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Technical Note: Differences in the diurnal pattern of soil respiration under adjacent *Miscanthus x giganteus* and barley crops reveal potential flaws in accepted sampling strategies.

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Abstract. For convenience, measurements used to compare soil respiration (R_s) from different land uses, crops or management practices are often made between 09:00-16:00, with an implicit assumption that R_s is largely controlled by temperature. Three months' continuous data presented here show distinctly different diurnal patterns of R_s between barley (*Hordeum vulgare*) and *Miscanthus x giganteus* (*Miscanthus*) grown on adjacent fields. Maximum R_s in barley occurred during the afternoon and correlated with soil temperature, whereas R_s peaked in *Miscanthus* during the night and was significantly correlated with earlier levels of solar radiation, probably due to delays in translocation of recent photosynthate. Since daily mean R_s in *Miscanthus* coincided with levels 40% greater than the mean in barley, it is vital to select appropriate times to measure R_s if only single daily measurements are to be made.

Keywords

Soil respiration, *Miscanthus x giganteus*, barley, diurnal patterns, photosynthesis, carbon dioxide (CO_2), greenhouse gas

(GHG), solar radiation, PAR

1 Introduction

Soil respiration (R_s) is a major process in the global carbon (C) cycle, contributing approximately 30% of ecosystem respiration (Bond-Lamberty and Thomson, 2010). Though the controls on R_s are less-well described than for photosynthesis, as atmospheric carbon dioxide (CO_2) concentrations pass 400 ppm it is becoming increasingly important to improve our understanding of this important biological process. The implications that changes in R_s might have for climate change have long been discussed (Schlesinger and Andrews, 2000) and in recent years the attention given to the potential of soils to sequester large amounts carbon to mitigate rising levels of atmospheric CO_2 through management practices (e.g. Gattinger et al., 2012) demands that we measure all aspects of the global carbon cycle, including R_s, as accurately as possible.

The most common method used to measure R_s is the closed chamber technique (Mosier, 1989) with manual chambers tending to be monitored from a weekly to monthly basis (e.g. Drewer et al., 2012; Toma et al., 2011; von Arnold et al., 2005). R_s is generally accepted to be largely controlled by soil temperature (Bond-Lamberty and Thomson, 2010) with the consequence that many studies consider it sufficient to use a single simultaneous daily measurement of R_s to test for

5 differences between different land uses or vegetation types and to extrapolate long-term budgets, (e.g. Barrena et al., 2013; Finocchiaro et al., 2014; Gauder et al., 2012; Johnson et al., 2010; Shvaleva et al., 2014; von Arnold et al., 2005; Zhang et al., 2013). Whilst the importance of selecting appropriate and synchronous sampling times is commonly recognised, measurement "windows" often vary across two hours (Kessavalou et al., 1998; Zhang et al., 2013) to as much as seven (Finocchiaro et al., 2014) or even eight hours (Gao et al., 2014), generally between 09:00-16:00; however, none of these

10 cited studies provided any data to support these windows which are largely based on minimising time delays between comparisons and assumptions that minimised temperature changes are the key to measurement parity. Although work has been undertaken to ascertain the most suitable time of day to sample R_s manually (e.g. Savage and Davidson, 2003; Wang et al., 2012), these studies have focussed on a single vegetation type or land use thus do not resolve the issue of selecting the most appropriate sampling time at which to make comparisons between different experimental treatments or crops.

15 In the current work the aim was to compare the R_s fluxes between two adjacent crops, as part of a fuller quantification of ecosystem C budgets. The two crops monitored in this study were the conventional arable crop barley (*Hordeum vulgare*), the second most widely planted arable crop in the UK (DEFRA, 2014), and the perennial grass species *Miscanthus x giganteus* (henceforth *Miscanthus*), which is increasingly cultivated as an energy crop. In this study the use of automated chambers allowed the collection of near-continuous measurements of R_s and the resulting data set was used to investigate the

20 effect of sampling time and crop on R_s, and how this might differ across a period of several months.

