ORIGINAL PAPER

Comparison of vineyard evapotranspiration estimates from surface renewal using measured and modelled energy balance components in the GRAPEX project

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Abstract

Surface renewal (SR) is a biometeorological technique that uses high frequency air temperature measurements above a crop surface to estimate sensible heat flux (H). The H derived from SR is then combined with net radiation (R_n) and ground heat flux (G) measurements to estimate latent heat flux (LE) as the residual of an energy balance equation. Recent advances in SR theory enabled its use beyond research settings, and led to the development of an inexpensive, stand-alone SR system for use in commercial agricultural settings. However, these commercial applications require replacing expensive net radiometers with clear sky models designed to estimate R_n for the energy balance approach, while also assuming G is zero on a daily basis. The accuracy of substituting R_n measurements with modelled values is unknown, and the assumption of an inconsequential G requires additional testing. Here, we compare the accuracy of the SR derived estimates of H and LE when R_n is either measured directly or modelled, and we compare results to two eddy covariance (EC) LE observations, namely LE measured via EC with an infrared gas analyzer (EC_{IRGA}) and LE solved as a residual in the surface energy balance (EC_{resid}). These measurements were collected at the Grape Remote sensing Atmospheric Profile & Evapotranspiration eXperiment (GRAPEX) conducted over a vineyard within the Lodi, CA wine growing region. LE from SR using tower R_n data measured directly onsite was significantly correlated with LE from EC_{resid} and from EC_{IRGA} with a least squares regression slope ~ 1. LE derived with the modelled incoming solar radiation (SWi) and DisALEXI R_n approaches were also significantly correlated with LE from EC_{resid}, but both modelling approaches overestimated LE at higher fluxes. Patterns were similar, but with more scatter for correlations between LE from EC_{IRGA} and LE from SR using either modelled or remotely sensed R_n. Incorporating direct measurements of G had minimal impact on the agreement of several SR approaches and LE from both EC approaches, however, when differences did occur direct measures of G reduced scatter and bias especially for the empirical SR approach. Our results suggest that LE derived from the new SR method requires fairly accurate R_n modelling approaches to obtain reliable and unbiased estimates of daily LE in comparison to measured LE using EC techniques.

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Introduction

Effective irrigation management requires accurate estimates of crop evapotranspiration (ET). Surface renewal (SR) is a biometeorological technique that can be used to estimate the ET of crop surfaces (McElrone et al. 2013). The SR technique uses high frequency air temperature measurements from fine-wire thermocouples to estimate the sensible heat flux density (H) associated with air parcels that transiently reside within crop canopies during the turbulent exchange process (Paw U and Brunet 1991; Paw U et al. 1995). Air temperature time-series data from the fine-wire thermocouples exhibit ramp-like shapes that represent coherent structures that dominate surface-layer energy and mass exchange

(Gao et al. 1989), and the amplitude and period of the ramps are resolved using a structure function procedure (Van Atta 1977) to calculate H in the SR methodology (Paw U et al. 1995; Spano et al. 1997). The H captured with SR is then used to estimate latent heat flux density (LE) as the residual of a surface energy balance using the following equation:

$$LE = R_n - G - H, \tag{1}$$

where R_n is net radiation and G is the ground heat flux density. Assumptions associated with the energy balance approach are that lateral heat flux and changes of heat storage are negligible. The SR technique has been shown to accurately measure H and subsequently estimate LE on a wide range of crops, such as tomatoes, broccoli, lettuce, wheat, sorghum, maize, cotton, citrus, grapevines, and avocado.

While H measurements obtained with SR have been well correlated with standards such as eddy covariance (EC), SR flux measurements have required calibration to account for linear bias in the data and correct for inconsistencies across sites and crop surfaces (Paw U et al. 1995). Until recently this calibration has been done with an alpha factor that is obtained from the slope of the regression of H from EC measurements versus un-calibrated H measurements from SR. The alpha calibration hypothetically accounts for the uneven heating within the coherent structure that arises from the non-uniform vertical distribution of heat sources in the plant canopy (Paw U et al. 1995). The need for the alpha calibration obtained with expensive research grade sensors (e.g., sonic anemometer) has limited the use of SR to research applications. Shapland et al. (2014) showed that

inconsistencies in the alpha calibration measured in previous studies could be corrected by compensating the frequency response characteristics of SR measurement thermocouples, thus causing alpha to converge near the theoretically predicted value. This development provided the opportunity to create an inexpensive, stand-alone SR system to measure H without the need for calibration, and commercial sensors are now available to growers (Shapland et al. 2012b, c). Viable commercial implementation of the SR technique requires that expensive research grade sensors are either replaced with inexpensive ones that provide sufficiently accurate measurements of R_n and G or with modelled values. For example, the original research grade SR system used net radiometers while commercial SR systems now model R_n for sites where clear sky models can be used effectively (i.e., growing locations with limited summer cloud or fog cover like California's Central Valley). It is currently unknown how effective such replacements are for accurate determination of LE.

