

# Surface energy flux measurements in a flooded and an aerobic rice field using a single eddy-covariance system

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**Abstract** About 90 % of the global rice production takes place in Asia, while European production is quantitatively modest. Italy is the Europe's leading producer, with over half of total production concentrated in a large, traditional paddy rice area in the north of the country. High irrigation requirement for continuous flooding encourages the adoption of water saving techniques. In 2013, an intense monitoring activity was conducted on two fields characterized by continuous flooding and intermittent irrigation regimes, with the aim of comparing their agronomical and hydrological effects, including their influence on the energy balance. An eddy covariance station was installed on the levee between the two fields, to monitor latent (LE) and sensible (H) heat fluxes as a function of wind direction. Additionally, the fields were instrumented with net radiometers, soil heat flux (G) plates, thermistors, tensiometers, and multilevel moisture probes. Three footprint models were applied to determine position and size of the footprint area at each monitoring time step, providing similar results. Two half-hourly turbulent fluxes datasets were obtained, one for each irrigation regime, each one comprising about 10 % of the daytime time steps over the agricultural season. The reliability of the monitoring performed with a single EC station was confirmed by the energy balance closure ( $H + LE$  versus  $R_n - G$ ), showing an imbalance lower than 10 % for both the regimes. A detailed analysis of the effect of the storage terms on the ground heat flux

estimation and a more thorough analysis of the radiation balance for the two plots were also performed.

**Keywords** Surface energy fluxes · Eddy covariance technique · Evapotranspiration · Flooded rice · Aerobic rice · Northern Italy

## Introduction

Rice is of great importance both from a food supply point of view, since it represents the main food in the diet of over half the world's population, and from a water resources point of view, since it consumes almost 40 % of the water amount used for irrigation (Bouman et al. 2007a). About 90 % of global production takes place in Asia (EUROSTAT 2013), while European production is quantitatively modest (about 3 million tons). However, Italy is the Europe's leading producer, with over half of total production and a high quality level. The most important rice-growing region consists of the portion of the Po river plain located east of the Ticino river, straddling the regions of Lombardy and Piedmont in northern Italy.

Rice is traditionally grown in banded fields that are kept flooded from crop establishment to close to harvest by maintaining a ponded water depth of about 5–10 cm (Bouman et al. 2007a). Owing to this particularly demanding water management and to the large harvested area, it is estimated that the total seasonal water input to irrigated rice (rainfall plus irrigation) can be up to 2–3 times more than for other cereals, like wheat or maize (Tuong and Bhuiyan 1999, Tuong et al. 2005).

The increasing scarcity of water threatens the sustainability of the irrigated rice production system and hence the food security and livelihood of rice producers and

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consumers. Therefore, a more efficient use of water is becoming a pressing need. In the last years, several strategies are being applied to reduce the water consumption of rice, such as saturated soil culture (Borell et al. 1997), alternate wetting and drying (Li 2001; Tabbal et al. 2002), raised beds (Singh et al. 2002), and aerobic rice (Bouman et al. 2007b). In particular, aerobic rice greatly reduces seepage, percolation, and evaporation losses, as no standing water is present at any time during the cropping season. Moreover, the rainfall use becomes more effective, which helps in enhancing water productivity. At the same time, this irrigation regime allows to reduce the loss of sediment and soil fertility (Tabbal et al. 2002; Dunn and Gaydon 2011, Belder et al. 2007; Yadav et al. 2011; Bouman et al. 2007b; Govindarajan et al. 2008; Lampayan and Bouman 2005).

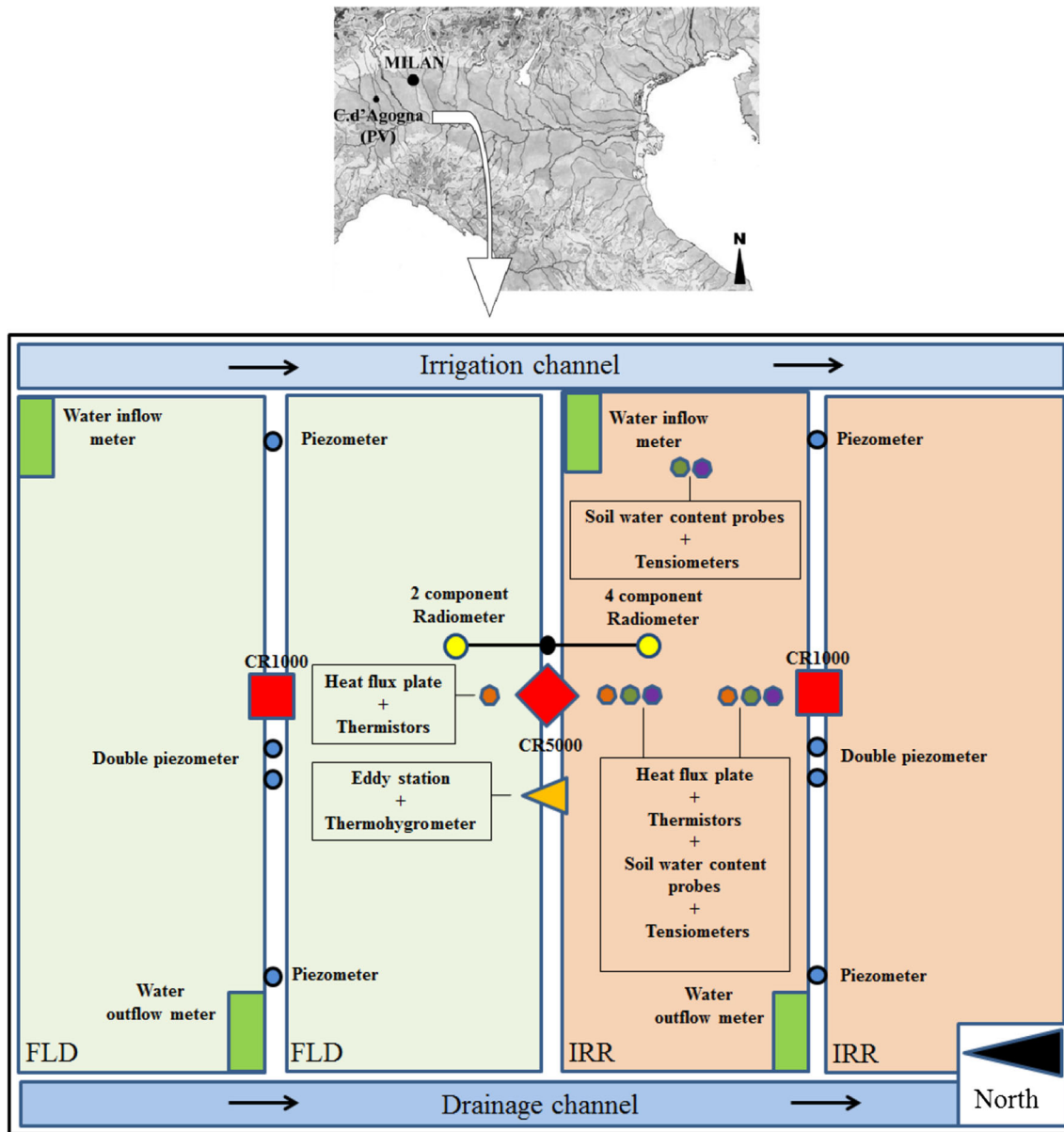
Studies that aim to compare energy exchanges between rice fields and the atmosphere in the case of different irrigation managements are still rare in the literature (to the authors knowledge entirely absent in northern Italy) and, for this reason, of particular interest. Experimental campaigns for the monitoring of surface energy fluxes over rice fields are mainly conducted in Asia territories (Alberto et al. 2011). Zhao et al. (2008) used the eddy covariance (EC) method to study the effects of conversion of marshland to croplands (rice and soybean cultivation) on water and energy exchanges in north eastern China. Tsai et al. (2007) studied the surface energy components of a rice paddy in Taiwan using an EC system. Some studies compared the EC technique with other micrometeorological methods (flux variance and surface renewal) to estimate sensible and latent heat fluxes (Zhao et al. 2010; Castellvi and Snyder 2009; Hsieh et al. 2008). Saito et al. (2007) examined the nature of vertical transport of sensible heat and water vapor density due to mesoscale motions and how they were observed by EC systems. Furthermore, Gao et al. (2003) conducted EC measurements on fluxes of water vapor, heat, and CO<sub>2</sub> in a near surface layer over a rice paddy in Central Plain of China, and Saito et al. (2005) reported the seasonal variation of CO<sub>2</sub> exchange in a rice paddy field at Mase site in Japan. As reported by Alberto et al. (2011), only few studies over non-irrigated upland rice or sprinkler-irrigated rice have been conducted (Tyagi et al. 2000; Campbell et al. 2001a, 2001b; Castellvi et al. 2006).

Despite the efforts to investigate surface partitioning of the available energy into sensible and latent heat fluxes (Rowntree 1991; Dickinson et al. 1991), there is still considerable uncertainty on the magnitude of the energy fluxes from rice ecosystems (Miyata et al. 2000, Yan et al. 2012). Paddy rice fields are very different from other crops, because the presence of water on the ground substantially affects the surface energy balance components (Terjung

et al. 1989; Tsai et al. 2007). Differences between flooded and aerobic conditions on flux exchanges in rice fields were early studied by Harazono et al. (1998). They presented the energy balance components measured above a rice canopy during both the drained and flooded periods for a short period of time (about 10 days). They showed that the soil heat flux was strongly influenced by the water column on the ground, and that the water storage term became as large as soil heat flux during daytime reaching values of about 5–8 % of net radiation. Moreover, they showed that during daytime hours, in aerobic conditions, latent heat accounted for about 72–73 % of net radiation, whereas both sensible and soil heat fluxes accounted for about 7–8 %. Under flooded conditions, latent heat flux was 65–79 % of net radiation, while sensible and soil heat fluxes were about 8 and 15 %, respectively.