2 Methods & materials

2.1 Study site and experimental design

Soil respiration (R_s) was measured using automated chambers and infrared gas analyser (IRGA, Licor LI-8100-101A, Lincoln NE, USA) with multiplexers (Electronic workshops, Department of Biology, University of York, York UK) beneath

25 a seven year-old stand of *Miscanthus* and an April-sown spring barley in adjacent fields on a farm in the east of the United Kingdom (see Drewer et al., (2012) for a full site description). Chambers (n=6) were placed at random within separate plots at least 1.5 m apart in the two fields and so were treated as independent replicates; chambers were seated over PVC collars (diameter 20 cm) inserted *ca.* 2 cm into the soil which remained in situ throughout the study, which was undertaken from May to August 2013. Collars did not exclude roots and no above-ground vegetation was included. Soil temperature and

30 moisture at 5 cm depth were also measured every 15 minutes adjacent to each chamber collar and averaged over hourly intervals (Delta-T DL2 and GP1 loggers, SM200 soil moisture probes and ST1 temperature probes; Delta-T, Cambridge

UK), and hourly meteorological data (solar radiation, air temperature) were recorded onsite using a weather station (WP1, Delta-T, Cambridge UK).

2.2 Data processing and analyses

The chambers were programmed to close for two minutes during measurement, with a 30 second 'dead band' to allow for mixing of the headspace in a continuous cycle between chambers; fluxes were calculated as linear regressions of CO_2 concentration against time and corrected for volume and temperature using the Licor software (see Licor manual) and subsequent analyses were conducted using SAS 9.3 (SAS Institute, Cary NC USA). In the first instance the R_s flux data were hourly averaged for each of the individual three months of the study, but to enable diurnal patterns to be more clearly identified, deviation from the daily mean was ascertained by subtracting hourly fluxes from the daily mean R_s and the data for each month were subsequently averaged. Cumulative R_s fluxes were calculated by trapezoidal integration for each chamber within both crops and averaged to estimate the total flux; data were not gap-filled, instead where there were gaps in the data for one crop, the corresponding fluxes from the other were omitted from the calculation to estimate cumulative flux. This resulted in a loss of 15 days over the study period (five days in May, six in June and four in July) which represented a total coverage of 80%. . These estimates were then used to investigate the influence of sampling hour on the monthly cumulative estimate of R_s by comparing cumulative fluxes calculated using individual sampling hours (e.g. deriving a cumulative estimate of R_s by integrating only fluxes measured between 14.00 and 15.00) and those using all measurements for each month. These estimates were tested for normality and differences in the whole-period cumulative flux were tested using one-way analysis of variance; the effect of crop, sampling hour and month were tested using a mixed-effects model accounting for the repeated estimated totals from each chamber for each month (PROC MIXED in SAS, using the 'repeated' statement and an autoregressive covariance structure) .

Ancillary environmental data (soil temperature, soil moisture, solar radiation and air temperature) were averaged hourly and over each month using the same method applied to fluxes of R_s. These hourly averaged data were used in regression models to explain the diurnal pattern in R_s, and more detailed analyses were undertaken by performing separate regressions with flux measurements taken during the typical daily measurement window (09:00-16:00) and outside of this window. A further analysis was completed by performing regressions of fluxes against 'lagged' measurements of solar radiation, i.e. the effect of prior levels of solar radiation on R_s was tested.

3 Results and discussion

At the start of the study period (May) R_s tended to be higher in the *Miscanthus* than the barley (Fig 1), but this reversed during June and higher fluxes of R_s were consistently seen under the barley until the end of July. Highest rates of R_s were seen in the barley during early July (*ca.* 1500 mg m^{-2} h^{-1}) and declined soon after, whereas R_s climbed steadily under the *Miscanthus* until it reached a maximum of *ca.* 800 mg m^{-2} h^{-1} towards the end of July (Fig 1).

3.1 Diurnal pattern of R_s

The hourly monthly averaged fluxes revealed strong diurnal patterns for R_s in both crops (Fig. 2). Consistently, R_s peaked between 12:00-15:00, was lowest around 05:00 and daily means at 09.00 and *ca.* 20.00 for all three months in barley, but R_s changed distinctly in the *Miscanthus* across the 3 months of the study. The magnitude of the daily variation in R_s was

5 remarkably different between the two crops (Fig. 2): for both barley and *Miscanthus* the daily minima were *ca.* 10 % below the daily mean across the study, but where the maxima in barley increased from *ca.* 15% in May, to 20% in June to as much as 40% above the daily mean in July, it declined in *Miscanthus* from 20% in May, through 15% in June and finally just 10% above the daily mean in July (Fig. 2). During May the daily pattern of R_s was similar for *Miscanthus* and barley but in June, although R_s peaked around 15:00, after initially declining it increased again so that for the period 20:00 to 04:00 was greater

10 than the daily mean. This pattern for R_s changed again through July, when the lowest daily R_s was seen at 09:00 coinciding with the daily mean for barley, whilst R_s for *Miscanthus* did not increase above the daily mean value until 18:00 peaking at 21:00, fully five hours later than the peak in the barley.

