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Title

Estimation of zero-plane displacement height and aerodynamic roughness length on rice fields

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Abstract

The estimation of aerodynamic roughness length (z_0) and zero-plane displacement height (d) is of primary importance in the application of a number of models that simulate soil-vegetation-atmosphere interactions at different spatial scales. Many efforts to directly measure z_0 and d in the case of various surfaces were conducted in the past from multi-level measurements of wind speed over homogeneous surfaces, but results reported in the literature are still rare for some canopies and can only be used as a rule of thumb.

In this work, values of d and z_0 along the whole agricultural season for two rice fields located in northern Italy and characterized by different irrigation managements (continuous flooding and intermittent irrigation) were obtained from single level turbulence measurements performed by an eddy covariance (EC) system installed on the levee between the two fields. Throughout the growing season, d and z_0 appeared to be well correlated (R^2 greater than 90%) with the vegetation height (h_v) and the mean value of the ratio between d and h_v was about 0.75 for both rice fields, while the ratio between z_0 and h_v was about 0.06 and 0.05 respectively for the flooded and the intermittent irrigation treatments. Moreover, d and z_0 did not show any clear dependence on wind speed or stability conditions of the atmosphere.

Riassunto

Stime accurate della lunghezza aerodinamica (z_0) e dell'altezza di dislocamento (d) sono estremamente importanti per molti modelli che simulano gli scambi di massa ed energia nei sistemi suolo-vegetazione-atmosfera a differenti scale spaziali. In passato sono stati fatti molti sforzi per misurare direttamente z_0 e d attraverso rilevamenti multilivello della velocità del vento su superfici vegetate in modo omogeneo: i risultati presenti in letteratura sono tuttavia ancora scarsi per molte tipologie di vegetazione e di conseguenza spesso si ricorre a regole pratiche che forniscono una stima approssimata dei valori di z_0 e d.

In questo studio, i valori di z_0 e d per l'intera stagione agraria si sono ottenuti da misure di turbolenza effettuate ad un solo livello tramite una stazione micrometeorologica *eddy covariance* installata sull'argine di separazione tra due appezzamenti coltivati a riso nel Nord Italia, caratterizzati da differenti gestioni irrigue (sommersione continua e irrigazione intermittente con riso aerobico). I risultati mostrano che durante l'intera stagione agraria, z_0 e d sembrano essere ben correlati (R^2 maggiore del 90%) con l'altezza della vegetazione (h_v): il valore medio del rapporto tra d e h_v è pari a circa 0.75 per entrambi i trattamenti irrigui, mentre il rapporto tra z_0 e h_v è di circa 0.06 per il riso caratterizzato da sommersione e 0.05 per il riso aerobico. Infine, nessuna chiara correlazione si è riscontrata tra le condizioni di stabilità atmosferica o la velocità del vento ed i valori di z_0 e d.

Keywords: aerodynamic roughness length, zero-plane displacement height, eddy covariance, paddy field, aerobic rice, northern Italy.

Parole Chiave: Lunghezza aerodinamica, altezza di dislocamento, tecnica eddy covariance, riso in sommersione continua, riso aerobico, Nord Italia

1 Introduction

In many studies focusing on the estimation of flux exchanges in the soil-vegetation-atmosphere system at large scales (meteorological modeling applications) or at the single field scale (micrometeorological data analysis), aerodynamic roughness length and zero-plane displacement height are required (e.g., Sugita and Brutsaert 1990, Toda e Sugita 2003, Zhou et al. 2006).

