ESTIMATING ECOSYSTEM RESPIRATION USING SATELLITE REMOTE SENSING

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SUMMARY

Here we report a method for estimating ecosystem respiration (R_e) by exclusive use of remotely sensed land surface temperature (T_r) from NASA's moderate resolution imaging spectroradiometer (MODIS) sensors. A combination of daytime and nighttime MODIS T_r data was used to model an 8-day mean value of land surface temperature ($T_{r(mean)}$), which was then used in a modified Arrhenius-based *Lloyd and Taylor* [1994] respiration model to simulate 7 years of ecosystem respiration of a temperate deciduous forest. These model outputs were then compared with respiration estimates of the site measured by eddy covariance (EC) method. Measured and modeled values were highly correlated ($R^2 = 0.87$, RMSE = 0.64 μ mol CO_2 m^{-2} s^{-1}). This study demonstrates the potential of estimating "per-pixel" ecosystem respiration by exclusive use of remotely sensed data from the existing space-based sensors.

MATERIALS AND METHODS

Conventionally, temperature sensitivity of ecosystem respiration (R_e) is expressed by an exponential function of soil temperature or air temperature (T_s and T_a respectively) known as Q_{10} (the factor by which respiration rate increases with every 10^o C increment of temperature). Recent studies showed that, for the forested flux-tower sites in the USA, a reasonably strong Q_{10} based exponential relationship ($R^2 = 0.6$) exists between the16-day average R_e and 16-day composite values of radiometric land surface temperature (T_r) from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor [1]. But the principal limitations of Q_{10} based R_e estimation method are its constant temperature response relationship to respiration, and its site specificity [2]. In this paper we examine whether a more robust physiological based modeling framework, originally proposed for soil respiration only, can be utilized to estimate R_e from MODIS T_r.

Our study areas was Morgan Monroe State Forest (MMSF) in south central Indiana (39.3232^o N, 86.4131^o W). For this study, we used eddy covariance (EC) estimates of R_e from the flux tower at MMSF, and T_r data of the flux tower footprint from MODIS. The EC system was located at the top of the 46 m tall tower and consisted of a three-dimensional sonic anemometer (C-SAT, Campbell Scientific Inc. (CSI), Logan, UT) and a closed-path infrared gas analyzer (IRGA, LI-6262 and LI-7000, Li-Cor, Lincoln, NE). Sampling frequency was 10 Hz with fluxes calculated hourly. The flux values (F_C) were then subjected to quality control, including outlier rejection, and a $u_* \leq 0.3$ m s^{-1} (u^* is the friction velocity) criterion to reject values obtained under low turbulence conditions where the change of CO_2 storage in the canopy air space could be important [3]. Values of F_C that passed the quality control criteria were considered acceptable as estimates of net ecosystem exchange (NEE).

NEE values during the nighttime were those of the R_e flux (no photosynthesis). In this study, those values were considered as "measured" R_e (or $R_{e(meas)}$). Any data gap in the hourly R_e time series, caused by missing data points and by the above-mentioned quality control procedure, was filled by a simple parametric model that links T_s to $R_{e(meas)}$:

$$R_{e(calc)} = a_1 \exp\,(a_2\, T_s) \qquad 1$$

In equation (1), $R_{e(calc)}$ is the calculated respiration value used to fill the data gaps and also to estimate the daytime respiration. Parameters a_1 and a_2 were derived annually by non-linear regression between the $R_{e(meas)}$ and corresponding T_s measured at 5 cm soil depth. Adding the $R_{e(calc)}$ values of daytime and data-gap hours to the $R_{e(meas)}$ of nighttime hours resulted in the total daily values of EC-based R_e. These daily R_e values were then averaged for 8 consecutive days beginning from January 1^{st} of each year to conform to the time series of T_r data used in this study.

We downloaded 1 km pixel resolution MODIS 8-day composite T_r data from the Oak Ridge National Laboratory's Distributed Active Archive Center (DAAC) web site (www.modis.ornl.gov/modis) and extracted the pixel in which the flux tower is located. We also noticed that the tower pixel and the surrounding 7×7 pixels had very similar T_r values, further validating the assumption that the flux tower footprint was representative of the surrounding biomes.