Cumulative R_s flux was higher from barley over the entire study period ($F_{[1,8]}$=6.62, p<0.04), there was a strong and significant effect of the chosen sampling hour on that estimate ($F_{[23,568]}$= 4.28, p< 0.0001) and a resulting strong significant

15 difference between monthly totals ($F_{[2, 568]}$= 901.35, p< 0.0001). There was a significant interaction between sampling hour and crop type ($F_{[23,568]}$= 3.40, p< 0.0001), emphasising that it is not at all valid to assume that measurements made in the adjacent two crops at the same time were sufficient for comparisons of total R_s flux. Indeed, if the same protocol were used over several months, the significant interaction between crop and month ($F_{[2,568]}$= 202.44, p< 0.0001) shows that the shift from higher R_s in the *Miscanthus* in May to higher fluxes from the barley in June and July would be totally missed.

20 Questions must be raised regarding the validity of using blanket, common sampling strategies to compare R_s between different vegetation types, given the marked diurnal changes in R_s demonstrated here. For example, considering only the measurements taken around 15:00 in this study, in May not only would the cumulative R_s from both crops be overestimated, it would be concluded that R_s from barley was higher than or the same as for *Miscanthus*, when that clearly is far from correct (Fig. 3). Over the entire study, measurements made singly at just 15:00 would further bias the conclusions, so that in

25 July R_s from the barley would be overestimated by 40%, whilst there would be a slight underestimate from the *Miscanthus*, introducing the real possibility of not only exaggerating differences between crops, but also of creating artefactual differences simply resulting from the choice of a standardised measurement protocol.

3.2 Environmental control of R_s

30 Analysis of environmental variables showed that R_s in the barley was a function of soil temperature (Fig. 4). This was also true in the *Miscanthus* between 09:00-16:00 when soil temperature had a strong positive effect on Rs (Fig. 4) but it did not explain the night-time increase in R_s. Outside of this time window R_s was strongly positively correlated with the level of

solar radiation seen earlier in the day (Fig. 5) and we suggest that solar radiation serves as a proxy measurement of photosynthesis, with the delay a function of photosynthate translocation to roots and the rhizosphere. Having witnessed a similar such lag in an oak savannah system, Baldocchi et al. (2006) propose a similar explanation. Although there is the potential that a discrepancy between depth of R_s source and the measurement depth of soil temperature (5 cm) might explain

5 the asynchronicity, however, hysteresis between response of R_s to soil temperature across many depths has been shown (e.g. Oikawa et al., 2014) and would suggest that such a response as seen in *Miscanthus* in this study is controlled by something other than soil temperature. This is further supported by the study of Gavrichkova & Kuzyakov (2008) which showed that under constant temperature a diurnal response in R_s will still be evident under maize (*Zea mays*) but not from unplanted controls, and another study which demonstrated that shading maize plants will reduce the diurnal pattern in R_s (Kuzyakov

10 and Cheng, 2004). This suggestion is further strengthened as this delay increased as the *Miscanthus* crop grew taller; from six hours in May, to seven in June and ten in July. It is known that translocation is slower in taller vegetation and may also be slowed as transpiration increases (Kuzyakov and Gavrichkova, 2010), as would be expected later in the summer. An obvious physical difference between the two crops monitored in this study is that of size, with *Miscanthus* exceeding 3 m when fully grown and barley less than 0.5 m, so the speed of translocation in barley may be quicker and therefore the effect

15 of photosynthesis in this crop is more confounded with soil temperature (Kuzyakov and Gavrichkova, 2010). Differences in the diurnal pattern of R_s have been demonstrated between grass species and mesquite trees in savannah ecosystems (Barron-Gafford et al., 2011), which reflect the differences presented here of temperature decoupled peak in R_s under the taller mesquite trees occurring later in the day. Such a lag in R_s cannot be assumed under all tall vegetation, however, as studies under maize and switchgrass (*Panicum virgatum*), which share the physiological traits of height and C4 photosynthesis with

20 *Miscanthus*, demonstrated a clear diurnal relationship between R_s and soil temperature (Han et al., 2008; Huang et al., 2016).