Generally, z_0 and d are estimated using the wind profile method, where three wind velocity measurements at different heights above the ground have to be simultaneously performed (Stull 1988, Asanuma et al. 2000). This method is particularly expensive and requires the use of a meteorological tower as a support for the anemometers installation (Foken 2008). Moreover, the profile equation may not be applied where wind is very weak, and the vertical wind speed gradient is smaller than the accuracy limit of the sensors (Gao et al. 2003). As a possible alternative to the approach illustrated above, Rotach (1994) proposed the use of temperature and vertical wind velocity variances to estimate d and successively z_0 through the resolution of the wind profile. This method is attractive, since it requires measurements at a single level typically performed by eddy covariance stations. However, a rigorous application and validation of the method over different areas has not been yet carried out, and thus its robustness is still not well understood (Toda and Sugita 2003, Mori et al. 2010). Martano (2000) proposed a new approach to quantify z_0 and d by using a single-level sonic anemometer data set. Starting from wind velocity, Reynolds stress and sensible heat flux dataset at one height, the method for the determination of z_0 and d can be reduced to a simpler least square procedure for one variable only (Gao et al. 2003). Values of z_0 and d can be determined from the similarity wind profile law from single-level measurements of wind speed and sensible fluxes by solving a simple and straightforward one-dimensional minimum problem. The procedure requires no specialized software and a very little computational effort, however, high frequency data (10 or 20 Hz) acquisition is recommended (Martano 2000). In a recent study of Graf et al. (2014) three different approaches for estimating d and z_0 - including Martano's (2000) model - were investigated, showing the good correlation of the Martano method with the results obtained by the other two more sophisticated models based on the flux-variance similarity theory (Foken 2008).

Data for the on-site estimation of roughness length and displacement height are not always available, therefore, in many soil-vegetation-atmosphere models (SVAT models), z_o and d are approximated following simple rules of thumb. In many land surface models, such as BATS (Biosphere- Atmosphere Transfer Scheme) and SiB (Simple Biosphere model), z_0 and d are taken as constant in function of crop typology (Dorman and Sellers, 1989; Dickinson et al., 1993). In the CLM (Common Land Model) (Dai et al., 2003), z_0 is taken as a constant ratio of vegetation height (i.e., $z_0 = 0.07h$). In other models, z_0 assumes values in the range 0.06-0.2 meters (Dudhia et al. 2005; Grell et al. 1995; Hagemann 2002).

Only few researches tried to estimate roughness parameters on rice surfaces, and in many cases discrepancies in the values of z_0 and d were reported (Kim et al. 2001). In the works of Gao et al. (2003), Kotani and Sugita (2005) and Tsai and Tsuang (2005), z_0 for a rice paddy with a crop height of about 60 cm varied between 10^{-3} and 10^{-1} meters. From these studies, it can be inferred that the $z0$ value over rice paddies strongly varies with the site. Zeng and Wang (2007) showed that z_0 over a cropland is not only dependent on the specific crops, but also on obstacles in the area such as buildings, trees and the aboveground biomass. In addition to these factors, z_0 and d are strongly connected with the evolution of the vegetation height, and their values change over the growing season (Jacob and Boxel 1988). Nevertheless, in the literature the evaluation of the roughness parameters above rice fields during the entire growing season is still absent. Crop homogeneity over the field, crop typology, stiffness of the stem are just some elements that can influence roughness parameters (Hansen 1993, Jacob and Boxel 1988).

In this technical note *d* and z_0 were evaluated using the Martano's (2000) method over the entire growing season for a traditional paddy rice field and an aerobic rice field in northern Italy, and the obtained results were compared with the standard prediction methods quoted in the literature. The peculiarity of this study lies also in using only one EC system to monitor these aerodynamic parameters for the two different fields. Moreover, this technical note gives a contribution to the increasing of experimental information on rice crop in northern Italy, which are still scarce.

2 Material and Methods

2.1 Experimental set-up and measurements

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) (45°14'49.64''N, 8°41'55.32''E) over rice fields under different water regimes (Fig. 1). A complete description of the site characteristics and the instrumentation installed is reported in Facchi et al. (2013) and Masseroni et al. (2014). In this paper, only instruments necessary to measure the variables used into the Martano's (2000) method are described.