A scrupulous analysis of daily patterns of turbulent fluxes over a rice paddy in China was reported by Gao et al. (2003). They investigated fast and slow response meteorological variables, determining surface roughness using the Martano (2000) method and analysing the adequacy of the fetch through an accurate footprint analysis described in Harazono et al. (1998). Footprint analysis is largely used to quantify the contributing source areas to the scalar flux measurement (Tsai et al. 2010). This is especially important when the ecosystems of interest are inhomogeneous (natural ecosystems) or their extensions are limited (agricultural fields). The ratio of fetch-to-height quoted in literature is extremely variable. Originally, a rule of thumb strongly recommended was that the ratio between the two terms had to be about 100–1 (Dyer 1963). Baldocchi and Rao (1995) found that this ratio could be reduced to 75–1, while in the works of Horst (1999), Tsai and Tsuang (2005) a ratio of 28–1 was reported. In literature, different footprint models were adopted to evaluate the fetch of turbulent fluxes over rice fields. Schuepp et al. (1990) analytical footprint model was used in the works of Gao et al. (2003), (2006) over an homogeneous field of about one hectare, while Hsieh et al. (2000) model was implemented in the study of Tsai et al. (2010) over an heterogeneous terrain of about 80 hectares. Generally, the range of applicability of these models is based on the stability conditions of the atmosphere (Masseroni et al. 2014).

Following this research framework, in this study the surface energy balance fluxes measured in two rice fields characterized by different irrigation treatments (continuous flooding and intermittent irrigation) and located in northern Italy were analyzed and compared. Latent and sensible heat fluxes were acquired using only one EC system installed on the levee between them. The results of three analytical footprint models were examined and compared to select, at each time step, the turbulent fluxes originated from each of the two fields. Two



**Fig. 1** Position of the Castello D'Agogna site, experimental design, and instruments installed

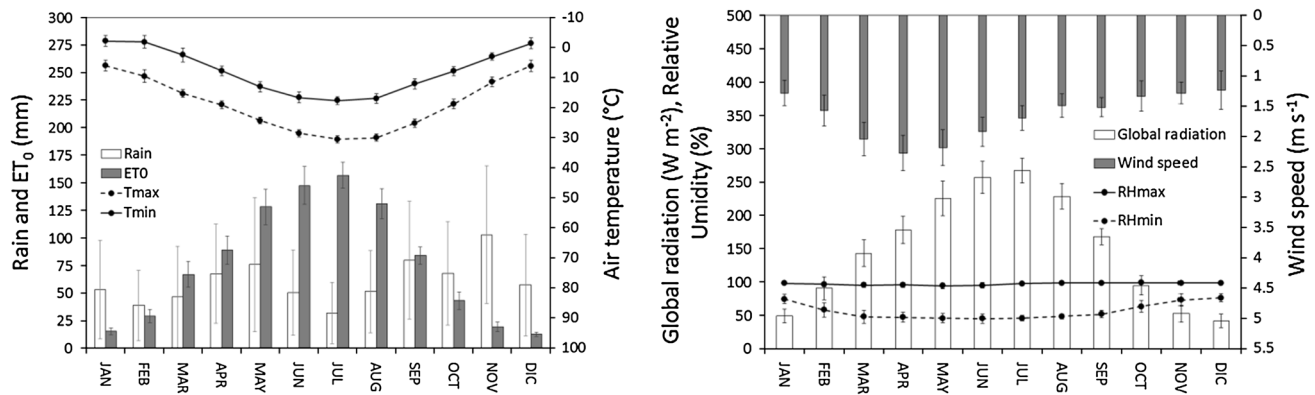
software for the post-elaboration of surface turbulent fluxes were compared: the first one is Eddy Pro 4.2.1 (LICOR, USA), widely recognized and adopted by the international community, while the second is a code developed for a more operational use, which requires half-hourly data as inputs instead of high-frequency data (Corbari et al. 2012). The effects of soil and water energy storages on the soil heat flux  $G$  for the two irrigation treatments, as well as the differences in net radiation  $R_n$  over the two canopies, were moreover assessed. Finally, the energy balance closure for the two irrigation treatments was computed, allowing to assess

the reliability of the EC measurements performed with a single eddy covariance station over the two fields.

### Materials and methods

#### The Castello D'Agogna experimental site

In the agricultural season 2013, an intensive monitoring activity was carried out at the National Rice Research Centre (NRRC) located in Castello d'Agogna (Pavia, Italy), with the purpose of comparing the water and energy



**Fig. 2** Averages and standard deviations of monthly values for the main climatic parameters at the C.d'Agogna site over the last 21 years (1993–2013). Monthly total amounts are reported for rain and ETo, while for the other parameters monthly averages are shown

balance components of rice (*Gladio cv.*) under different water regimes, and assessing the possibility of reducing the high water inputs related to the conventional practice of continuous flooding.

The experiments were laid out in four plots of about  $20 \times 80$  m each (Fig. 1), with two replicates for each of the following water regimes: (i) continuous flooding with wet-seeded rice (FLD) and (ii) surface irrigation every 7–10 days with dry-seeded rice (IRR). The experimental plots were entirely surrounded by flooded rice fields. Starting from May 2013, one out of the two replicates of each treatment was instrumented with: water inflow and outflow meters, sets of piezometers, tensiometers, and multisensor moisture probes. Moreover, an eddy covariance station was installed on the levee between the FLD and IRR irrigation regimes. All the data were automatically recorded and sent by a wireless connection to a PC, so as to be remotely controlled, thanks to the development of a GUI written in Java (Chiaradia et al. 2013).

The experimental site of Castello D'Agogna is characterized by a humid subtropical climate according to the Koppen classification system. Specifically, the Po valley presents a transitional climate between the Mediterranean climate, dominated by anticyclonic patterns, and the Central European climate, dominated by the oceanic influence of westerly circulations (Confalonieri et al. 2009). Standard meteorological variables (rainfall, global radiation, air temperature and humidity, wind speed, and direction), to which is added the net radiation, are measured at hourly intervals over a grass coverage located in the experimental NRRC farm, about 100 m from the experimental fields, by a Regional Environmental Protection Agency agro-meteorological station (hereinafter referred to as ARPA station). During the agricultural season (April–September), the average temperature at the experimental site is about  $20^{\circ}\text{C}$ , while rainfall is around 360 mm, with a marked variability from year to year. The air humidity is always

high and implies the presence of foggy months during the winter and hot and muggy in the summer. Figure 2 shows the pattern of the meteorological variables measured at the ARPA station over the last 21 years (1993–2013), where the ETo (reference crop evapotranspiration) was calculated according to the FAO Penman–Monteith equation described in Allen et al. (1998).

The rice cultivar was *Gladio*, and it homogeneously covered the surface of the parcels. The sowing date was May 28th for the IRR regime, and June 7th (almost 10 days later) for the FLD regime. Germination was about ten days after the seeding for both the irrigation treatments. Flowering started on August 18th for the FLD and 21th for the IRR treatments. The harvesting date was October 14th for both the regimes.

The irrigation schedule was different for the two compared techniques and the irrigation events and the flooding periods in 2013 will be reported in Sect. 3.4. In that year, due to an exceptionally rainy spring, all the operations were postponed for a few weeks with respect to the standard schedule in northern Italy. The FLD treatment was flooded 24 h before the sowing, to allow the “washing” of the fields and reduce the problems of phytotoxicity due to the application of the oxadiazon herbicide in pre-sowing. Subsequently, an alternation between flooding and drying periods was kept, so as to allow a good rooting of seedlings, prevent soil hardening, and control algae. Once a good settlement of the crop was reached and the canopy covered uniformly the ground (end of June), the FLD treatment was dried for the weed control and nitrogen fertilization operations. Twenty-four hours after the fertilization the normal water level (8–12 cm) was restored until the crop reaches the differentiation of the panicle stage (mid- July). In that moment, a brief dry allowed the distribution of the third dose of nitrogen fertilizer, and then fields were flooded again until the definitive drying period (early September). The irrigation water management in the

**Table 1** Results of the goodness of fit analysis between PEC and EddyPro 4.2.1

	RMSE	95 % of RMSE	NSE	95 % of NSE	%NSE Very good (0.90–1.00)	%NSE Good (0.80–0.89)	%NSE Satisfactory (0.65–0.79)	%NSE Unsatisfactory (<0.65)
LE	0.24	[0.19–0.29]	0.93	[0.89–0.95]	90	9	1	0
H	0.31	[0.27–0.36]	0.90	[0.87–0.94]	87	10	3	0

case of aerobic rice (IRR) was typical of a crop subjected to periodic irrigation. The first irrigation event was about 30 days after the sowing, then water was provided to the fields every 7–10 days for a total of 12 events in 2013 (Fig. 8). The irrigation inflow in the IRR field lasted on average for 6–7 h, with a mean water level in the field of 3–5 cm. The water management satisfied the definition of aerobic rice, in fact both redox electrodes and tensiometers installed in the IRR parcel (refer to Sect. 2.2 for more details) showed that after a maximum of 2–4 days from the end of each irrigation event, soil in the root zone was again in unsaturated conditions (Table 1).

Overall, during the agricultural season three fertilizer treatments were applied in the FLD parcel and four in the IRR parcel, for a total of 160 N Kg ha<sup>-1</sup> for both irrigation treatments (60 + 60 + 40 in the first treatment and 50 + 40 + 40 + 30 in the second). Rice yield was found to be 9.78 and 7.80 tons per hectare, respectively, for FLD and IRR.

A detailed soil survey was carried out before the agricultural season. Five soil profiles were opened within the fields surrounding the study site (to avoid affecting the infiltration rate in the experimental parcels). For each genetic horizon disturbed and undisturbed soil samples were collected: the latter were used for bulk density determination, the others for routine chemico-physical analysis. Moreover, 18 explorations with a manual drill were carried out in each parcel. Measuring points were located at a constant distance over parallel transects, but transects were shifted with respect to one another, so that points were located at the vertices of triangular meshes. At each point, morpho-pedological characteristics were qualitatively described, and disturbed soil samples were collected at three different depths (0–35 cm; 40–75 cm; more than 90 cm) to be analyzed for soil texture. Results of the survey show that soils in the experimental plots are characterized by a plugged horizon of 35–40 cm with texture of loam or silty loam and a soil bulk density of 1.4–1.5 g cm<sup>-3</sup>. Below the plugged horizon there is a plow sole that extends for 10–15 cm (up to about 50 cm) with a soil bulk density of about 1.5–1.7 g cm<sup>-3</sup> and a hydraulic conductivity in the order of 10<sup>-6</sup> m s<sup>-1</sup>. Horizons below the sole show a greater variability in terms of texture (from silty clay loam to sand) and enrichment of organic substance with respect to the plugged horizon, allowing the identification of three main soil typologies. Following the USDA classification (Soil Taxonomy 11th, 2011), soils in

the site can be mainly classified as Aeric Epiaquepts coarse loamy (silty) mixed mesic.