4 Conclusions

In this study strong, clear diurnal patterns in R_s have been demonstrated, and these are not consistent between different crops, even at a single location. Without the use of an automated flux measurement system, this discrepancy would not have

25 been identified, however it is acknowledged that manual sampling techniques have an important role to play particularly when cost of equipment and access to power are a common limitation. It is therefore a matter of great importance that sampling strategies founded upon single daily measurements of R_s are undertaken at a time representative of the daily mean flux, and in order to do so it is absolutely vital that a thorough understanding of the diurnal variation is used to guide any sampling strategy. It is therefore suggested that especially in manual sampling experimental designs, the diurnal pattern of R_s

30 is first established by measuring across a full 24 hour cycle and that this is revised periodically, since it has been shown here that the diurnal cycle may change greatly over several months. Failure to do so may lead to inaccurate long term estimates, and in experimental contrasts it may cause grossly incorrect (by as much as 40%) conclusions to be drawn. Since R_s is such a critical component of the global carbon cycle, it is essential that our understanding of this process, and how it is effected by

management practices, be founded upon accurate data, which will only be achieved through well planned sampling strategies.

References

Baldocchi, D., Tang, J. W., and Xu, L. K.: How switches and lags in biophysical regulators affect spatial-temporal variation of soil respiration in an oak-grass savanna, Journal of Geophysical Research-Biogeosciences, 111, 13, 2006.

Barrena, I., Menendez, S., Dunabeitia, M., Merino, P., Stange, C. F., Spott, O., Gonzalez-Murua, C., and Estavillo, J. M.:

5   Greenhouse gas fluxes (CO_2, N_2O and CH_4) from forest soils in the Basque Country: Comparison of different tree species and growth stages, Forest Ecology and Management, 310, 600-611, 2013.

Barron-Gafford, G. A., Scott, R. L., Jenerette, G. D., and Huxman, T. E.: The relative controls of temperature, soil moisture, and plant functional group on soil CO_2 efflux at diel, seasonal, and annual scales, Journal of Geophysical Research-Biogeosciences, 116, 16, 2011.

10   Bond-Lamberty, B. and Thomson, A.: A global database of soil respiration data, Biogeosciences, 7, 1915-1926, 2010.

Clifton-Brown, J. C., Stampfl, P. F., and Jones, M. B.: Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions, Global Change Biology, 10, 509-518, 2004.

DEFRA: Farming statistics, final crop areas, yields, livestock populations and agricultural workforce at June 2014, 2014.

Drewer, J., Finch, J. W., Lloyd, C. R., Baggs, E. M., and Skiba, U.: How do soil emissions of N_2O, CH_4 and CO_2 from

15   perennial bioenergy crops differ from arable annual crops?, Global Change Biology Bioenergy, 4, 408-419, 2012.

Finocchiaro, R., Tangen, B., and Gleason, R.: Greenhouse gas fluxes of grazed and hayed wetland catchments in the US Prairie Pothole Ecoregion, Wetlands Ecology and Management, 22, 305-324, 2014.

Gao, Q., Hasselquist, N. J., Palmroth, S., Zheng, Z. M., and You, W. H.: Short-term response of soil respiration to nitrogen fertilization in a subtropical evergreen forest, Soil Biology & Biochemistry, 76, 297-300, 2014.

20   Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P., Stolze, M., Smith, P., Scialabba, N. E. H., and Niggli, U.: Enhanced top soil carbon stocks under organic farming, Proceedings of the National Academy of Sciences of the United States of America, 109, 18226-18231, 2012.

Gauder, M., Butterbach-Bahl, K., Graeff-Honninger, S., Claupein, W., and Wiegel, R.: Soil-derived trace gas fluxes from different energy crops - results from a field experiment in Southwest Germany, Global Change Biology Bioenergy, 4, 289-

25   301, 2012.

Gavrichkova, O. and Kuzyakov, Y.: Ammonium versus nitrate nutrition of *Zea mays* and *Lupinus albus*: Effect on root-derived CO_2 efflux, Soil Biology & Biochemistry, 40, 2835-2842, 2008.

Han, G.-x., Zhou, G.-s., and Xu, Z.-z.: Temporal variation of soil respiration and its affecting factors in a maize field during maize growth season, Shengtaixue Zazhi, 27, 1698-1705, 2008.