Daytime and nighttime 8-day composite T_r values of the terrestrial surface are available at 1 km pixel resolution from the two existing MODIS sensors onboard Terra and Aqua platforms (termed "MOD11A2" and "MYD11A2" respectively). Terra overpass is at ~10:30 AM and PM local times daily, and Aqua overpass is at ~1:30 AM and PM local times daily. The T_r values from nighttime Aqua are slightly lower than those from nighttime Terra. But the daytime T_r values from Aqua are in general a few degrees (^oK) higher than those from daytime Terra (data now shown). Following the method of Weiss and Hays [4] for estimating mean daily air temperature from 3 temperature measurements throughout the diurnal cycle, we calculated a weighted mean 8-day T_r using Terra and Aqua data:

$$T_{r(mean)} = \frac{T_{r(Aqua-Night)} + T_{r(Aqua-Day)} + 2T_{r(Terra-Night)}}{4} \qquad 2$$

$T_{r(mean)}$ in equation (2) is a representation of the 8-day mean land surface temperature, and the numerator terms in the right side of the equation denote the 8-day composite daytime or nighttime T_r values from Terra or Aqua. We used nighttime Aqua, daytime Aqua, and nighttime Terra to represent the 7:00 AM, 2:00 PM and 9:00 PM T_r values respectively.

In this paper we used the 8-day composite $T_{r(mean)}$ values (from equation (2)) in a modified Arrhenius-based temperature response function of Lloyd and Taylor [2] to simulate ecosystem respiration:

$$R_{e(mod)} = R_{10}\exp\left[308.56\left(\frac{1}{56.02} - \frac{1}{T_{r(mean)} - 227.13}\right)\right] \qquad 3$$

This is a two-parameter model based on kinetic theory [*Kavanu,* 1951], which accounts for decreasing Q_{10} values with increasing temperatures. In equation (3), $R_{e(mod)}$ is the modeled R_e, and R_{10} is the value of R_e at 10°C $T_{r(mean)}$. The unit of $T_{r(mean)}$ in the numerator of equation (3) is in °K. Given that the $T_{r(mean)}$ was calculated from MODIS data (equation(2)), this model is essentially dependent on only one parameter, namely the R_{10}, which we estimated from an exponential fit between $T_{r(mean)}$ and 8-day average of EC-based R_e values. The study period reported in this paper includes seven years, beginning from the day of year (DOY) 185 of 2002 to the DOY 361 of 2008.