#### Measurement of soil water status, micro-climate, fluxes, and crop parameters

The general monitoring scheme was almost the same for the two instrumented parcels, with the only exclusion of the soil water content probes, not installed in the case of the FLD treatment. In fact, in the IRR parcel three multilevel FDR water content probes (EnviroSCAN, Sentek, Australia) equipped with four sensors at the depths of 10, 30, 50, and 70 cm were installed to monitor the soil water content in the three main soil typologies. In the vicinity of these, three sets of four tensiometers were also positioned at the same depths (Spectrum Technologies, USA). For the FLD treatments, only one set of four tensiometers was installed in the most widespread soil type in the parcel. In order to verify the redox condition of the soil, two electrodes (SenTix ORP, WTW, Germany) were installed in the IRR field, while only one was positioned in the FLD field. Electrodes were installed at a depth of 10 cm and read every 3–4 days.

A 3D sonic anemometer (Young RM-81000, Campbell Scientific, USA) and an infrared gas analyzer (LI-COR 7500, LICOR, USA) for the measurement of energy and gas (H<sub>2</sub>O, CO<sub>2</sub>) exchanges were installed in early June 2013 on the narrow levee separating the two irrigation treatment IRR and FLD, as shown in Fig. 1. This choice was done to verify the possibility of using only one eddy covariance system for monitoring heat and water vapor fluxes in different rice environments, and also because the experimental fields have a limited size, thus the position of the instruments at the edge between two irrigation treatments allowed to double the homogeneous surface for each treatment (i.e., the two replicates of the same irrigation treatment were located at the two sides of the station). Instruments were held at about one meter over the canopy along the whole monitoring period (June 7th–October 2nd). This choice was supported by the results shown in Arriga (2008), who revealed that the quality of H<sub>2</sub>O and CO<sub>2</sub> fluxes could be extremely compromised if the distance between the apparatus and the surface (soil or top of the homogeneous canopy) is less than 30–40 cm. Sonic anemometer was mounted on the top of an adjustable pole thrust into the soil, while gas analyser was fixed on an aluminum arm at the same height of the anemometer but with an horizontal separation of about 30 cm and a tilt of about



30° with respect to the vertical direction. During the whole experimental period, the position of the eddy covariance station was into the equilibrium boundary layer which constitutes a necessary condition for its proper functioning as shown in the work of Kaimal and Finnigan (1994).

A four component net radiometer (CNR1, Kipp & Zonen, USA) was installed in IRR, while in FLD only a pyrgeometer and a pyranometer (CGR3 and CMP3, Kipp & Zonen, USA) were mounted on an arm and oriented toward the ground. This expedient was used to reduce the cost of instrumentation, since the downward solar and longwave components could be considered equal for FLD and IRR fields. At the beginning of the measurement campaign, radiometers were located at the height of one meter from the ground. Successively, they were lifted of 20 cm for three times in the season (on June 25th, July 4th, and July 19th).

Devices for the measurements of soil heat flux (HFP01, Hukseflux, USA) were installed in both fields. In particular, two heat flux plates were installed in the IRR field, while a single device was used in the FLD field, since a lower spatial variability of the flux was expected for this irrigation treatment. The heat flux plates were installed at 8 cm below the soil surface. To calculate the ground heat flux at the soil surface ( $G$ ,  $W\ m^{-2}$ ), two thermistors (107L, Campbell Scientific, USA) were respectively installed at 2 and 6 cm near each soil heat plate. In FLD, in addition to the soil-storage term, also the water storage term needed to be calculated. To allow that water temperature and water level in the FLD field were monitored over time by means of a pressure transducer (PR-41X, Keller Industry, USA). In the IRR treatment, the two  $G$  data series were averaged together, while in the FLD treatment the  $G$  flux monitored at a single point was assumed to be representative of the whole field.

A thermohygrometer (HMP155A, Vaisala, USA) installed at the height of about 2 m from the ground, opportunely shielded to avoid direct solar radiation, completed the installation.

Half-hourly data acquired by all the installed instruments were stored in different data loggers by Campbell Scientific Industry (USA). In particular, eddy covariance instruments were connected on a CR5000, while the remaining devices were connected at two CR1000 placed on the levees separating two plots characterized by the same irrigation treatment. Power supply was guaranteed by solar panels and batteries connected to each data logger. Two panels of about 100 W were used to power supply separately two batteries of about 100Ah connected with the CR5000 and the eddy covariance instruments (anemometer and gas analyser). This was done since at the power up moment the gas analyser needs about 2.5Ah, while the data logger supports only about 1.8A. Thus, for a long monitoring activity, eddy covariance instruments should be powered separately by the data logger, given that the latter

could not be able to allow the restart of devices in case of malfunctioning. One solar panel of about 14 W was used to power supply two batteries of about 18A connected with each CR1000 data logger.

Data were sent using a wireless connection to a personal computer “base station” located in the NRRC offices. In order to facilitate the remote check of the data time series acquired, a Java interface (Chiaradia et al. 2013) was developed to enable an easy visualization of the variables which was conducted every morning. Real time control of the experimental apparatus allowed to minimize lost data for malfunctioning, which were found to be 7 % over the whole monitored dataset during the agricultural season.

An expansion memory card was used to store the high-frequency data (10 Hz) of wind velocity components and gas concentrations in the CR5000 data logger. Data on the card were downloaded manually at the end of each week.

Rain was monitored by the ARPA meteorological station in the NRRC farm.

Figure 3 shows the position of the main instruments involved in the monitoring of the energy balance components, installed on the levee between the T2 and T3 fields.

In addition to the continuous monitoring, periodic measurement campaigns (14 dates) were carried out to monitor the crop evolution (crop height and leaf area index). Leaf area index (LAI) was measured manually by a LP-80 AccuPAR Ceptometer (Decagon Device, USA).

#### Fluxes calculation

The EC technique provides unique measurements of water and energy fluxes between the biosphere and the atmosphere at the ecosystem scale (Papale et al. 2006). It is based on high frequency (10–20 Hz) measurements of wind speed and direction as well as  $H_2O$  concentrations at a point over the canopy using a three-axis sonic anemometer and a fast response infrared gas analyzer (Aubinet et al. Aubinet et al. 2000). Assuming perfect turbulent mixing, these measurements are typically integrated over periods of half an hour (Goulden et al. 1996), building the basis to calculate energy and water balances from daily to annual time scales. Fluxes of other gases entering or exiting the ecosystem (e.g.,  $CO_2$ ,  $CH_4$ ,  $NH_3$ ) can be determined using specific gas analyzers.

#### Latent and sensible heat fluxes

Turbulent fluxes of latent and sensible heat, were calculated using two different procedures: the PEC software (Corbari et al. 2012), directly applied on half-hourly data, and the Eddy Pro 4.2.1 software (LICOR, USA), based on the processing of high-frequency data.



**Fig. 3** Pan of the rice fields and zoom on the eddy covariance station mounted on the levee between FLD and IRR treatments. In the *bottom right box*, the installation of four thermistors and a soil heat flux plate

PEC software is fundamentally based on the methodology described in Kondo and Tsukamoto (2012), implementing only the corrections that in most situations show to exert the greater influence in the determination of turbulent fluxes, that are the two proposed, respectively, by Webb et al. (1980) and van Dijk et al. (2003), and described in Masseroni et al. (2013). Using the PEC software, only half-hourly data are required to calculate turbulent fluxes. Detection of spikes was performed following the Vickers and Mahrt (1997) method.

Eddy Pro 4.2.1 was applied using the high-frequency data (10 Hz) acquired during the experimental campaign. In this application of the software, the raw data processing is characterized by double rotation for tilt correction (Wilczak et al. 2001), block average for extracting turbulent fluctuation (Gash and Culf 1996) and a covariance maximization for time lags compensation. Air density fluctuations are compensated by Webb et al. (1980) correction, while the humidity effect on sensible heat is corrected by means of the van Dijk et al. (2003) method. Analytical corrections for low and high-pass filtering effects are also computed using Moncrieff et al. (2004) and Moncrieff et al. (1997) procedures, respectively. High-frequency cospectral losses caused by path-length averaging and sensor separation were applied (Kaimal and

Kristensen 1991). Statistical screening as suggested by Vickers and Mahrt (1997) is additionally performed.

For both the procedures, the quality of turbulent fluxes was checked through the Mauder and Foken criteria (2004), in which steady state and integral turbulence characteristic tests are the base of the quality control (Foken and Wichura 1996).

To verify the reliability of PEC software with respect to Eddy Pro 4.2.1, a correlation analysis for latent and sensible heat fluxes was used. The same approach was proposed by Ueyama et al. (2012) to evaluate the effects of each correction step, by comparing computed turbulent fluxes before and after each operation. In addition, Nash–Sutcliffe (NSE) (Nash and Sutcliffe 1970), and root mean square error (RMSE) indices were calculated. When the estimation is perfect, NSE is equal to 1 and RMSE to 0. To quantify the goodness of the fit among the two models, the statistical significance of the selected indicators (NSE and RMSE) was investigated using the bootstrapping method (Efron 1979), a Monte Carlo sampling technique useful to simulate the indicators' probability distributions, as described in the work of Ritter and Carpena (2013). For the case study, 2000 resamplings were considered. Four performance classes for NSE were established in accordance with the ranges defined by Moriasi et al. (2007), from a

Very good probability to fit well EddyPro 4.2.1 data to unsatisfactory one.