30   Huang, J., Gao, Z. J., Chen, J., Zhang, H., and Xu, B. C.: Diurnal and seasonal variations of soil respiration rate under different row-spacing in a *Panicum virgatum* L. field on semi-arid Loess Plateau of China, Journal of Arid Land, 8, 341-349, 2016.

Johnson, J. M. F., Archer, D., and Barbour, N.: Greenhouse Gas Emission from Contrasting Management Scenarios in the Northern Corn Belt, Soil Science Society of America Journal, 74, 396-406, 2010.

Kessavalou, A., Mosier, A. R., Doran, J. W., Drijber, R. A., Lyon, D. J., and Heinemeyer, O.: Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management, Journal of Environmental Quality, 27, 1094-1104, 1998.

Kuzyakov, Y. and Cheng, W.: Photosynthesis controls of CO_2 efflux from maize rhizosphere, Plant and Soil, 263, 85-99, 2004.

Kuzyakov, Y. and Gavrichkova, O.: REVIEW: Time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls, Global Change Biology, 16, 3386-3406, 2010.

Mosier, A. R.: Chamber and isotope techniques, Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, 47, 175-187, 1989.

Oikawa, P. Y., Grantz, D. A., Chatterjee, A., Eberwein, J. E., Allsman, L. A., and Jenerette, G. D.: Unifying soil respiration pulses, inhibition, and temperature hysteresis through dynamics of labile soil carbon and O_2, Journal of Geophysical Research-Biogeosciences, 119, 521-536, 2014.

Savage, K. E. and Davidson, E. A.: A comparison of manual and automated systems for soil CO_2 flux measurements: trade-offs between spatial and temporal resolution, Journal of Experimental Botany, 54, 891-899, 2003.

Schlesinger, W. H. and Andrews, J. A.: Soil respiration and the global carbon cycle, Biogeochemistry, 48, 7-20, 2000.

Shvaleva, A., Silva, F. C. E., Costa, J. M., Correia, A., Anderson, M., Lobo-do-Vale, R., Fangueiro, D., Bicho, C., Pereira, J. S., Chaves, M. M., Skiba, U., and Cruz, C.: Comparison of methane, nitrous oxide fluxes and CO_2 respiration rates from a Mediterranean cork oak ecosystem and improved pasture, Plant and Soil, 374, 883-898, 2014.

Toma, Y., Fernandez, F. G., Sato, S., Izumi, M., Hatano, R., Yamada, T., Nishiwaki, A., Bollero, G., and Stewart, J. R.: Carbon budget and methane and nitrous oxide emissions over the growing season in a Miscanthus sinensis grassland in Tomakomai, Hokkaido, Japan, Global Change Biology Bioenergy, 3, 116-134, 2011.

von Arnold, K., Nilsson, M., Hanell, B., Weslien, P., and Klemedtsson, L.: Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests, Soil Biology & Biochemistry, 37, 1059-1071, 2005.

Wang, Y. D., Wang, H. M., Wang, Z. L., Zhang, W. J., Guo, C. C., Wen, X. F., and Liu, Y. F.: Optimizing manual sampling schedule for estimating annual soil CO_2 efflux in a young exotic pine plantation in subtropical China, European Journal of Soil Biology, 52, 41-47, 2012.