Accurate estimates of R_n are extremely important for energy balance approaches used to estimate crop ET (e.g., Nouvellon et al. 2000). R_n at the surface can be either modelled or measured directly, but direct measurement of transmitted radiation through a canopy is often not practical for implementation in commercial agricultural settings with deployment of numerous systems. To evaluate the effectiveness of R_n modelling to replace direct measurements, we compared LE flux measurements in the 2015 and 2016 growing seasons with a combination of direct measurements of R_n and those estimated with three different modelling approaches (Fig. 1 top box). This combination was compared
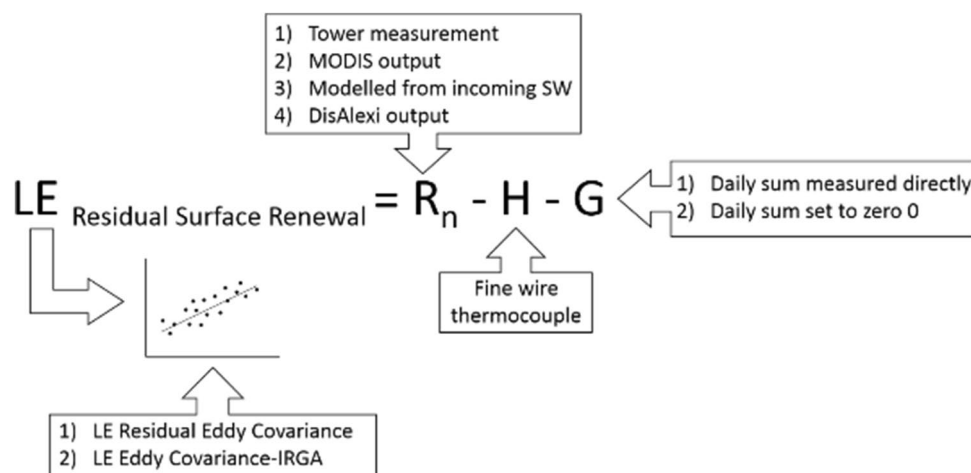

Fig. 1 Schematic of comparisons presented in this manuscript. Latent heat flux (LE) was determined using the surface renewal method to estimate sensible heat flux (H) with a fine-wire thermocouple and combined these with four different radiation inputs (i.e., tower measurements, MODIS output, Modelled from incoming solar radiation (SWi), and DisALEXI output) and with two different estimates of ground heat flux (i.e., the daily sum measured directly and the sum assumed to be zero on a daily basis). Surface Renewal LE estimates were then compared against LE from two eddy covariance (EC) approaches: (1) measured with an infrared gas analyzer (EC$_{IRGA}$) and solved as a residual in the surface energy balance (EC$_{resid}$)

using direct measurements of G and using the assumption that daily G summation $= 0$ (Fig. 1 right box). SR stations were established in a *Vitis vinifera* L. cv. Pinot noir vineyard used for the Grape Remote sensing Atmospheric Profile & Evapotranspiration eXperiment (GRAPEX) for comparison with ET estimates from a variety of other techniques.

Methods

Site description

As part of the USDA-ARS Grape Remote sensing Atmospheric Profile & Evapotranspiration eXperiment (GRAPEX), the south vineyard of the two Pinot noir vineyards, located at the border of Sacramento and San Joaquin counties, was instrumented in 2015 and 2016 with a surface renewal station to compliment measurements from the existing flux towers. Intensive observation periods (IOPs) covered 2 to 4 phenological stages each year. The smaller southern field (Site 2; 21 ha) contains grapevines that were planted in 2011. The height of the vines ranged between 2 and 2.5 m, row spacing was ~3.35 m, and average vine spacing along the row was 1.52 m. The majority of vegetative growth was located within the top ½–1/3 of the vine by the end of the season.

Instrumentation

A 10 m radio tower is stationed in the south vineyard and instrumented with a complete surface energy balance eddy covariance flux and wind profile system, providing measurements of net radiation (R_n), ground heat flux (G), incoming solar radiation (SWi), relative humidity (RH), sensible heat flux (H), and latent heat flux (LE). R_n was measured directly onsite with a four-component radiometer (CNR-1, Kipp and Zonen, Delft, Netherlands) mounted at 6 m AGL oriented toward the southwest. Ground heat flux (G) was computed from an average of 5 soil heat flux plates (HFT-3, Radiation Energy Balance Systems, Bellevue, Washington) deployed at a depth 8 cm along a diagonal transect across the inter-row space. Each ground heat flux plate was inserted with a pair of Type E (Chromel-Constantan) thermocouples located at 2 and 6 cm below the soil surface and above the ground heat flux plates. Soil moisture sensors (HydraProbe, Stevens Water Monitoring System, Portland, Oregon) were co-located with each ground heat flux plate at a depth of 5 cm below the surface to provide measured soil water content, which is required to correct the measured ground heat flux plate data to include an estimated soil heat flux storage to arrive at a final total ground heat flux estimate. The turbulent energy fluxes for LE and H heat fluxes were measured via EC by co-locating an infrared gas analyzer

(IRGA) (EC-150, Campbell Scientific, Inc., Logan, UT) with the sonic anemometer at the 5 m height on both towers. All sonic anemometers and IRGA sensors were mounted in a vertical configuration facing due west and sampled at a frequency of 20 Hz. Details of the full processing of the EC data are provided in Alfieri et al. (this issue). First, non-physical values and data spikes were removed from the high frequency data using a moving window algorithm. Then, a two-dimensional coordinate rotation was applied to the wind velocity data so that the coordinate system was aligned into the prevailing wind direction followed by correcting for sensor displacement and frequency response attenuation. The moisture and carbon dioxide fluxes were then corrected for buoyancy and water vapour density effects. Hourly fluxes were calculated.

A SR station was deployed approximately 10 m to the west of the tower. The SR tower measured air temperature ($f = 1$ Hz) with a 76 micrometer diameter Type E thermocouple (FW3, Campbell Scientific, Inc. Utah, USA) placed approximately 50 cm above the vine canopy and was periodically raised as the canopy grew.