#### *Soil heat flux and water storage*

The soil heat flux at the soil surface was calculated by adding the measured flux at the depth of 8 cm to the energy stored in the layer above the heat flux plates. The specific heat of the soil and the change in soil temperature over the output interval are required to calculate the stored energy (Campbell Sci. 2012).

Soil bulk density of the plugged horizon was measured in five different profiles, and the average value of  $1.435 \text{ kg m}^{-3}$  was adopted for G calculation. The volumetric soil water content was monitored by three multilevel Sentek probes in the IRR field. For this study, the volumetric soil water content measured at the depth of 10 cm by the probe installed in the most representative soil type in the field was considered. The values measured during the agricultural season from the sensor installed at 10 cm, together with those measured by the tensiometer installed next to the sensor at the same depth, were used to experimentally determine the soil water retention curve. In the case of the FLD treatment, the volumetric soil water content at a depth of 10 cm was calculated from the soil water potential measured by the tensiometer placed at the same depth, using the retention curve derived for the corresponding soil type in the IRR treatment. A value of  $940 \text{ J kg}^{-1} \text{ K}^{-1}$  for the heat capacity of dry soil is considered to be a reasonable value for most mineral soils (Campbell Sci. 2012) and was adopted in this study.

When water covered the soil in the FLD field, also the energy stored in the water had to be taken into account.

#### Footprint analysis

In order to assign the measured turbulent surface energy fluxes to one of the two irrigation regimes (FLD and IRR), a meticulous footprint analysis was necessary. The footprint analysis has to be used to confirm which measured fluxes originate from the specific treatments (Alberto et al. 2011; Tsai et al. 2007). For practical purposes, the use of simple analytical footprint models is warmly advised in respect to Lagrangian or LES models (Kljun et al. 2002; Leclerc et al. 2003). This is mainly due to the restricted computational cost of these models and their wide range of applicability over different stability conditions of the atmosphere (Hsieh et al. 2000).

Three analytical footprint models were implemented and compared in this study. Since the levee is almost oriented east to west, when wind originated from first or fourth sector (from  $0^\circ$  to  $90^\circ$  or from  $270^\circ$  to  $360^\circ$ ), measured fluxes were considered to come from the FLD field direction. Viceversa,

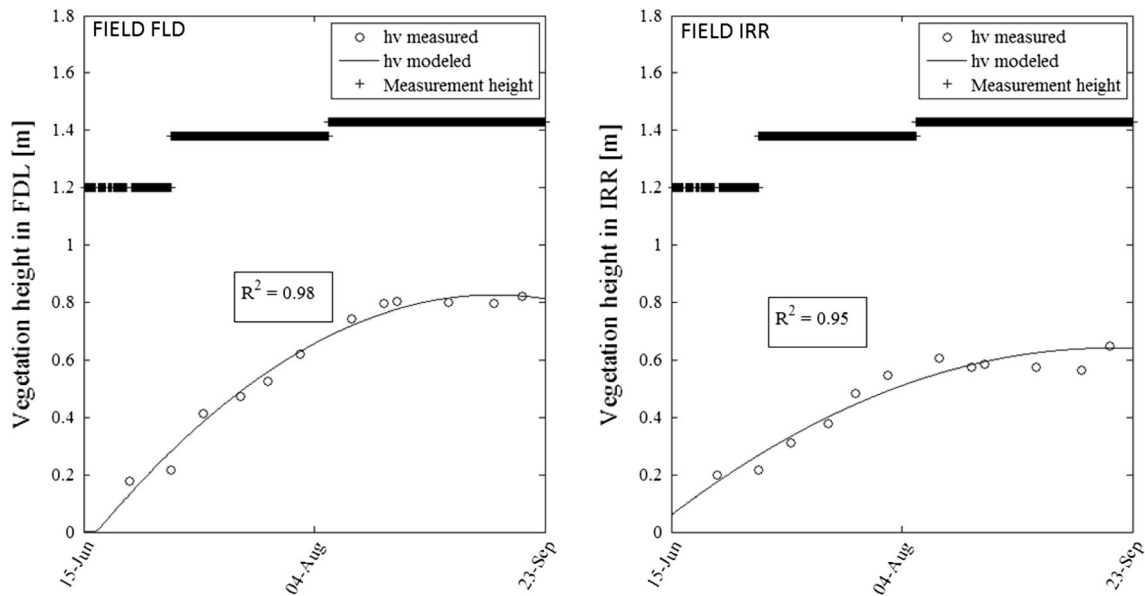
when wind originated from second or third sector (from  $90^\circ$  to  $270^\circ$ ) fluxes were considered to arrive from the IRR direction. A circle with a radius equal to the distance between EC station and field edges (40 m in all the directions) was afterward considered: all half-hourly data corresponding to a modeled fetch that fell outside the circle were discarded. The fetch, calculated using the footprint models, was computed for a ratio between scalar flux and source strength ( $F/S_o$ ) equals to 80 % according to Hsieh et al. (2000).

The three adopted footprint models are listed below. Since the mathematical formulations of the models are widely documented in the literature, only their main characteristics and the stability range of their applicability are briefly described.

Hsieh et al. (2000) model is constituted by a combination of Lagrangian stochastic model results and dimensional analysis. It analytically relates atmospheric stability, measurement height, and surface roughness length to obtain an approximated analytical expression which describes the footprint function. The results are organized in non-dimensional groups and related to the input variables by regression analysis. The advantages of this model are evident: the hybrid model can be expressed by a set of explicit algebraic equations, while some of the complexity and skill of the full model is retained through the regression. However, the pitfall of any approximation or parameterization is that its validity is strictly limited to the range of conditions over which it is developed. The applicability of this model is guaranteed for a measurement height which varies up to 20 m, a roughness length included between 0.01 and 0.1 m and a Monin–Obukhov length range from  $-0.1$  to 50 m.

Kormann and Meixner (2001) model belongs to the class of the Eulerian analytic flux footprint models which explore several approaches to approximately resolve the advection–diffusion equation. Schuepp et al. (1990) were the first scientists who proposed a purely analytical approach, based on an approximate solution of the diffusion equation given by Calder (1952) for thermally neutral stratification and a constant wind velocity profile. As stated by the authors, it suffers from the restriction of neutral stratification. Their suggestion, to correct the wind velocity in the footprint calculation based on thermal stability, has no mathematical basis. Instead, Kormann and Meixner (2001) model includes parameterizations of power law for wind velocity and eddy diffusivity extending the applicability of their footprint model to the whole atmospheric stability range. However, some model limitations are present, such as its usage in areas where wind velocity and eddy diffusivity profiles are horizontally homogeneous, and at heights where the effects of a finite mixing depth are negligible. In addition, this model assumes that turbulent diffusion in streamwise direction is small compared to advection, a form of Taylor's hypothesis (Foken 2008a), and are thus confined to flow situations with





**Fig. 4** Crop height for rice in the FDL and IRR treatments: together with the measured data, also an interpolating quadratic polynomial curve and the position of the eddy covariance instruments over the canopy are shown

relatively small turbulence intensities. As reported in Neftel et al. (2008), for the application of this model a check for the consistency of meteorological conditions has to be performed. If a data is characterized by  $z_m/L$  values smaller than  $-3$  or greater than  $+3$ , the data have to be ignored. Similarly, data with a ratio between friction velocity and wind velocity greater than 1 should be neglected.

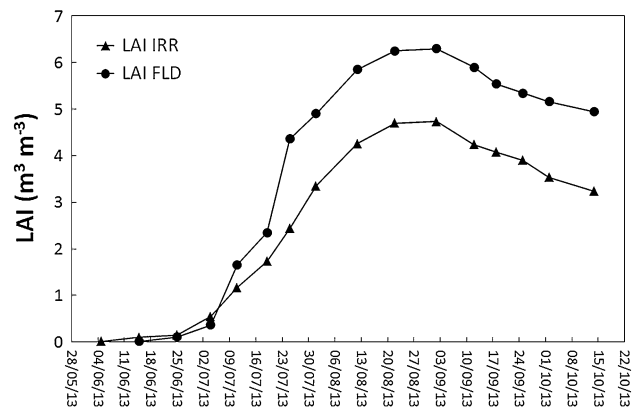
Schuepp et al. (1990) model is based on the use of analytical solutions of the diffusion equation as approached in the work of Gash (1986). This model is strongly simplified and its applicability cover only neutral stability conditions of the atmosphere.

The fetch lengths obtained by the three models for the rice crop subjected to the two irrigation regimes were compared graphically using the boxplot, where median, first and fourth quartile range, minimum and maximum values of data were computed. Considering only half-hourly data for which the three models could simultaneously be implemented, an univariate analysis of variance (ANOVA) was performed to reveal if the difference among the footprint length means obtained by applying the three models can be considered statistically significant at a level of 5 % (Acutis et al. 2012).

