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Why is the thermodynamic efficiency of carbon uptake by terrestrial vegetation so low despite its optimal functioning?

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Optimality concepts have been used to successfully infer ecophysiological properties and functioning of terrestrial vegetation from the leaf- to ecosystem scale. In many cases this implies, roughly speaking, that vegetation is as productive as it can possibly be. However, when vegetation activity is looked at in terms of its energy conversion from the radiant energy in sunlight to the chemical energy stored in carbohydrates, it has a very low conversion efficiency of about 1% or less. This is much less than what would be expected from thermodynamics applied to the photochemical conversion process. How do these two seemingly contradictory views fit together? Here I suggest that thermally-driven gas exchange between vegetation canopies and the lower atmosphere represents the major bottleneck, explaining the low thermodynamic efficiency of carbon uptake and setting a strong constraint to any form of vegetation optimality. Gas exchange intimately links the carbon taken up by vegetation from the atmosphere for photosynthesis during the day with the water loss by evaporation, with evaporation being a major component of the surface energy balance. The magnitude of this exchange is, however, not externally set by atmospheric conditions, but predominantly determined by the local heating of the surface, creating buoyancy and thus this exchange. Thermodynamics sets a strong constraint on the magnitude of this locally generated exchange by the maximum power that can be derived from the absorption of solar radiation to generate the associated kinetic energy. I use global, observation-based radiation and precipitation datasets and this thermodynamic constraint to quantify surface energy balance partitioning over land as well as the associated rate of evaporation at the climatological scale. I then use a typical value for the water use efficiency observed in vegetation to convert this evaporative flux to a carbon uptake flux by vegetation and show that the derived fluxes of water and carbon compare very well to observation-based estimates across regions. This means that the low thermodynamic efficiency of terrestrial carbon uptake should not be attributed to an inefficient use of light, but rather to the low efficiency by which radiative heating generates gas exchange that is needed to supply canopies with carbon dioxide and that maintains evaporation. This interpretation has broad implications for the role of vegetation in the Earth system. It implies that physically-driven gas exchange with the atmosphere - and not energy directly - is a major constraint on vegetation activity, shaping its geographic patterns. Given this constraint, vegetation may then maximize its carbon uptake for the given evaporative flux, but it has comparatively little control over evaporation and surface energy balance partitioning if sufficient water is available. Applied to global warming, this then implies that the response of evaporation is mostly determined by changes in the radiative forcing and

water availability, and not by stomatal responses.