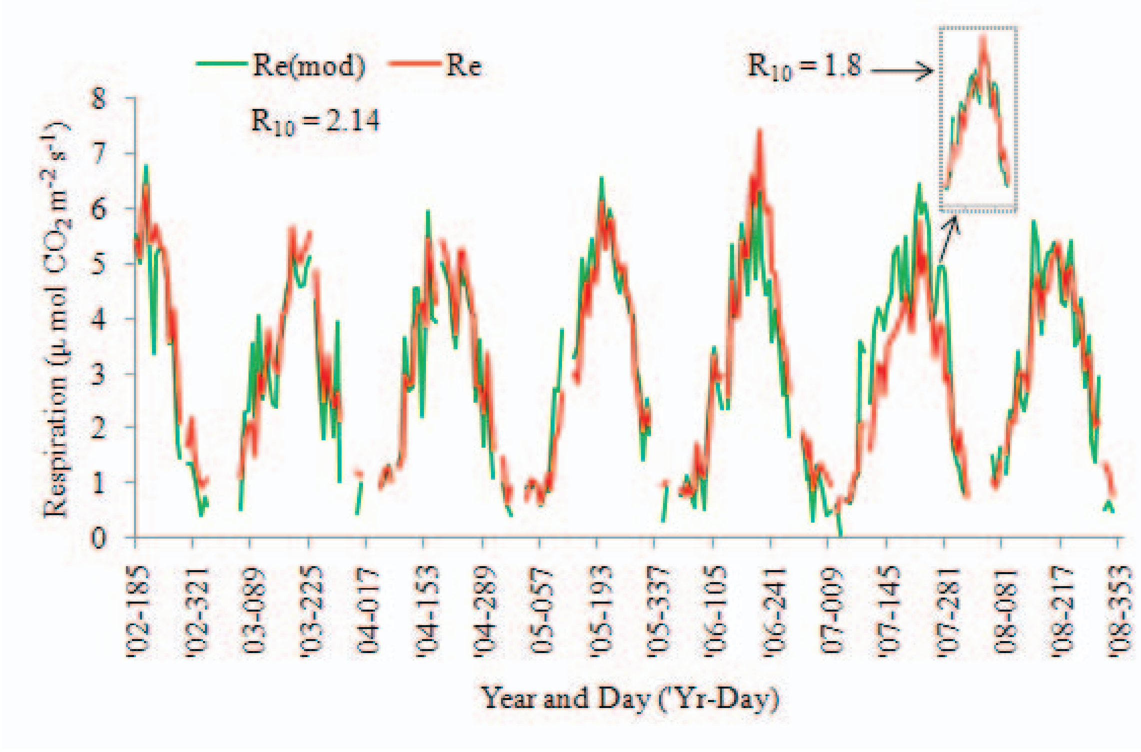
RESULTS AND DISCUSSIONS

The 8-day composite $T_{r(mean)}$ of the MMSF tower pixel compared well with the 8-day average T_s of the site, resulting in an adjusted R^2 value >0.9. One noticeable exception was that while $T_{r(mean)}$ values were negative in some cases, T_s values never went below zero, indicating that the soil did not freeze in this site during the study period. This mismatch is not unusual since T_r measures the radaitive surface temperature and T_s measures the kinetic soil temperature. For estimating $R_{e(mod)}$, we needed the value of R_{10} parameter. An exponential fit between 8-day composite $T_{r(mean)}$ and 8-day average R_e values for the whole study period provided the R_{10} value equal to 2.14 μ mol CO_2 m^{-2} s^{-1}. This value is quite similar to ecosystem respiration values at 10° C reported in other studies.

We compared $R_{e(mod)}$ with R_e. The regression line ($R^2 = 0.87$) was very close to the 1:1 line, even though data scatter existed around it. The RMSE between $R_{e(mod)}$ and R_e was 0.64 μ mol CO_2 m^{-2} s^{-1} and the mean absolute error (MAE) was 0.49 μ mol CO_2 m^{-2} s^{-1}. Residuals did not show any over- or under-estimation bias for the whole range of R_e (0-8 μ mol CO_2 m^{-2} s^{-1}). The $R_{e(mod)}$ followed the temporal trend of R_e well, except in 2007 when it slightly, but consistently, overestimated R_e throughout the growing season (Figure 1). 2007 was an exceptional year for the study site. In the first week of April a severe weeklong cold spell froze and killed many new buds and leaves, thus delaying the start of the growing season and also decreasing the respiration rate, resulting in an R_{10} value of 1.8 μ mol CO_2 m^{-2} s^{-1} for 2007. Given that equation (3) is dependent on this parameter, use of a higher R_{10} (i.e., 2.14) resulted in higher $R_{e(mod)}$ values for 2007. When R_{10} value of 1.8 was used instead, the $R_{e(mod)}$ simulated the R_e of 2007 quite well (Fig. 1, inset).

This dependence of the model on R_{10} value may be considered a weakness, but it also shows that an appropriate R_{10} value can provide a remarkably good simulation of R_e, even in an exceptional year. Another strength of this model is that it is less sensitive to higher values of $T_{r(mean)}$. Temperature response of respiration decreases as $T_{r(mean)}$ increases (equation (3)). This trait would ensure that any drought-induced

Figure 1. Time series of R_e and $R_{e(mod)}$ for the study period.



temperature increase during summer may not lead to undue overestimation of $R_{e(mod)}$, as long as the appropriate R_{10} value is known. For example, 2007 also had a month-long drought in August, causing increase in surface temperature and decrease in respiration. But when the correct R_{10} value for that year was used, the model did not overestimate the summer respiration (Figure 1, inset). One point of caution may be that this model attributes respiration to temperature only, whereas other environmental and biotic factors may also play crucial roles in determining respiration.

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