## Results and discussions

### Crop biometric parameters

Figure 4 and 5 show the crop height and the leaf area index (LAI) for the two irrigation regimes. In Fig. 4 crop height

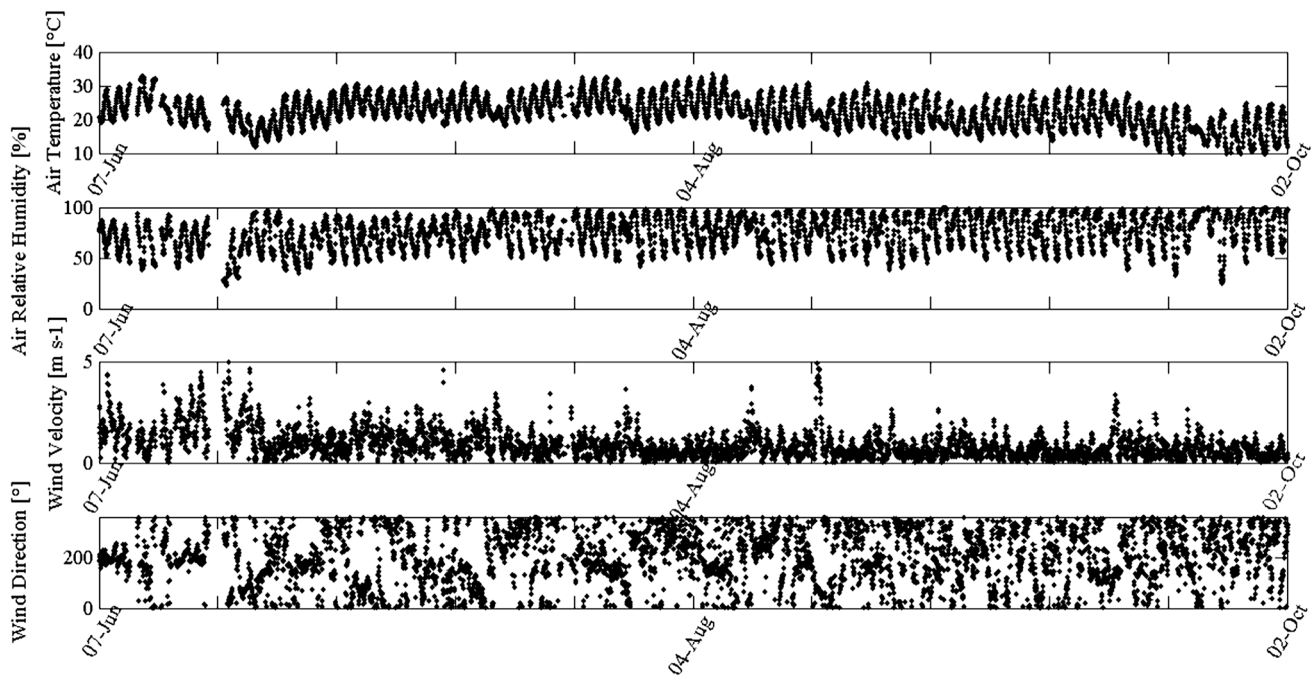


**Fig. 5** LAI measurements for rice in the FDL and IRR treatments

measurements collected in periodic campaigns carried out along the agricultural season are reported, together with the eddy covariance instruments height over the crop, and a continuous quadratic polynomial curve used to interpolate the vegetation height measurements, that show a good agreement with the monitored data in both situations.

For the turbulent fluxes computation, displacement height and roughness length were assumed to be respectively 0.75 and 0.1 of the vegetation height as suggested by Oue (2005) for rice canopies.

Rice crop in the case of IRR treatment was lower than in FDL treatment all over the season, and it was characterized by a lower LAI value. As shown in Fig. 5, LAI in FDL and IRR treatments reached, respectively, peaks of about 6.5 and 5  $m^2 m^{-2}$  between the flowering and the milky-waxy



**Fig. 6** Half-hourly meteorological data measured over the rice fields

maturity stages. Each point represented in Fig. 5 is obtained by the mean of one repetition of LAI measurement in six points of the field for each irrigation treatments. The mean standard deviation of LAI measurements did never exceed the value of 0.5.

#### Temperature, humidity and wind conditions

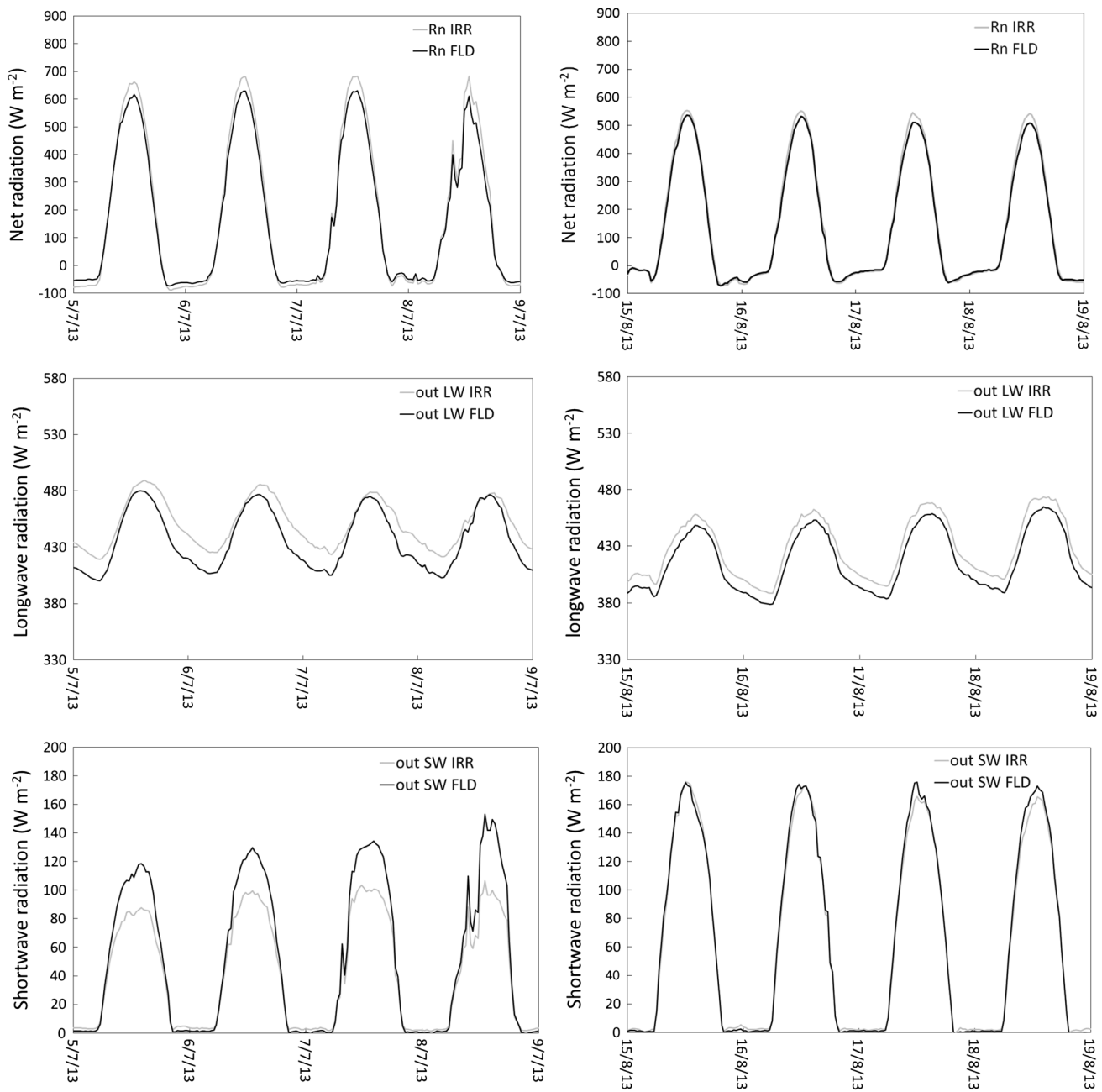
Figure 6 shows the meteorological condition observed by the eddy covariance station during the experimental campaign. Air temperature and relative humidity (RH) measured by the termohyrometer undergo a marked diurnal cycle. The mean air temperature in the measuring period is about 24 °C, while the air humidity exceeds 80 %. The thermal excursion can reach up to 10 °C from daytime to nighttime, while for air humidity it rarely exceeds 50 %. The values of wind speed confirm the low wind conditions typical of the Po Valley, especially at night, as shown also in Facchi et al. (2013a, b) and Masseroni et al. (2011a, b). Wind velocity usually varies from 0.2 to 3 m s<sup>-1</sup>, higher values are found during daytime and lower at nighttime. This leads to strong stability conditions during the night, while conditions of severe atmospheric instability sometimes occur during daytime hours. It can be observed that in June wind mainly originated from south–west (around 200° from the north), while for the rest of the monitored period no prevalent direction could be detected. A time pattern in wind direction cannot be detected even at sub-daily scale. The observed wind direction distribution allowed us to

achieve our goal, namely to have different time steps in the season for which the measured fluxes come from one or the other of the two irrigation treatments.

#### Solar radiation

Net radiation represents the total available energy that the rice system can use to perform its physiological processes, and it is the difference between incoming and outgoing radiation of both short and long wavelengths. When considering the radiation balance for the FLD and IRR fields over the entire agricultural season, two different periods can be noted. The first one is characterized by an absent to limited canopy cover: soil and water under the rice canopy are thus completely or partially exposed to the incoming radiation. In the second period, which is found to start around July 15th (LAI with a value of 1.5–2.0 m<sup>2</sup> m<sup>-2</sup>, as shown in Fig. 5), the canopy is instead fully developed. Figure 7 shows the temporal pattern of net radiation measured over the two treatments, together with the outgoing longwave and shortwave radiation (incoming radiations are obviously the same for the two fields) for 4 days respectively falling in the first period (July 5th–July 9th, on the left side of figure), and in the second period (August 15th–August 19th, on the right side of figure).

In the first period, net radiation during daytime hours measured for FLD is always higher than that for IRR of 50 W m<sup>-2</sup> or more, while in the second period this difference decreases to around 20–30 W m<sup>-2</sup>. These

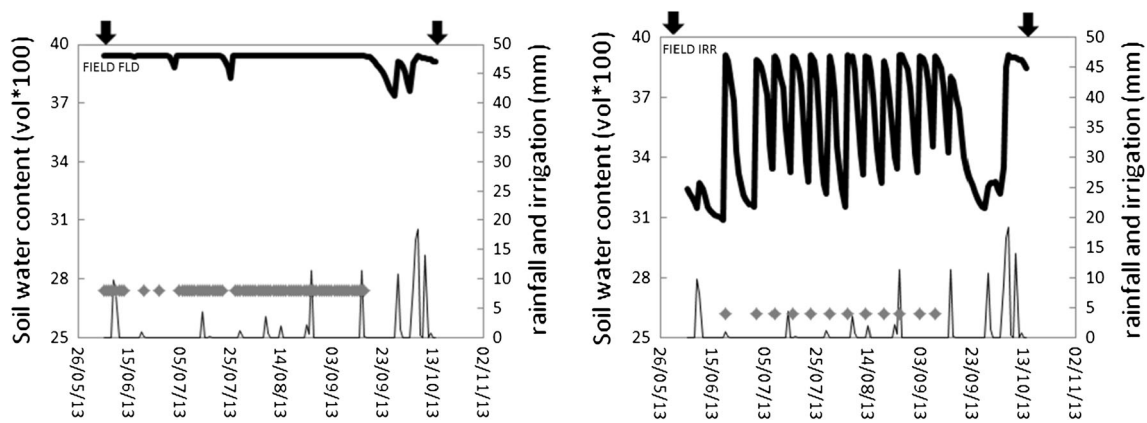


**Fig. 7** Half-hourly values of net, outgoing longwave, and outgoing shortwave radiation in FLD and IRR during two different periods of time: July 5th–9th (on the *left*), and August 15th–19th (on the *right*); data on the x-axis are positioned at midnight

behavior is confirmed by data collected in 2012 at the same experimental site (Facchi et al. 2013a). For both periods longwave radiation from IRR is slightly higher than for FLD. Maximum differences between the two series, in the order of 30–40  $\text{W m}^{-2}$  for the first period and of 10–20  $\text{W m}^{-2}$  in the second period, are found early in the morning or in the late afternoon. The shift in the daily peak values between the two series in the first period is probably due to the different behavior of the two surfaces (i.e., water

and soil). The shift disappears in the second period due to the shielding effect of the canopy cover.

