



The effect of warming on grassland evapotranspiration partitioning using laser-based isotope monitoring techniques

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Abstract

The proportion of transpiration (T) in total evapotranspiration (ET) is an important parameter that provides insight into the degree of biological influence on the hydrological cycles. Studies addressing the effects of climatic warming on the ecosystem total water balance are scarce, and measured warming effects on the T/ET ratio in field experiments have not been seen in the literature. In this study, we quantified T/ET ratios under ambient and warming treatments in a grassland ecosystem using a stable isotope approach. The measurements were made at a long-term grassland warming site in Oklahoma during the May–June peak growing season of 2011. Chamber-based methods were used to estimate the $\delta^2\text{H}$ isotopic composition of evaporation (δ_E), transpiration (δ_T) and the aggregated evapotranspiration (δ_{ET}). A modified commercial conifer leaf chamber was used for δ_T , a modified commercial soil chamber was used for δ_E and a custom built chamber was used for δ_{ET} . The δ_E , δ_{ET} and δ_T were quantified using both the Keeling plot approach and a mass balance method, with the Craig–Gordon model approach also used to calculate δ_E . Multiple methods demonstrated no significant difference between control and warming plots for both δ_{ET} and δ_T . Though the chamber-based estimates and the Craig–Gordon results diverged by about 12‰, all methods showed that δ_E was more depleted in the warming plots. This decrease in δ_E indicates that the evaporation flux as a percentage of total water flux necessarily decreased for δ_{ET} to remain constant, which was confirmed by field observations. The T/ET ratio in the control treatment was 0.65 or 0.77 and the ratio found in the warming treatment was 0.83 or 0.86, based on the chamber method and the Craig–Gordon approach. Sensitivity analysis of the Craig–Gordon model demonstrates that the warming-induced decrease in soil liquid water isotopic composition is the major factor responsible for the observed δ_E depletion and the temperature dependent equilibrium effects are minor. Multiple lines of evidence indicate that the increased T/ET ratio under warming is caused mainly by reduced evaporation.

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1. INTRODUCTION

Evapotranspiration (*ET*) plays a critical role in the hydrological cycle and represents the process that links both the energy and water cycles (Wang and Dickinson, 2012). In semi-arid environments, *ET* is a major pathway of water loss and can account for up to 95% of the precipitation input (Huxman et al., 2005; Wang et al., 2012a). Transpiration (*T*), the water vapor loss from plants, is a vegetation-controlled process and *T/ET* ratios reflect the influence of vegetation on the hydrological cycle. *T/ET* changes in response to temperature increases provide important insights into biological feedbacks, especially for those that might occur under potential global warming scenarios. Global warming is expected to increase *ET* and lead to greater aridity in water-limited systems, according to many global climate model simulations (Gleick, 1989; Zavaleta et al., 2003). However, these model predictions usually do not consider biological feedbacks, which may be important in regulating the overall climate change impacts on water cycling. In a recent investigation, it was observed that increased CO₂ can improve plant water use efficiency during photosynthesis, possibly counteracting the expected drying due to higher temperatures (Morgan et al., 2011). Nevertheless, the global warming effect on ecosystem *T/ET* changes has not been well investigated and experimental evidence for a warming effect on ecosystem *T/ET* is lacking. Understanding the implications and outcomes of these potential changes in vegetation response to climate change is of considerable importance.