Zhang, Z. H., Duan, J. C., Wang, S. P., Luo, C. Y., Zhu, X. X., Xu, B. B., Chang, X. F., and Cui, S. J.: Effects of seeding ratios and nitrogen fertilizer on ecosystem respiration of common vetch and oat on the Tibetan plateau, Plant and Soil, 362, 287-299, 2013.
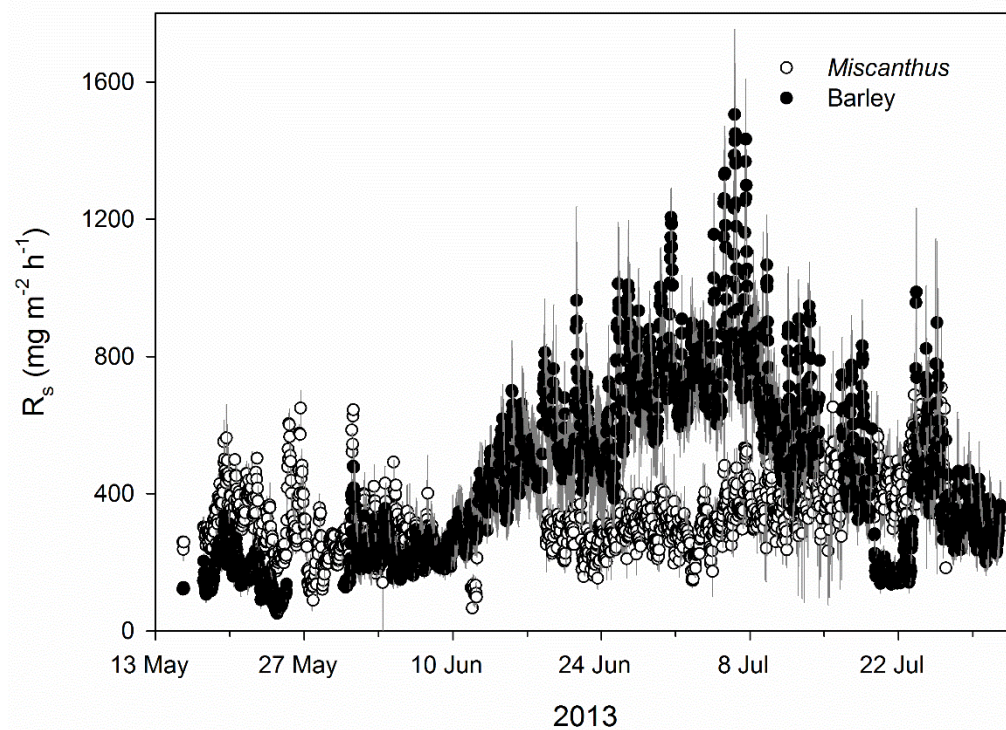
Figure 1. Mean (± 1SE, n=6) R_s from under *Miscanthus* and barley crops during summer 2013, measured using Licor automatic flux chambers.
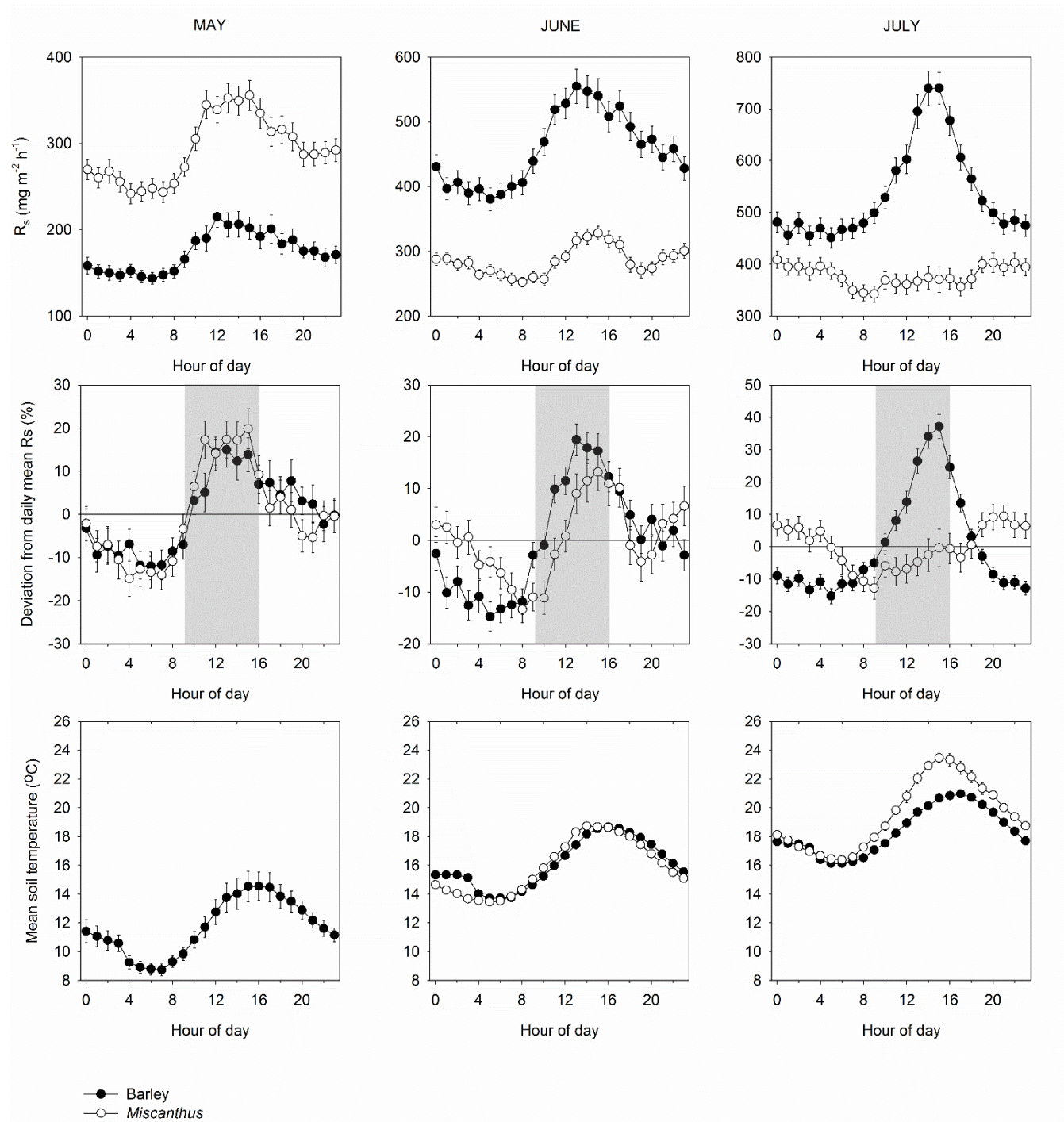
Figure 2. The diurnal pattern of R_s **and soil temperature at 5 cm depth** for each month of the study for barley and *Miscanthus* crops. Values shown are mean (± 1SE) average hourly absolute values of flux R_s (top row) and deviation from the daily mean (middle row). The shaded area of the middle panels represents the typical measurement window during which