Shortwave radiations show marked differences between the first and the second periods. During the former, outgoing radiation from FLD is larger than that from IRR of 40  $\text{W m}^{-2}$  or more. Shortwave albedo was found to be 0.22 in FLD and 0.14 in IRR all over the period. The turbidity of water covering the soil makes it practically opaque and gives it a light brown color. This could explain



**Fig. 8** Daily values of SWC at 10 cm (thick black line), rainfall (thin black line), and irrigation events (gray dots) for the IRR and FLD irrigation treatments; black arrows indicate seeding and harvesting dates

the higher albedo in the FLD treatment compared to IRR, where the soil is dark since it is moistened by periodic irrigations and rain (Fig. 8, on the left). In the second period, shortwave radiation is almost the same for the two treatments (differences of about  $10 \text{ W m}^{-2}$  are registered) and albedo is equal to 0.26, being that of the fully developed canopy.

#### Soil moisture and rain

Figure 8 illustrates the daily pattern of soil water content (SWC) at 10 cm, rainfall and irrigation events for the irrigation treatments IRR and FLD. Irrigation shown in figure should be considerate as an indication of the presence of water in the field, not as an absolute value of the irrigation amount provided. For the IRR treatment, SWC and soil water potential were measured contemporaneously at three sites: the SWC pattern shown in Fig. 8 is that measured for the most widespread soil type. Seeding and harvesting dates for the two treatments are also illustrated in figure.

#### Soil heat flux and water storage

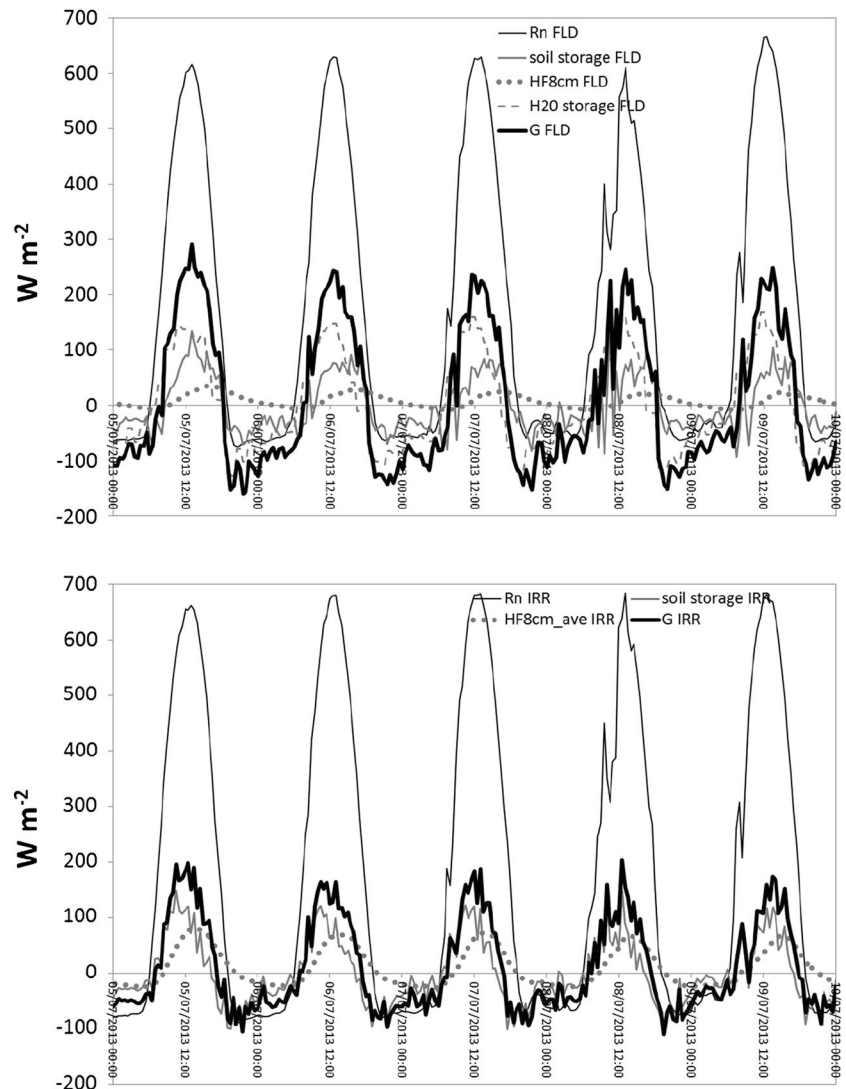
Figures 9 and 10 show, on the left side, the temporal pattern of measured soil heat flux at the depth of 8 cm (average of data recorded by two heat flux plates), of estimated heat storage in the soil above the heat flux plates (average of data recorded by four thermistors), and of estimated soil heat flux at the soil surface for the IRR treatment. In the case of the FLD treatment (on the right side) together with the soil heat flux at the depth of 8 cm (data from one heat flux plate) and the estimated heat storage in the soil above the heat flux plate (average of data from two thermistors), also the estimated heat storage in the water above the soil surface (data recorded by one thermometer) and the estimated heat flux at the water surface are reported in figures. Looking at the data for the first

period (July 5th–July 9th), a net radiation higher in the case of the IRR treatment compared to FLD treatment can be observed. The heat flow measured in the soil at a depth of 8 cm presents a wider amplitude in the case of the IRR treatment, reaching maximum daily values of about  $90 \text{ W m}^{-2}$  and minimum of  $-30 \text{ W m}^{-2}$ . The peak is phase-shifted by a few hours (1.5–3 h) compared with the peak of the net radiation. Considering the soil heat storage allows the realignment of the two peaks. The soil heat flux at the soil surface reaches daily maximum values around  $+200 \text{ W m}^{-2}$  and minimum values around  $-100 \text{ W m}^{-2}$ . In the case of the FLD treatment, the oscillations of  $G$  values measured at a depth of 8 cm are more contained, reaching maximum daily values of  $20 \text{ W m}^{-2}$  and minimum of  $-10 \text{ W m}^{-2}$ . The phase shift with respect to  $R_n$  increases (3.5–4.5 h). The amount of heat stored in the soil is always less than that stored in the water. Adding these factors to the heat flux measured at a depth of 8 cm depth, the resulting heat flux at the water surface is in phase with  $R_n$  and achieves maximum diurnal values around  $250 \text{ W m}^{-2}$  and minimum nocturnal around  $-150 \text{ W m}^{-2}$ .

The general observations made for the first period are also valid for the second period (August 15th–August 19th), with the difference of lower values of  $R_n$  and  $G$  measured at a depth of 8 cm as the season progresses. Measured  $G$  values span between 60 and  $-20$ , and 10 and  $-10 \text{ W m}^{-2}$ , respectively, in the case of IRR and FLD treatments.  $G$  estimated at the soil and at the water surface for the two treatments reaches daily maximum and minimum values of 120 and  $-70$ , and 130 and  $-120 \text{ W m}^{-2}$ , respectively, for IRR and FLD. In the case of FLD, the daily peak of  $G$  is out of phase with respect to  $R_n$ .  $G$  values at the soil/water surface are more similar between IRR and FLD treatments in the second half of the season, perhaps due to the extensive coverage provided by the fully developed vegetation.



**Fig. 9** Half-hourly values of  $G$  measured at a depth 8 cm, estimated heat stored in soil and water above the installed heat flux plates, and estimated  $G$  at the soil/water surface for the IRR and FLD irrigation treatments in the period July 5th–9th



In general, estimated  $G$  values at the soil/water surface along the whole agricultural season range from  $-200$  to  $+300 \text{ W m}^{-2}$ , in good agreement with those reported in other studies (e.g., Russo 2008).