Water isotopes are useful tracers in ecosystem hydrology (Dawson et al., 2002). The stable isotope composition ($\delta^2\text{H}$, $\delta^{18}\text{O}$) is defined as $\delta = (R/R_{\text{std}} - 1)$, where *R* is the ratio of rare to common isotope ($^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$) of a sample, and *R*_{std} is the ratio of the international standard on the *V-SMOW* (Vienna Standard Mean Ocean Water)-*SLAP* (Standard Light Antarctic Precipitation) scale. These isotopes can, for example, help identify plant water sources (Dawson and Ehleringer, 1991), hydraulic redistribution (Dawson, 1993), groundwater recharge rates (Cane and Clark, 1999) as well as differential rooting depth among adjacent plants (Jackson et al., 1999). Most applications have used liquid water extracted from soils and plants to follow these ecosystem processes, but recent advances in laser spectroscopy have allowed for water vapor isotopes to be measured *in situ* at high temporal resolution (e.g., 1 Hz) with analytical uncertainties similar to traditional cryogenic trapping methods (Wen et al., 2008; Wang et al., 2009, 2010; Griffis et al., 2011; Zhao et al., 2011). The development of such systems allows for the direct use of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ to study water vapor dynamics, including the partitioning of *ET* into *T* and evaporation (*E*) (Wang et al., 2010). These new approaches extend previous work that relied on cryogenic trapping (Harwood et al., 1998; Moreira et al., 2003; Newman et al., 2010).

Both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ provide a unique tool for *ET* partitioning (e.g., calculating *T/ET* ratios). The basis for using $\delta^2\text{H}$ and $\delta^{18}\text{O}$ to partition *ET* is that evaporation significantly fractionates the surface soil water (Luz et al., 2009). Plants, however, do not fractionate water during uptake (White et al., 1985; Ehleringer and Dawson, 1992). The

isotopic composition of transpiration (δ_T) is therefore assumed to be equal to the isotopic composition of plant source water. This assumption is generally valid for timescales much greater than the turnover time of water in the leaves and in the absence of rapidly changing environmental conditions because mass balance constraints require that the δ_T should be equal to that of the soil water in the rooting zone. This results in distinct isotopic compositions of evaporation (δ_E) and δ_T . By measuring the isotopic end members (δ_E and δ_T) along with the isotopic composition of aggregated *ET* (δ_{ET}), the *T/ET* ratios can be calculated via mass balance (Wang et al., 2012a). δ_{ET} is typically measured using a Keeling plot approach in which isotopic compositions of water vapor are measured at several heights above the canopy (Keeling, 1958). The resulting gradient in water vapor concentration and isotopic composition is used to extrapolate δ_{ET} derived from the ecosystem. The δ_T is typically measured using xylem or stem water under the assumption that the isotopic composition of xylem water is equivalent to δ_T under isotopic steady state (e.g., Yepez et al., 2005). The assumption of isotopic steady state can be made during times of high transpiration rate and stable vapor pressure deficit (Harwood et al., 1998), but the diurnal periods during which this applies depend on environmental conditions and plant species. Wang et al. (2012b) developed and verified a new method that uses a mass balance approach to calculate δ_T from *in situ* chamber measurements, which is applicable for both steady state and non-steady state conditions and is applicable to estimate δ_{ET} and δ_E . The δ_E has commonly been estimated using the Craig–Gordon evaporative fractionation model (Craig and Gordon, 1965), although numerical isotope modeling efforts are also widely used (Mathieu and Bariac, 1996; Braud et al., 2009; Haverd et al., 2011; Soderberg et al., 2012).

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values between plant organic matter and liquid water in both leaf and surrounding environments provide important information on current and past environments (Terwilliger et al., 2002; McCarroll and Loader, 2004; Helliker, 2011). The utility of these liquid-organic isotopic relationships for generating information about the entire Soil–Plant–Atmosphere–Continuum (*SPAC*) depends on an understanding of how water isotopes change throughout the *SPAC*, including under warming conditions. Here we present work that demonstrates the effectiveness of coupled laser spectroscopy-chamber based isotope techniques for measuring *ET* partitioning. The work was performed under ambient and artificially warmed conditions to evaluate the effects of warming on the sources of contributions to *ET*. The objectives of this study are to: (1) evaluate the performance of multiple isotope-based *ET* partition methods for the estimation of δ_E , δ_{ET} and δ_T ; (2) combine estimates of δ_E , δ_{ET} and δ_T to partition *ET*; and (3) assess how warming scenarios influence surface vapor flux partitioning.

2. MATERIALS AND METHODS

2.1. Study site

The study was conducted at the University of Oklahoma's Kessler Farm field laboratory, which is located in central

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