A 3D sonic anemometer (Young RM-81000, Campbell Scientific, USA) was installed in early June 2013 on the narrow levee separating two rice fields characterized by different irrigation treatments: intermittent irrigation (IRR) and continuous flooding (FLD). This choice was done to verify the possibility of using only one eddy covariance system for monitoring turbulence fluxes (latent heat, LE, and sensible heat, H) in two different rice environments, and also because of the limited size (40m x 80m) of the experimental fields. The instrument was held at about one meter over the canopy along the whole monitoring period (7 June – 2 October). This choice was supported by the results shown in Arriga (2008), who demonstrated that the quality of the measurements could be extremely compromised if the distance between EC system and the surface (soil or top of a homogeneous canopy) is less than 30-40 cm. The sonic anemometer was mounted on the top of an adjustable pole thrust into the soil. During the whole experimental period, the position of the EC station was into the equilibrium boundary layer, which is a necessary condition for its proper operation as shown in the work of Kaimal and Finnigan (1994). High frequency (10 Hz) wind velocity components and sonic temperature data were stored in a compact flash card inserted into the CR5000 data logger (Campbell Scientific, USA) at which the sonic anemometer was connected.

In addition to the continuous monitoring, periodic measurement campaigns (12 dates) were carried out to monitor the crop biometric parameters along the cropping season (crop height, leaf area index).

Fig. 1. Experimental fields and EC system position. The complete description of the site characteristics and monitoring activity are illustrated in Facchi et al. (2013).

Fig. 1. Campi sperimentali e posizionamento della stazione eddy covariance. La descrizione completa delle caratteristiche del sito e delle attività di monitoraggio sono riportate in Facchi et al. (2013).

2.2 Analytical procedure

For the application of the Martano's (2000) method the wind profile is approximated by Eq. 1:

$$\bar{u} = \frac{u*}{k}\left[\ln\left(\frac{z_m - d}{z_0}\right) - \psi_m\left(\frac{z_m - d}{L}\right)\right] \qquad (1)$$

where $\bar{u}$ is the mean wind speed over the average time (30 minutes interval), $u*$ and L represent the friction velocity and the Obukhov length, z_m denotes the measurement height, while k is the von Karman constant equal to 0.4. ψ_m represents the integrated universal momentum function (Foken 2008), in which the small dependence on z_0/L can be negletted (Sozzi 2002).

The Obukov length is defined by Eq. 2:

$$L = -\frac{(u*)^3 T_v \rho c_p}{k g H_v} \qquad (2)$$

where T_v is the virtual temperature, g is the acceleration due to gravity (9.81 m s^{-2}), ρc_p is the volumetric heat capacity at a constant pressure (with c_p = 1005 J kg^{-1} K^{-1}), and H_v is the buoyancy flux (virtual heat). Here we approximate H_v and T_v by the heat flux and mean temperature based on the sonic temperature. Using variables based on the sonic temperature has the advantage that no additional humidity sensor (with possible failures) is needed (Graft et al. 2014)..

ψ_m is most commonly calculated by Eq. 3 for unstable conditions ($z_m/L < 0$) of the atmosphere (Paulson 1970):

$$\psi_m\left(\frac{z_m - d}{L}\right) = \ln\left[\frac{1 + x^2}{2}\left(\frac{1 + x}{2}\right)^2\right] - 2\arctan x + \frac{\pi}{2} \qquad (3)$$

with x defined as in Eq. 4:

$$x = \left(1 - \gamma\frac{z_m - d}{L}\right) \qquad (4)$$

where γ is a universal constant equal to 19.3 (Hogstrom 1988).

For moderately stable conditions ($0 < z_m/L < 1$) of the atmosphere, ψ_m is computed as in Eq. 5:

$$\psi_m\left(\frac{z_m - d}{L}\right) = -\beta\frac{z_m - d}{L} \qquad (5)$$

where β is another universal constant equal to 6.