Data analysis

The surface renewal method is used to estimate sensible heat flux (H) using the 1 Hz temperature data that is compensated for the thermocouple size (Shapland et al. 2014), which eliminates the need for calibration against eddy covariance H. Estimates of H by SR were calculated according to the following equation:

$$H = \alpha \times z \times \rho C_p \left(\frac{a}{d+s} \right), \tag{2}$$

where α is the alpha calibration factor described above, z is the thermocouple height (m), ρ is the air density (g m^{-3}), C_p is the specific heat of air at constant pressure (J g^{-1} K^{-1}), a is the average ramp amplitude (K), d is the duration of the air parcel heating (s), s is the quiescent period that follows the sweep-phase of the air parcel (s), and ($d+s$) are collectively called the ramp period (repetition intervals of ramps) (s).

The ramp characteristics were calculated from the raw temperature signal from the 76 mm thermocouple. The α calibration factor was determined using an empirical compensation method, in which the theoretical alpha coefficient of 0.5 is multiplied by the thermocouple compensation factor specific to the 76 μm diameter thermocouple used here (Shapland et al. 2014). Rather than applying the thermocouple frequency response compensation to the raw thermocouple temperature data, the thermocouple frequency response compensation was applied instead to the SR H values. The 2.16 compensation factor was determined previously as the slope of a regression analysis of H from raw 13 μm data

versus H from raw 76 μm temperature data (Shapland et al. 2014).

When SR is used to measure H, one can estimate LE using the residual of the energy balance with Eq. 1. Four different radiation inputs (i.e., tower measurements, MODIS output, modelled from SWi, and DisALEXI output) were used for R_n and two different estimates of G [i.e., the daily sum measured directly and the using the longwave net radiation sub-model in the standardized reference evapotranspiration equation (Blonquist et al. 2010)] with measured SWi, relative humidity, and air temperature from the south vineyard flux tower. The MODIS R_n output was estimated daily using the moderate resolution imaging spectroradiometer—MODIS at 1 km resolution. The DisALEXI R_n output was estimated with each LANDSAT 8 overpasses biweekly to monthly at 30 m resolution. Since The MODIS and DisALEXI R_n are for daytime only, a simple regression with Daily R_n was used to factor in the nighttime effect. This reduced the inherent bias caused using daytime instead of diurnal value. LE estimates from SR were then compared to EC_{resid} and EC_{IRGA} (Fig. 1).

Results and discussion

Direct measurements of net radiation (R_n) collected on the tower at the GRAPEX site matched most closely with modelled R_n based on the SWi (using modelling approaches presented by Parry et al. 2019, this issue) (Fig. 2). While these measurements matched well, there were periods of time in both growing seasons when they diverged. For example in 2015, when dips occurred in both estimates simultaneously (e.g., days 134, 137, 141, 161, 182, and 183) the modelled R_n based on SWi was always slightly lower than that measured directly on the tower (Fig. 2—top panel). A similar pattern was found in 2016 on days (e.g., days 118, 141, 142, and 156) (Fig. 2—bottom panel). Besides these slight differences, the only time that these values consistently diverged was from day 182–207, when the tower R_n value jumped slightly and remained consistently higher for the remainder of the period of observation (Fig. 2—bottom panel). R_n estimates from MODIS and DisALEXI were similar to one another across each season, and were consistent with tower R_n in both years (Fig. 2) similar to results found in previous studies (e.g., Cammalleri et al. 2014). The less frequent estimates of R_n from DisALEXI made it appear as though it was not responding to the intermittent dips measured directly and modelled with the onsite data (e.g., days 212, 216, and 218 in the 2015 season and days 142–144 in the 2016 growing season), and the values from MODIS showed similarly limited response even with a higher frequency of measurements during these periods (Fig. 2).

Daily summations of ground heat flux (G) showed that most of the values hovered around zero (Fig. 3); ~ 85% of the G values recorded during the 2015 growing season were within $\pm$ 0.5 W m^{-2} (Fig. 3 left panel). All points recorded across the 2 years of the study fell within $\pm$ 2.0 W m^{-2}, and a very small percentage of the total values fell outside of $\pm$ 1.0 MJ m^{-2} day^{-1} (Fig. 3; only 1 value in 2015 and 5 values in 2016 fell outside $\pm$ 1.0 MJ m^{-2} day^{-1}). G values showed greater scatter and divergence from zero in 2016 compared to 2015. Efforts to apply SR under commercial field conditions would benefit from elimination of G measurements to reduce cost and labour to maintain stations and sensors in the vineyard interrow where farm equipment frequents. Stoy et al. (2013—Supplemental Fig. 3) showed similar results where daily G was close to zero. While our current results show that daily G scatters about zero, this result may not be universally true and should be tested thoroughly in other experimental settings. Moreover, as shown below and in Table 1, assuming $G=0$ in all cases results in increase scatter with LE from EC_{resid} and EC_{IRGA}.

Values of LE from EC_{resid} and from SR using directly measured R_n tracked each other closely in both years of the study (Figs. 4, 5, 6 top left panel). This relationship improved when including daily measured G instead of assuming a value of zero on a daily basis (Table 1; Fig. 6 top row), but the slope for both relationships was essentially unity (Fig. 6 top row). There were some periods during both seasons when the LE from EC_{resid} was higher (e.g., days 222–224 in 2015- Fig. 4) than that from SR estimated with R_n from the tower. Similar relationships were found using a calibrated surface renewal approach over grapes (Shapland et al. 2012a; Spano et al. 2000; Snyder et al. 1996), and more recently in a vineyard containing a weighing lysimeter (Parry et al. in review), where LE estimates from SR matched closely (i.e., $R^2 > 0.9$ and slope ~ 1.0) with those from EC and ET measurements from the weighing lysimeter.