The magnitude of the calculated storage terms suggest that, in spite of the accuracy that can be achieved in the measurement of turbulent fluxes ( $LE$  and  $H$ ) using an eddy covariance station and of the net radiation ( $R_n$ ) by a four component net radiometer, the final energy imbalance ( $R_n - G$  versus  $LE + H$ ) may be due to the determination of  $G$ .  $G$  is in fact measured (often in a very limited number of points) at a depth of about 8 cm below the surface of the soil, but the storage terms that are added to this measurement to obtain the  $G$  value at the soil surface or at the water surface (in the case of a paddy field) are based on empirical formulations which can result in errors which can be also very relevant. The influence of  $G$  on the energy balance closure is explained in the work of Hossen et al. (2012) which analyzed surface energy partitioning over a double-

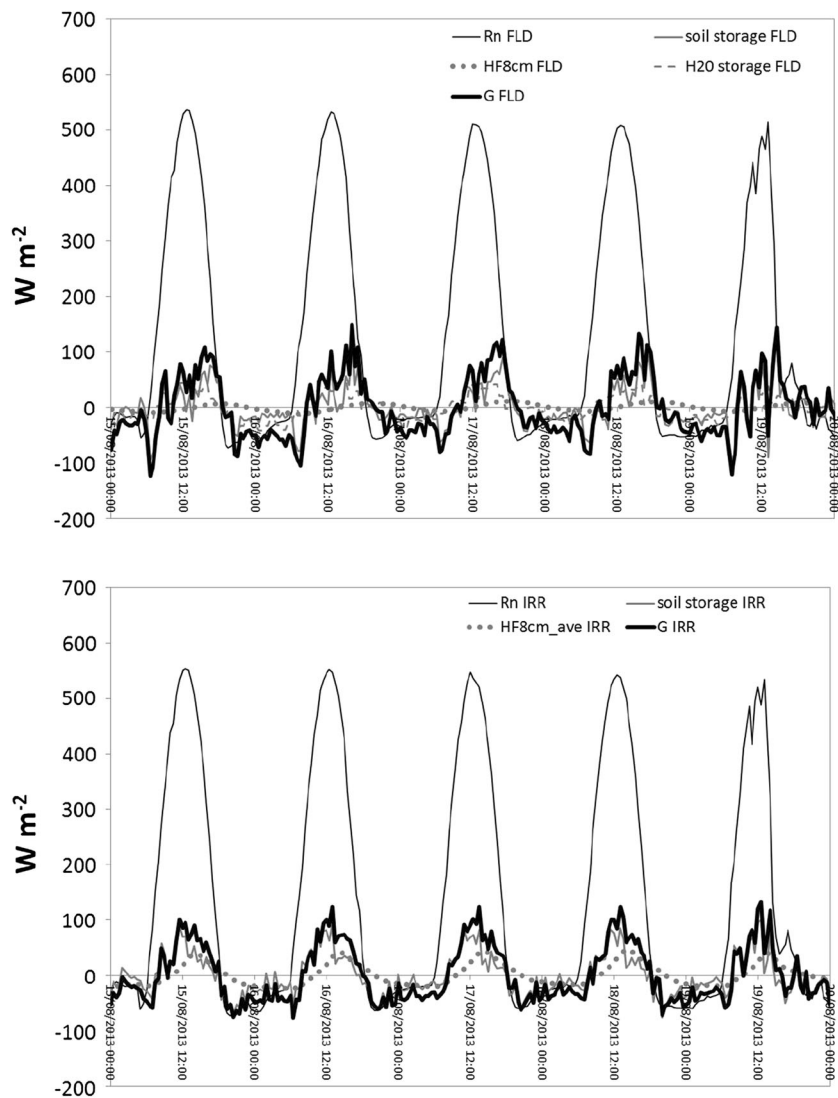
cropping paddy field in Bangladesh. They found that the closure in the flooded periods was almost the same as that in the drained periods if the heat storage change in the water layer was taken into account. Moreover, the energy balance closure in the flooded period was improved by 5 % by adding water heat storage term.

#### Latent and sensible heat fluxes

#### Comparison of post-elaborations software

When intensive experimental campaigns protracted for the entire growing season are conducted, the acquisition of high frequency measurements is often difficult and not always feasible (Masseroni et al. 2013). In that cases, a software which permits to calculate latent and sensible heat fluxes starting from averaged data becomes, therefore, very useful. PEC software was developed to compute turbulent fluxes over maize fields (Corbari et al. 2012). Despite its

**Fig. 10** Half-hourly values of  $G$  measured at a depth 8 cm, estimated heat stored in soil and water above the installed heat flux plates, and estimated  $G$  at the soil/water surface for the IRR and FLD irrigation treatments in the period August 15th–19th



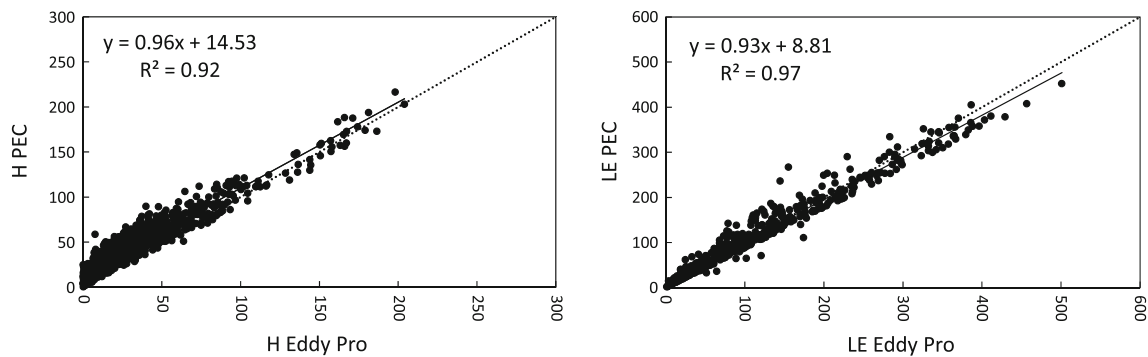
computation simplicity in respect to other models (Ueyama et al. 2012), the accuracy and reliability of the results were confirmed by a comparison with the Eddy Pro 4.2.1 software (Masseroni et al. 2013). To verify the applicability of the PEC software also in the case of rice canopies, a comparison among PEC and Eddy Pro 4.2.1 software was conducted also in this study.

On the total dataset, about the 40 % of turbulent fluxes belongs to class 0 with respect to Mauder and Foken criteria, while the 60 % belongs to class 1 and 2. Generally, the steady state test seems to fail during the sunrise and sunset, while the integral turbulence test fails in many cases during the night. The former situation could be caused by the lack of convective forces and the absence of temperature gradient in the air layers. The latter situation, instead, could be due to the absence of the shear stress in association with low wind velocities.

Stability conditions of the atmosphere were evaluated through the ratio between  $z_m$  and  $L$ . The latter term

represents the Monin–Obukhov length which, in absolute value, describes the distance from the soil where mechanical forces are balanced by convective ones (Sozzi 2002). During the experimental period,  $z_m/L$  ratio varied from  $-0.5$  to  $0.5$  respectively. Negative values represent convective situations while positive values reveal stable conditions. Strongly convective situation occurred during the midday of many days in July and August, while stable conditions were usually relegated to night time. Neutral situations were generally confined at the sunrise and sunset, nevertheless in not particularly sunny days, these atmospheric conditions were also evidenced during the daytime.

In Fig. 11, the scatter plot between sensible ( $H$ ) and latent heat ( $LE$ ) fluxes calculated by PEC and Eddy Pro software are shown. Only day time good quality data (class 0) were taken into account for the analysis. Respectively for  $H$  and  $LE$  fluxes the correlation shows a slope of 0.96 and 0.93 with a determination coefficient  $R^2$  of about 0.92 and 0.97. Despite the not perfect closure among the two



**Fig. 11** Correlation analysis between sensible heat  $H$  (on the *left*) and latent heat  $LE$  (on the *right*) fluxes obtained by EddyPro and PEC softwares

models, the influence on evapotranspiration fluxes can be considered negligible as explained in Masseroni et al. (2013), who showed that in terms of cumulated evapotranspiration (over a one year of measurement campaign over a maize canopy), the difference between PEC and EddyPro software was only about 10 mm. For the case study, when considering the cumulated ET value over the agricultural season, an overestimation of 1.3 % was found if PEC software is adopted instead of EddyPro.

In Table 1, the goodness of fit between the two models is summarized. The NSE values for both fluxes are larger than 0.9 with 95 % bootstrap confidence intervals of 0.81–0.94 for  $H$ , and 0.89–0.95 for  $LE$ . The RMSE values are equal to 0.24 and 0.31 respectively for  $H$  and  $LE$ , with a 95 % bootstrap confidence interval of 0.19–0.29 for  $H$  and 0.27–0.36 for  $LE$ . The probability of the PEC model to fit in a *Very Good* way the EddyPro results is greater than 80 % for both fluxes, with only about 10 % of data belonging to the *Good* class, and a negligible percentage of data falling into the *Satisfactory* class.

#### Comparison among footprint models

To evaluate the performance of the three models implemented in this work, a box plot statistical analysis was performed using the data of the entire growing season. In Fig. 12 some statistical information about the distributions of fetch length obtained by the three footprint models are summarized. The whiskers represent the minimum and maximum values of fetch respectively, the two extremities of the box represent the first and third quartile, while the marked lines in the boxes represent the median value of the fetch length distribution.

For both fields the maximum fetch value does not exceed 300 m, while the minimum value is about 50 cm from the eddy covariance station. Observing the fetch median values, they are slightly smaller in FLD with respect to IRR because the crop biometric parameters are quite different for the two irrigation treatments as shown in

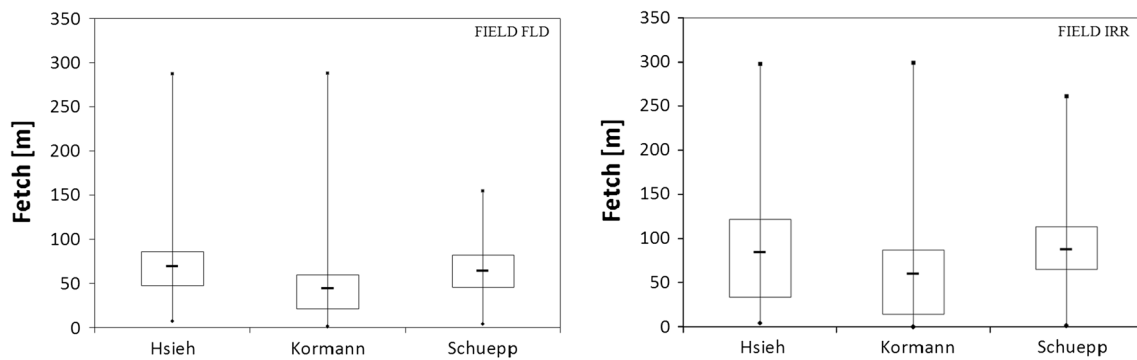
Fig. 4 and Fig. 5. In FLD, the 50 % of data, which are those included in the box, have a range of fetch of about 38 m for each footprint model, while a larger variability is observed for IRR, where that range varies from 48 m (for Schuepp model) to 87 m (for Hsieh model).