manual sampling would take place. Zero deviation represents the daily mean flux, positive deviation representing fluxes greater than the mean and negative fluxes smaller than the mean.

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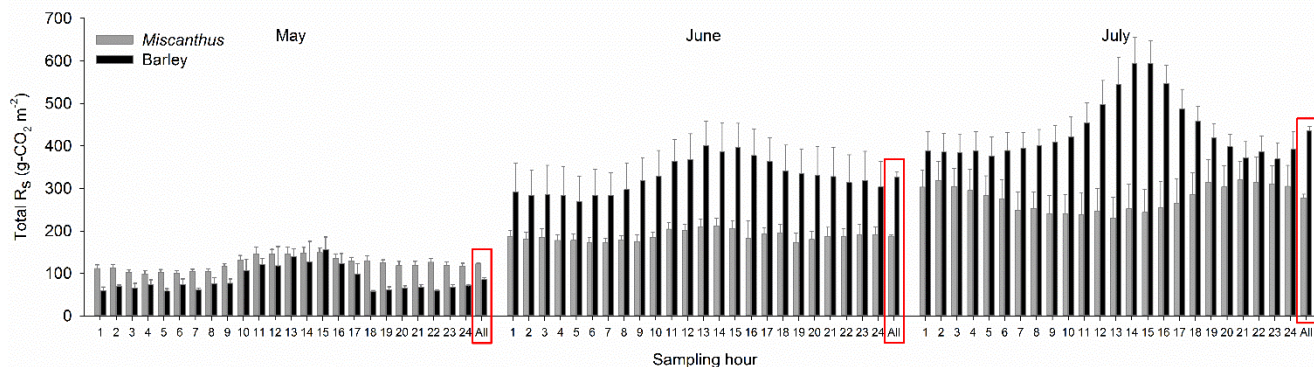
Figure 3. Estimates of the cumulative flux R_s under *Miscanthus* and barley crops using measurements taken using only single hours (1-24) or continuous measurements (All) across three months in summer 2013. Values shown are mean cumulative flux ($\pm$ 1SE, n=6).