For most of the 2015 growing season, LE estimates from SR using the three R_n modelling approaches followed LE from SR and from EC_{resid} using tower R_n measured directly (Fig. 4). The LE estimate from SR using modelled R_n from SWi fell below that of the other technique at several points in 2015 (Fig. 4), which corresponded with the dips in R_n measured onsite described above (e.g., days 134, 137, and 141—Fig. 2). Despite these differences, the SR LE estimated using modelled R_n from SWi tracked closely with the LE from EC_{resid} with the tower R_n data (r of ~ 0.88), albeit with a significant slope of 1.35 or 1.39 due to the bias (Table 1; Fig. 6). The LE estimate using MODIS R_n spiked higher than LE from the other methods on several days in the middle of the 2015 growing season (Fig. 4), but was in line with other methods throughout much of the 2016 growing season. LE estimates from SR based on the R_n from DisALEXI showed the best fit of all the model approaches (r of ≥ 0.96),
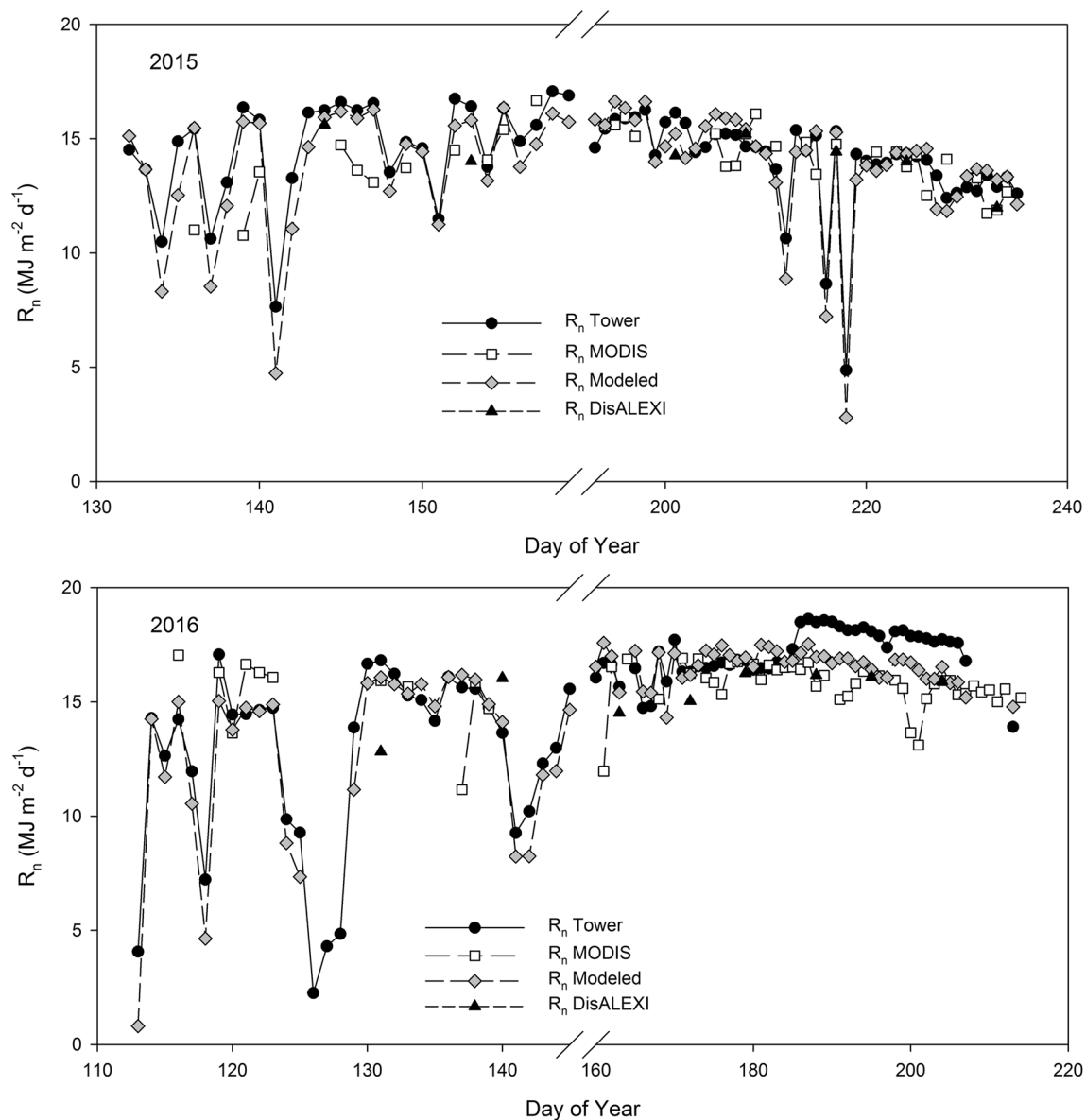
Fig. 2 Net radiation measurements or modelled values (MODIS, Modelled SWi, and DisALEXI) from the GRAPEX site captured across the 2015 (top panel) and 2016 (bottom panel) seasons

but the LE values generated by this approach were much greater compared to the LE from EC_{resid} (Fig. 6—bottom row; Table 1) that could be due far fewer data points for the DisALEXI comparison.