The ANOVA assumptions of normality and homogeneity of variances were verified using the Kolmogorov–Smirnov and Levene tests with an  $\alpha$ -value of 0.05 (Acutis et al. 2012). The application of the ANOVA on the three models resulted in a  $p$  value of about 0.1, therefore, the null hypothesis was not rejected, suggesting that any of the models can be adopted in the specific case study because they do not show substantial differences in the average length of the calculated fetch. However, in function of its wide application in many agricultural ecosystems (Kormann and Meixner 2001, Marcolla and Cescatti 2005, Kljun et al. 2004), Kormann model was taken into account to examine the fetch of half-hourly turbulent fluxes for further analysis in this work. The range of stability conditions during the whole measurement campaign was entirely within the thresholds suggested in Neftel et al. (2008), and thus no data had to be discarded.

Considering the Kormann and Meixner (2001) footprint model, only about 20 % of data had been shown to belong to FLD or IRR fields according to the selection criteria of  $F/S_o$  equal to 80 %, while the remaining data came mainly from the surrounding fields. Counting the data for each experimental month (from June to the end of September) the accepted fluxes can be considered evenly distributed in the entire growing season with about 25 % of the total amount of data for each period.

#### Energy balance closure

The EC technique provides a direct measurement of latent heat, which is the energy used for the evapotranspiration processes. However, the energy balance closure error for eddy covariance data has been well documented in the literature for the past two decades. Most studies showed



**Fig. 12** Box statistics for the Hsieh, Kormann, and Shuepp footprint models in the case of FLD (on the *left*) and IRR (on the *right*) irrigation regimes

that the sum of sensible and latent heat is less than available energy typically by 10–30 % (Foken 2008a; Wilson et al. 2002; Twine et al. 2000, Yoshimoto et al. 2005). Twine et al. (2000) reported that the primary reason for the energy imbalance is the error in the measured turbulent fluxes, which include mismatched sources of LE and H, inhomogeneous surface cover and soil characteristics, flux divergence or dispersion, non-stationarity of the flow, lack of a fully developed turbulent surface layer, flow distortion, sensor separation, topography, and instrument error. Therefore, they suggested that the eddy fluxes should be adjusted for energy balance closure using the Bowen ratio closure method. This method permits to retain the integrity of the Bowen ratio (sensible heat/latent heat).

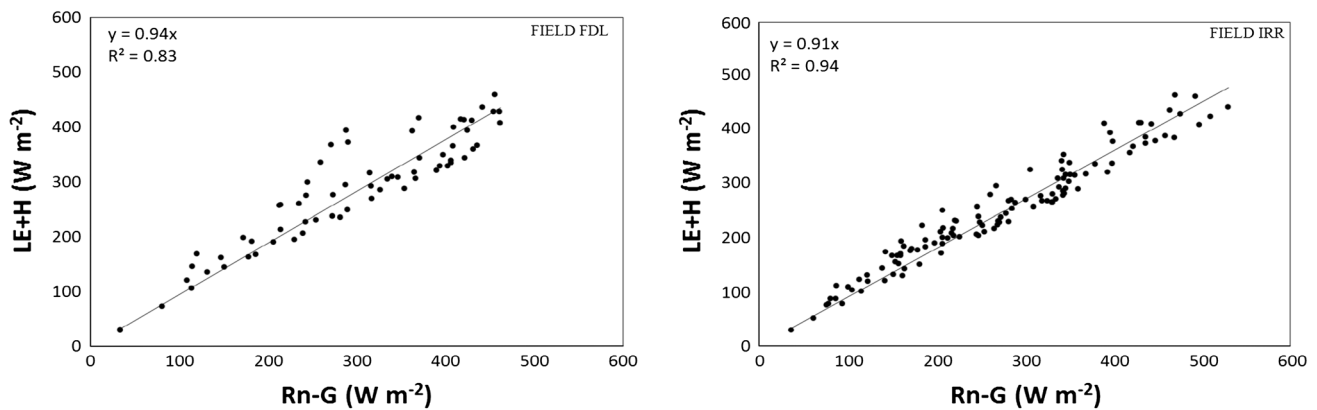
Considering only good quality daytime ( $R_n > 0$ ) data, with the fetch which satisfies the selection criteria, a percentage of 8 and 11 half-hourly data respectively for FLD and IRR treatments were selected and thus used for the energy balance computation. The mean Bowen ratio is found to be about 0.24 and 0.28 for FLD and IRR respectively. For FLD the Bowen ratio value is slightly greater than that reported in Tsai et al. (2007), where for a rice paddy in Taiwan a value of about 0.20 was computed. In Alberto et al. (2011), flooded rice had a consistently lower Bowen ratio (0.14) than aerobic rice (0.24). The only exception was the AERMOD study (USEPA 2004), where for wet conditions during daytime in spring the Bowen ratio was found to be about 0.30.

The higher Bowen ratio for the aerobic rice indicates that a larger portion of net radiation is used for sensible heat (Alberto et al. 2009). In many studies (Alberto et al. 2011, 2009), the seasonal and interannual variations in sensible heat for aerobic rice were weaker than those for flooded rice. In Alberto et al. (2011), the mean sensible heat in flooded rice during 2008 was particularly high as a consequence of the low precipitation during that year. Viceversa, latent heat was higher in 2009 than in 2008 during both the dry and wet seasons in both flooded and

aerobic rice fields, because of higher precipitation in 2009. Generally, flooded rice fields have higher latent heat and lower sensible heat than aerobic fields, as reported by Alberto et al. (2009). In their study, computing an average value over four cropping seasons, flooded rice fields showed to have a 19 % higher latent heat flux than aerobic rice fields. On the other hand, the aerobic rice fields had a 45 % higher sensible heat than flooded fields.

As shown in Fig. 13, despite the small amount of selected data for the two irrigation regimes, the slope of the energy balance closure is higher than 0.90 for both. For the FLD regime the data have a determination coefficient of about 0.83, while for the IRR regime it reaches the value of 0.94. These values are higher than those reported by Alberto et al. (2011) and Hossen et al. (2012), where the regression slope of the energy balance was about 0.72 and 0.75, respectively. Similar results to those reported in this work were obtained by Harazono et al. (1998), with a closure of 0.99 for drained and 0.95 for flooded conditions. Gao et al. (2003) on rice paddy obtained a closure of about 0.91, while Tsai et al. (2007) reported a closure of about 0.90 and Gao et al. (2006) showed a regression slope of 0.85. This result confirm the good quality of the selected latent heat and sensible heat fluxes, which could therefore be used for further applications, such as the calibration of surface energy balance models like those reported, among the others, by Lagos et al. (2009), Gharsallah et al. (2013) and Facchi et al. (2013a). As explained in Hossen et al. (2012) the lack of a complete energy balance closure has been reported for most of the eddy covariance studies (Wilson et al. 2002), and some of them identified that the measurement errors could be related to soil heat flux as well as horizontal energy advection, energy used in photosynthesis, and heat storage in the canopy and top soil (Mayer and Hollinger 2004; Tsai et al. 2007; Foken 2008b). Energy balance closure at our study site was nevertheless reasonable compared with those in previous studies. In this paper, we do not apply any corrections to the energy imbalance.





**Fig. 13** Energy balance closure ( $H + LE$  versus  $Rn-G$ ) in the case of FLD (on the left) and IRR (on the right) irrigation regimes

## Conclusions

This paper describes the energy balance components observed during the agricultural season 2013 in two rice fields in northern Italy characterized by different irrigation managements (continuous flooding, FLD, and intermittent irrigation, IRR). Net radiation during daytime central hours was found to be about  $50 \text{ W m}^{-2}$  lower in the FLD treatment than in the IRR treatment during the first part of the season (approximately until LAI is  $1.5\text{--}2.0 \text{ m}^2 \text{ m}^{-2}$ ), and almost equal for the remaining part of the monitoring period. This was mainly due to the different shortwave albedo of the two surfaces for the first period, mostly determined by irrigated soil and turbid water, which was respectively 0.22 in FLD and 0.14 in IRR. In the second period, an albedo of 0.26 was calculated for both the treatments, being that of the fully developed canopy. The soil heat flux measured at 8 cm depth in the soil was corrected adding the soil heat storage term in the case of the IRR treatment and, additionally, the water storage term when water covered the soil in the FLD field. This latter term proved to be of crucial importance, since in daytime hours it provided an average contribution of 54 % to the  $G$  flux at the water surface over the whole agricultural season. The  $G$  flux at the water surface in the FLD parcel was always higher or at least equal to  $G$  at the soil surface in the IRR treatment: along the season they reached respectively average values of about 17 and 14 % of the net radiation in daytime hours. This suggests that the accuracy in the estimation of the storage terms may have a crucial role on the energy imbalance, especially when paddy fields are considered.

Since at the monitoring site there is no clear preferential wind direction, in the study  $H$  and  $LE$  fluxes were measured using only one eddy covariance system installed on the levee between the two irrigation treatments. The use of three footprint models widely adopted in literature (Schuepp et al. 1990; Hsieh et al. 2000; Kormann and Meixner 2001) allowed the selection of half-hourly  $H$  and  $LE$  data

originating entirely from each one of the two treatments. The three models provided similar results, with slightly higher fetches in the case of IRR treatment, probably as a result of the lower crop height. The use of a single eddy covariance system, on the one hand, led to the availability of about 10 % of the half-hourly data from each of the two plots on the entire agricultural season, but on the other hand, allowed to use only one station for monitoring both fields. However, the low percentage of data belonging to each of the two treatments is probably influenced by the weak wind velocities and the atmospheric turbulent conditions of the Po Valley as suggested by Masseroni et al. (2014). Moreover, larger plots would determine a significant increase in the availability of data measured for each treatment. The energy balance closure for both fields was found to be very good, with a slope of 0.94 and 0.91 respectively for the FLD and IRR treatments ( $R^2$  of 0.83 and 0.94), confirming the good quality of the measured data. To obtain complete  $H$  and  $LE$  datasets along the season, the two selected eddy covariance subsets could be used in the calibration of surface energy balance models.

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