If *d* is known, z_0 can be estimated from a single dataset of $\overline{u}$, $u*$ and L obtained from a single-level eddy-covariance station inverting Eq. 1, as shown in Eq. 6. Averaging across multiple points in time can be used to yield more robust results (averaged z_0), and the standard deviation σ_{z0} can be used to quantify the uncertainty of the estimate (Martano 2000).

$$z_0 = \frac{z_m - d}{\exp\left[\frac{\overline{u}k}{u*} + \psi_m\left(\frac{z_m - d}{L}\right)\right]} \tag{6}$$

If *d* is unknown, Martano's (2000) method provids a mathematical algorithm that iteratively allows to obtain *d* from the minimization of the variance of a *S* variable.

Let *N* be the total number of measurements belonging to a generic sector around the station in each half hourly time step. Each high frequency measurement will be constituted by u_i, u_i^*, L_i variables, where the index *i* defines the *i*_th measurement over the total dataset of *N* values.

Let *d* be a first approximate value of the displacement height (not necessary the optimum value), then *S* and σ_S can be defined by Eq. (7) and (8) respectively.

$$S = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{u_i k}{u_i^*} + \psi_m\left(\frac{z_m - d}{L_i}\right)\right] \tag{7}$$

$$\sigma_S{}^2 = \frac{1}{N}\sum_{i=1}^{N}\left\{\left[\frac{u_i k}{u_i^*} + \psi_m\left(\frac{z_m - d}{L_i}\right)\right] - S\right\}^2 \tag{8}$$

For each choice of the *d* value, a $\sigma_S{}^2$ value can be computed. The value of *d* at which corresponds the minimum value of $\sigma_S{}^2$ represents the optimal displacement height. Knowing *d* and applying Eq. (6) allows the calculation of the roughness parameter z_0. For a detailed dissertation about the mathematical steps, the reader is referred to the Martano's (2000) work.

2.3 Quality and footprint-based data filtering

Before determining z_0 and *d*, measurements were filtered to ensure the quality of data in terms of good turbulence and wind speed according to the Mauder and Foken (2004) suggestions. In Tab. 1 the selection criteria are briefly summarized.

Tab. 1. Overview of the selection criteria for the application of the Martano's (2000) method

Tabella 1. Criteri di selezione dei dati per l'applicazione del metodo di Martano (2000).

To prevent situations dominated by an high fetch with fluxes predominantly coming from other fields in the surrounding area, a detailed footprint analysis was performed on the acquired data. The Hisieh et al. (2000) analytical model was applied with d and z_0 values of first approximation equal to $2/3h_v$ and $0.1h_v$ respectively (Foken 2008). A circle with a radius equal to the distance between EC station and field edges (40 m in all the directions) was afterwards considered: all half-hourly data corresponding to a modelled fetch that fell outside the circle were discarded. The fetch calculated using the footprint model, was computed for a ratio between scalar flux and source strength (F/S_o) equals to 80%, according to Hsieh et al. (2000).

In order to determine d and z_0 estimates as a function of time during the growing season, Martano's (2000) method was applied with a running window which advanced one day at time. Data were subdivided in two macro-groups as a function of the wind direction. The first group gathered data coming from the northern sector (Sector I), while the second group data coming from the southern sector (Sector II). In particular, data were taken into account only if the wind direction was included in a range of 40° with respect to the North-South reference direction, as shown in Fig. 1. Thus, unlike other works where data were divided into various sectors (Mori et al. 2010; Tsai et al. 2010), in this study the number of sectors was reduced to one for each irrigation treatment (representing in total 80° over 360°).

3 Results and discussion

3.1 Crop parameters

Fig. 2 shows the height of the rice crops for the irrigation treatments FLD and IRR along the agricultural season 2013. Dots represent the vegetation height measurements (h_v). A quadratic polynomial curve was used to interpolate the experimental measurements, obtaining a good agreement in both the situations. Eddy covariance instruments height (z_m) is also shown in the figure. Crop height was found to increase rapidly until about the middle of August when, more or less at flowering, it reached the maximum value for both treatments. As showed in the figure, crop height in the IRR field was lower than in the FDL field, with an average difference over the whole experimental period of about 12 cm.