LE estimates obtained from SR with the various R_n inputs were compared with LE from EC_{IRGA} (Fig. 7), and showed similar patterns to the LE from EC_{resid} comparisons in Fig. 6. Inclusion of direct measurements of G improved the relationships (i.e., higher r values and lower RMSE—see Table 1) for the directly measured R_n from the tower and MODIS R_n approaches (Fig. 7 top two rows), but showed little effect for the DisALEXI approach (Fig. 7

right vs. left hand column; Table 1). LE from EC_{IRGA} was most strongly correlated with LE from SR estimated with tower R_n (r of 0.8), while the other approaches exhibited weaker fits (r of 0.58–0.7 and larger RMSE values; see Table 1). The slopes (and bias) of the relationships were consistent within a given approach regardless of the EC approach they were compared against (i.e., slopes were similar within a given approach across both comparisons in Figs. 6, 7). For example, direct R_n measurements from the tower resulted in near unity slopes, while modelled R_n from SWi and DisALEXI R_n consistently overestimated LE compared to that of both EC_{resid} and EC_{IRGA}.
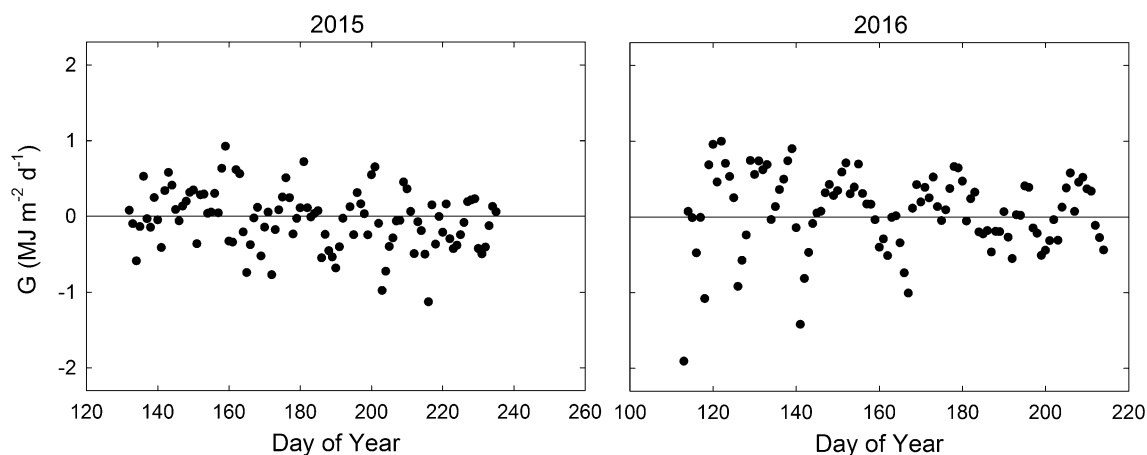
Fig. 3 Daily summations of ground heat flux (*G*) measured at the GRAPEX site over the 2015 and 2016 seasons

Table 1 Statistical analysis for relationships between LE estimates from surface renewal, eddy covariance and water vapour flux as represented in Figs. 6 and 7

	Tower		MODIS		Modelled SWi		DisALEXI	
	With *G*	Without *G*	With *G*	Without *G*	With *G*	Without *G*	With *G*	Without *G*
LE residual from Eddy covariance vs LE residual from surface renewal								
RMSE	0.85	1.73	2.17	2.78	2.06	2.06	1.81	1.85
BIAS	− 0.03	− 0.51	0.37	0.18	− 0.76	− 0.83	− 0.55	− 0.78
r	0.94	0.82	0.65	0.66	0.88	0.89	0.96	0.97
Water vapour flux from Eddy covariance (EC$_{IRGA}$) vs LE residual from surface renewal								
RMSE	2.05	2.77	2.45	2.73	3.75	3.79	3.85	3.98
BIAS	− 1.41	− 1.83	− 1.02	− 1.21	− 2.56	− 2.62	− 2.56	− 2.79
r	0.80	0.69	0.62	0.58	0.68	0.70	0.68	0.69

Units for RMSE and BIAS are MJ m^{-2} day^{-1}

Conclusions

The SR technique is currently being used as a commercial product to provide site specific crop ET estimates for growers and irrigation managers for a variety of crops in California's Central Valley. To make this application cost-effective, R_n is being modelled and *G* is assumed to equal zero on a daily basis. We evaluated the effectiveness of various R_n modelling approaches to replace direct measurements, and compared output using direct measurements of *G* and using daily *G* summation equal to zero. The SR LE estimates using direct measurements of R_n and *G* were strongly correlated with LE from EC$_{resid}$ and from EC$_{IRGA}$. Estimates of LE from SR derived with modelled SWi and DisALEXI R_n approaches were both significantly correlated with LE from EC$_{resid}$, but both