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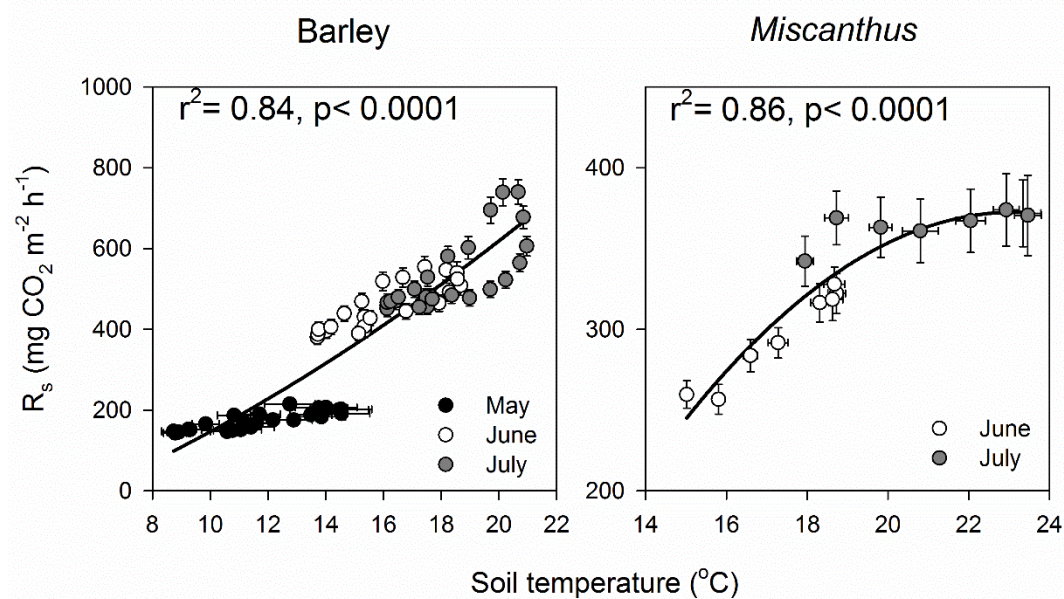
Figure 4. Regression models of monthly mean average hourly (± 1SE, n=6) flux R_s and soil temperature at 5 cm depth for barley (left panel) and *Miscanthus* (right panel). Data shown include full 24 hour period for barley, but only data from the typical manual measurement window of 09:00- 16:00 (see text) for *Miscanthus*. Soil temperature data were not available for *Miscanthus* during May.
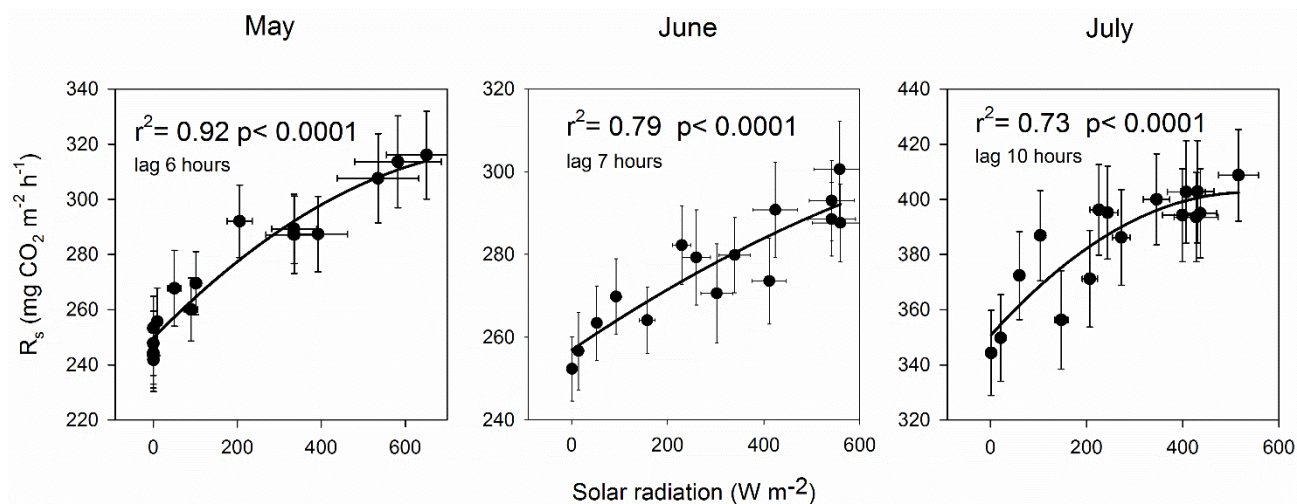
Figure 5. Response of R_s to preceding levels of solar radiation in *Miscanthus* outside of the typical manual measurement window (see text). Values shown are hourly means ($\pm$1SE n=6) averaged over each month. The lag time is the length of the offset between the measured solar radiation and the R_s, e.g. for May the relationship shown is that of solar radiation at 12.00 and R_s measured at 18.00 (lag time= 6 hours).

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