Fig. 2. Crop height for rice in the FLD (on the left) and IRR (on the right) treatments: together with the measured data, also an interpolating quadratic polynomial curve and the position of the eddy covariance instruments over the canopy are reported.

Fig. 2. Altezza della coltura nei trattamenti irrigui FLD (a sinistra) e IRR (a destra): accanto ai dati misurati vengono illustrate anche una curva interpolante polinomiale quadratica e la posizione della stazione eddy covariance al di sopra della vegetazione.

3.2 Displacement height and roughness length

In Fig. 3 (a and b) the temporal patterns along the whole growing season of crop height (h_v), displacement height (d), and roughness length (z_0) for the two rice crops are plotted. It can be noted that z_0 increases in the first part of the growing season reaching a constant value of about 0.08 and 0.06 m between the end of July and the middle of August, respectively for FDL and IRR. The d trend is similar to that of h_v: it increases rapidly in the first part of the growing season, going from bare soil to a condition in which crop elements form a closed canopy, while from the end of August it tends to decrease as a consequence of leaf senescence.

In Fig. 3 (c and d) the relationships between z_0 and d with respect to h_v are shown. The regression lines for the whole experimental period were calculated with null intercept. For both treatments, the ratio d/h_v is about 0.75, while the ratio z_0/h_v is about 0.06 and 0.05 for FDL and IRR respectively. In both cases, correlation coefficients are grater then 90%.

The regression coefficients found for FDL and IRR irrigation treatments are similar to each other, and in line with the results reported in the literature for different crop typologies and different geographical regions (Tab.2).

As an additional analysis, the z_0 and d dependence from wind speed and stability condition of the atmosphere was explored according to the methodology described in Hansen (1993) and Gao et al. (2003). Hansen (1993) showed that d and z_0 could also be a function of wind speed. In fact, when the wind speed increases, the canopy tend to flex in the along wind direction and flattening reduces the crop height (Foken 2008). Moreover, Motheith (1965) attributed the variations of d and z_0 values to a transfer of momentum from the canopy top to layers deeper in the canopy and this phenomenon is strongly correlated to the stability conditions of the atmosphere. In our work, the correlation coefficient was computed between geometrical parameters (d and z_0) and turbulent ones (wind speed and z_m/L) as suggested by Hansen (1993). Despite the effort, no evident correlation between stability of the atmosphere or wind speed and roughness parameters was found, given that correlation coefficients for both the irrigation treatments were less than 0.1.

Fig. 3. Changes in crop height (h_v), displacement height (d), and roughness length (z_0), during the whole growing season for the IRR and FLD irrigation treatments (a and b), and regression analysis between d or z_0 and h_v for the two treatments (c and d).

Fig. 3. Andamento dell'altezza colturale (h_c), dell'altezza di dislocamento (d) e della lunghezza di rugosità (z_0) durante la stagione irrigua per i trattamenti IRR e FLD (a e b) e analisi di regressione tra d, z_0 e h_c per i due trattamenti (c e d).

Tab. 2. Comparison of z_o and d relations with h_v observed in this study with those in other works.

Tab. 2. Confronto tra le relazioni tra z_o, d e h_v osservate in questo studio con quelle proposte da altre ricerche.

4 Conclusion

The results achieved in this study show that the dependence of d and z_0 on h_v is very strong for rice crops in northern Italy, whatever the irrigation management adopted (FDL or IRR). The regression coefficients between d or z_0 and h_v proved to be very similar for the two irrigation treatments, and in line with the results reported in the literature for many crop typologies around the world. For both the irrigation treatments, the ratio d/h_v was found to be about 0.75, while the ratio z_0/h_v was calculated as about 0.06 and 0.05 respectively for FDL and IRR; correlation coefficients (R^2) were always higher than 90%.