overestimated LE from EC$_{resid}$ and EC$_{IRGA}$ at higher fluxes. LE residual derived from MODIS R_n performed the weakest overall. Neglecting *G* had minimal impact on the general agreement between LE from SR and LE from both EC approaches, but assuming $G = 0$ did cause greater scatter. Our results suggest that LE from SR requires a more rigorous R_n modelling approach using satellites if there are no local net radiation measurements that can be used. For example, errors of LE estimations using the modelled R_n from SWi and the DisALEXI (Figs. 6, 7) are consistent with the error structures of the corresponding R_n estimations (shown in Fig. 2) such as the modelled R_n from SWi being consistent with R_n tower measurements at high values while tending to underestimate R_n at low values. Otherwise significant bias in daily LE could result (Table 1).
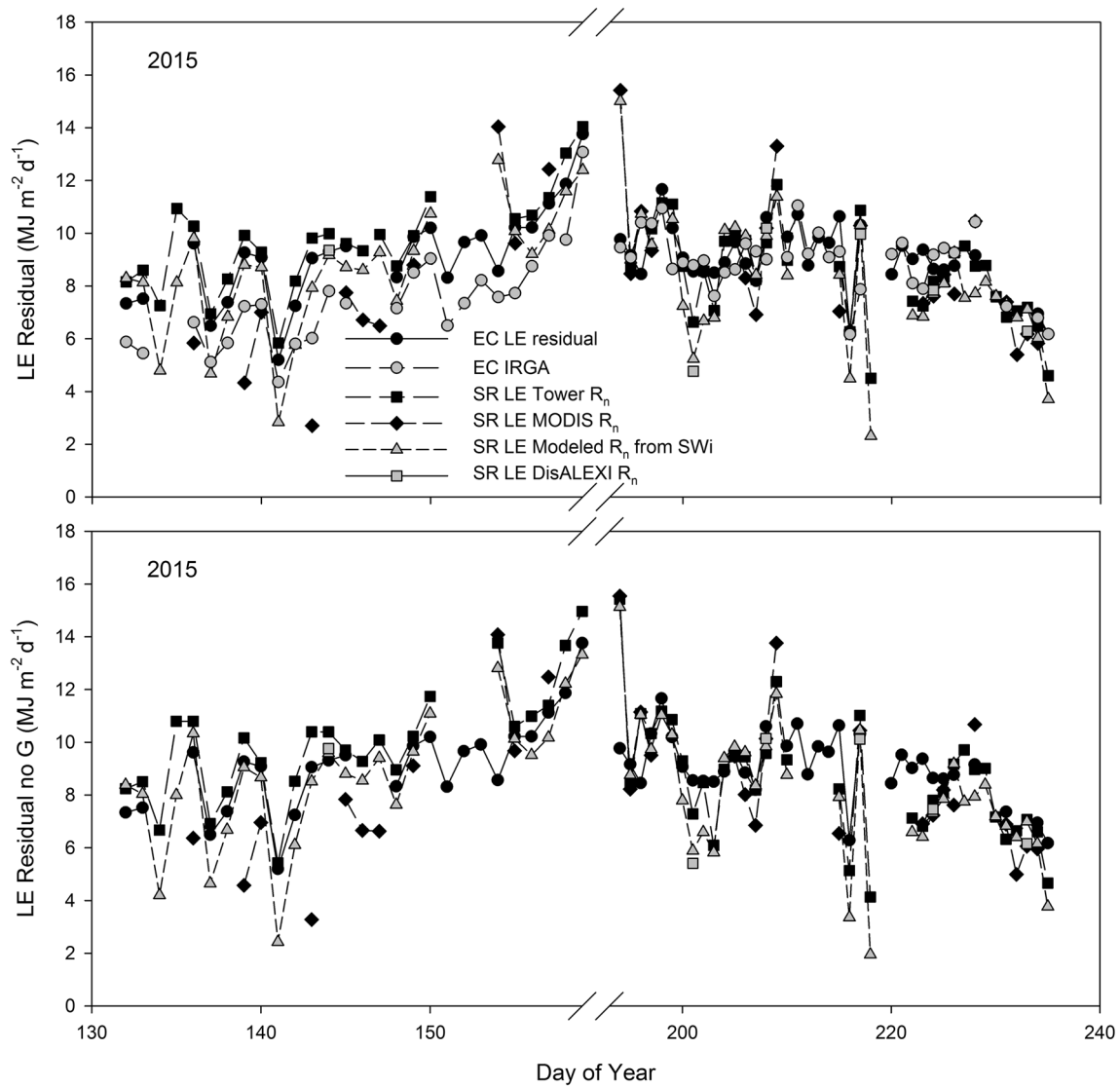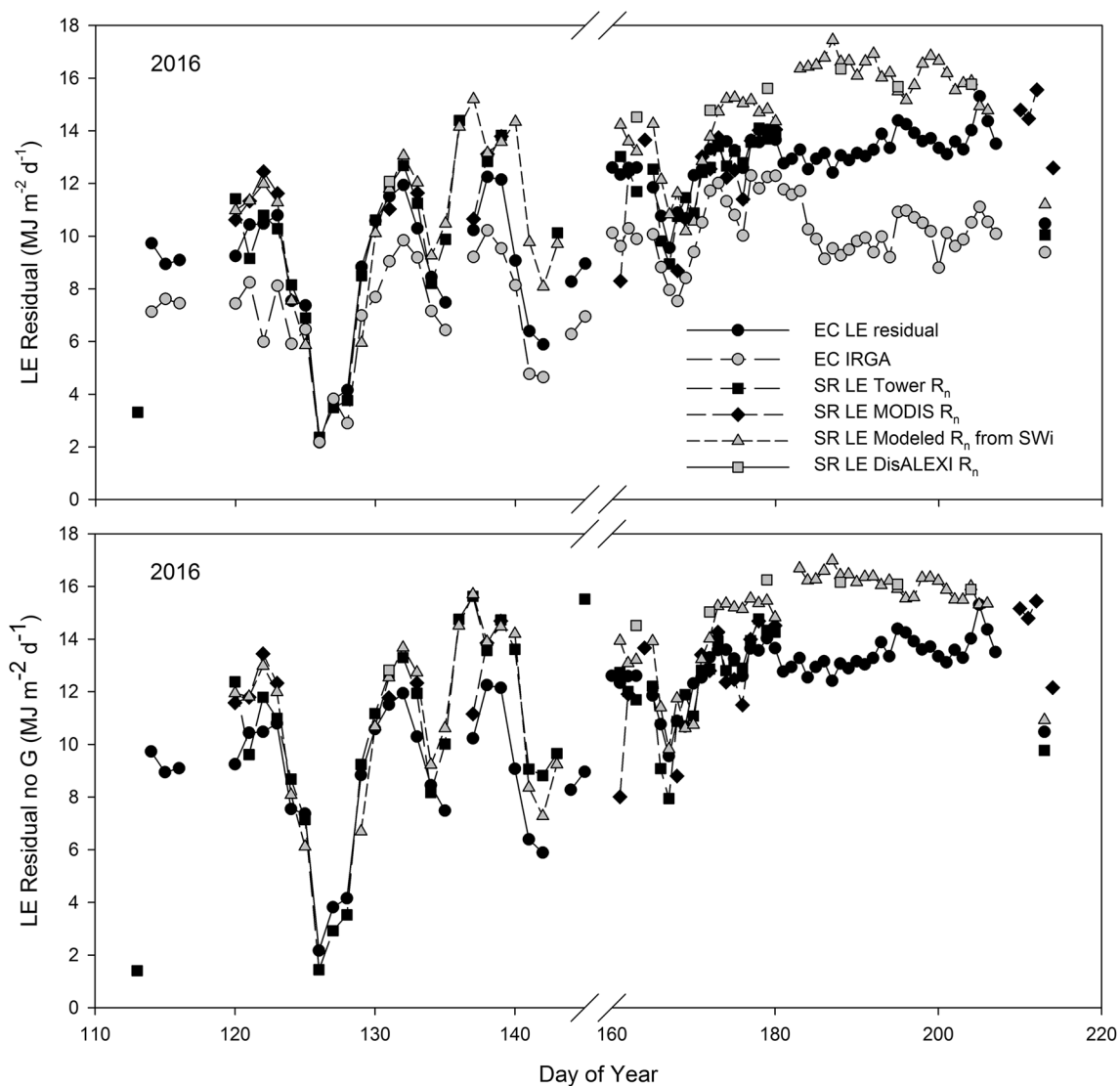
Fig. 4 Estimates of latent heat flux (LE) from Eddy covariance and Surface Renewal using direct measurements and modelled values of net radiation from the GRAPEX site captured during the 2015 growing season. Three different modelled net radiation values were used from the MODIS, Modelled SWi, and DisALEXI (see comparison in Fig. 2), and were the residual was calculated using the ground heat flux measured directly (top panel) or assumed to equal zero on a daily basis (bottom panel)

