production.

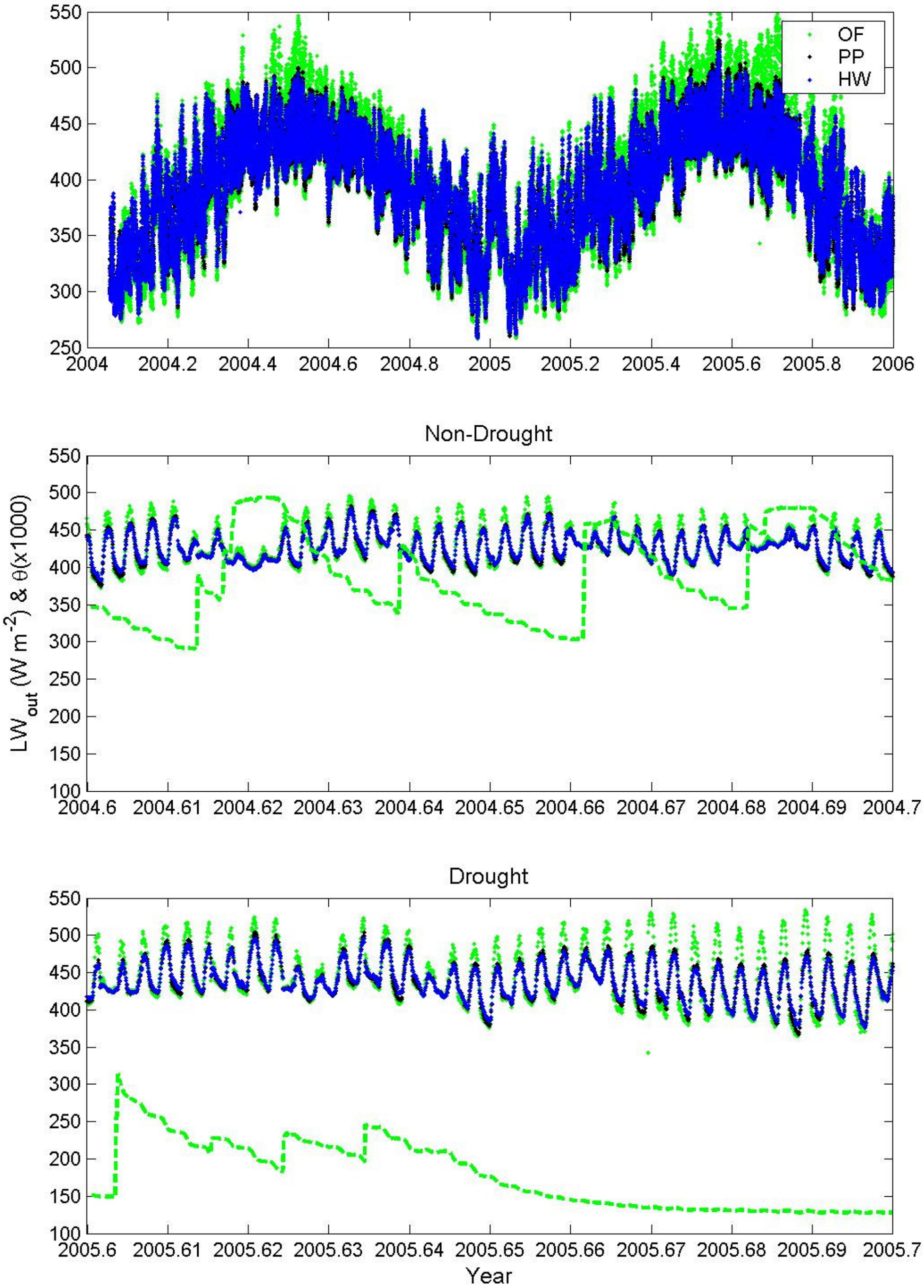

Figure 1 (top) Longwave outgoing radiation (LW_{out}) for the adjacent Duke Forest old field (OF), planted pine (PP) and hardwood forest (HW) ecosystems over a two year period. (middle) LW_{out} during the peak summer-time period of a year with normal precipitation statistics, and (bottom) LW_{out} during drought conditions during the growing season as quantified by the soil moisture (dashed green line, multiplied by 1000 to place on a common scale).

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