Fig. 5 Estimates of latent heat flux (LE) from Eddy covariance and Surface Renewal using direct measurements and modelled values of net radiation from the GRAPEX site captured during the 2016 growing season. Three different modelled net radiation values were used from the MODIS, Modelled SWi, and DisALEXI (see comparison in Fig. 2), and were the residual was calculated using the ground heat flux measured directly (top panel) or assumed to equal zero on a daily basis (bottom panel)
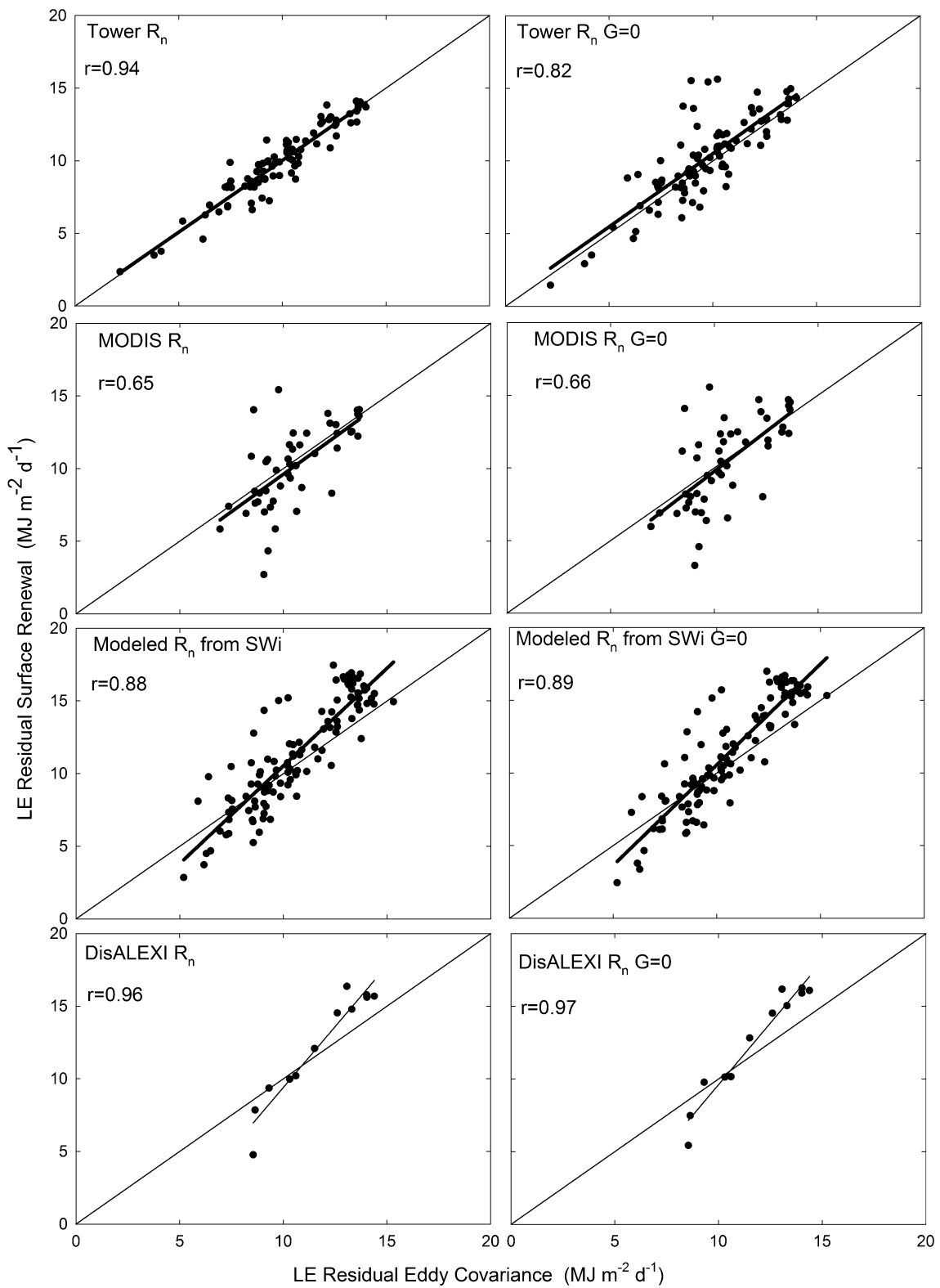
Fig. 6 Relationships between latent heat flux (LE) residual estimates derived using Eddy Covariance and Surface Renewal with direct measurements of net radiation (top row) and modelled radiation (bottom 3 rows) with ground heat flux measured directly (left column) or assumed to equal zero on a daily basis (right column)
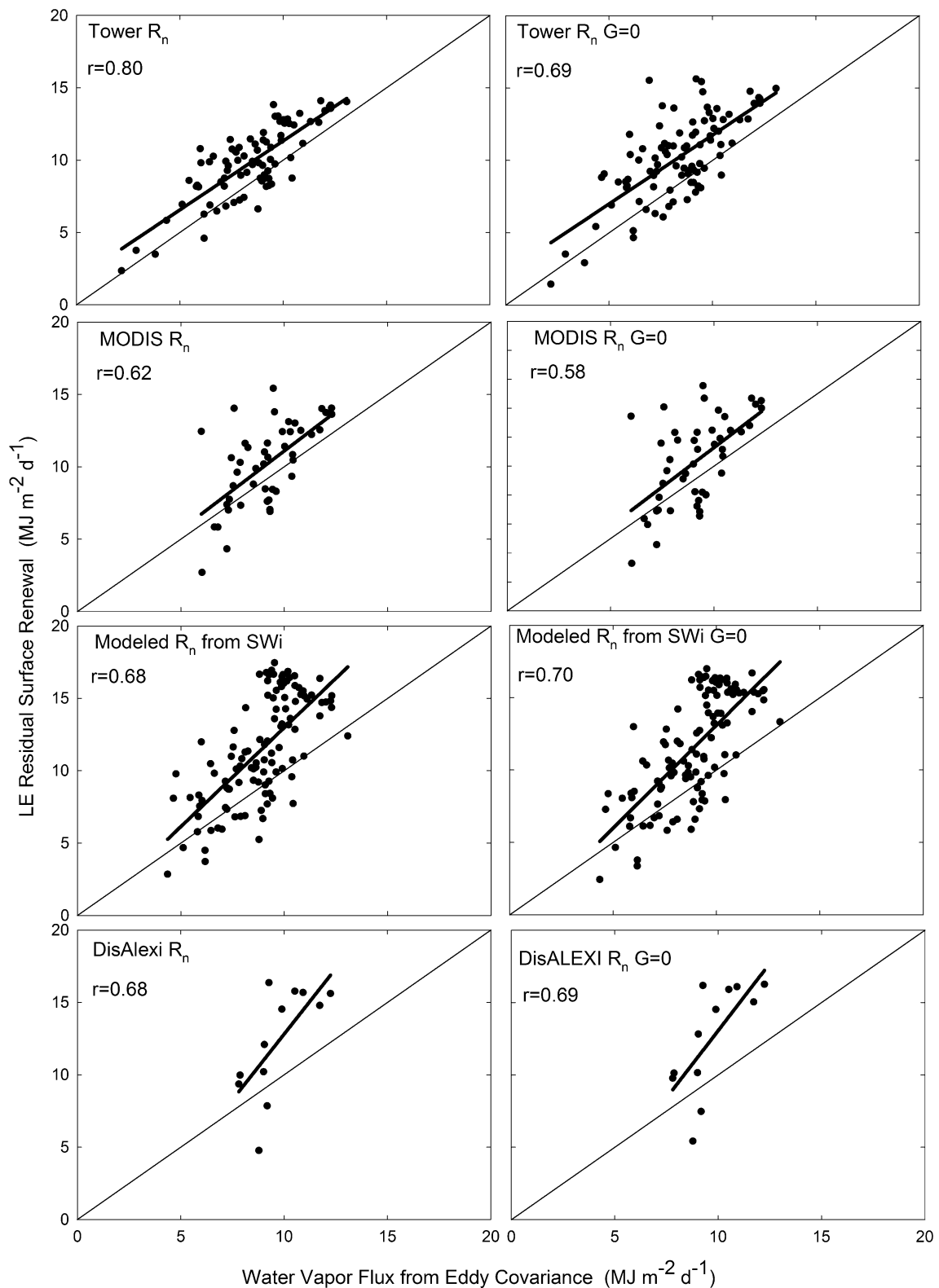
Fig. 7 Relationships between latent heat flux (LE) from Eddy Covariance using water vapour concentration measurements and LE residual estimates derived using Surface Renewal with direct measurements of net radiation (top row) and modelled radiation (bottom 3 rows) with ground heat flux measured directly (left column) or assumed to equal zero on a daily basis (right column)

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