Martano's (2000) model proved to be a valid method to estimate the evolution of the aerodynamic roughness parameters along the entire growing season. It demonstrates to be sensible to the different crop growing phases, including senescence, when crop height tends to decrease.

If the in-situ estimation of roughness parameters using more complex profile methods is not feasible, the Martano's method could be considered as a more viable alternative. General rules for estimating roughness parameters should be taken into account only in cases where the direct measurement is impossible, and be based on crops and soil/climatic conditions as close as possible to those in which the study is being conducted.

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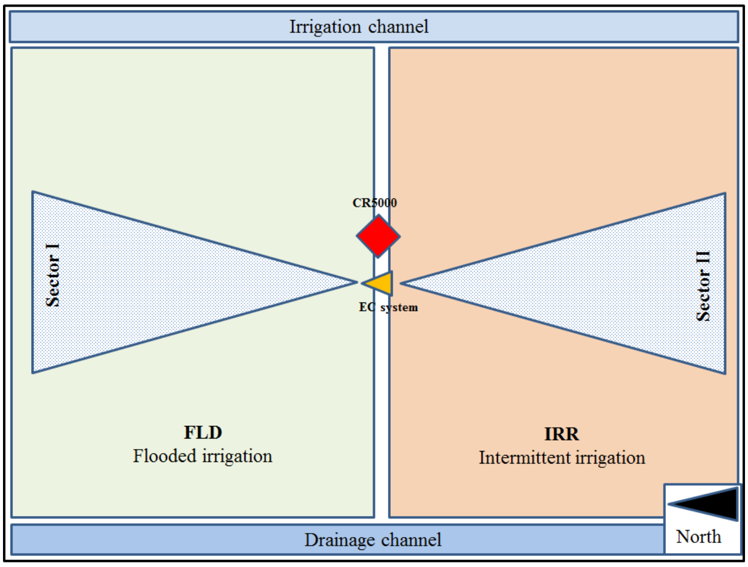

Fig. 1. Experimental fields and EC system position. The complete description of the site characteristics and monitoring activity are illustrated in Facchi et al. (2013).

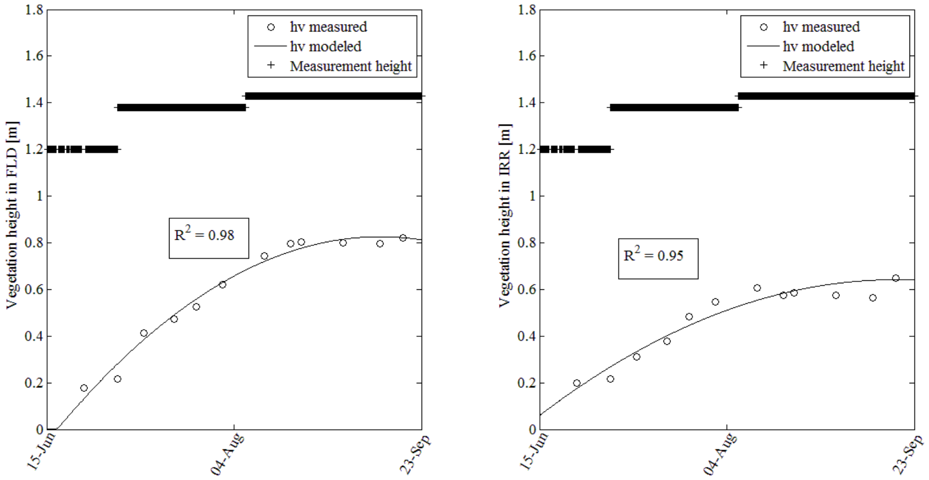

Fig. 2. Crop height for rice in the FLD (on the left) and IRR (on the right) treatments: together with the measured data, also an interpolating quadratic polynomial curve and the position of eddy covariance instruments over the canopy are reported

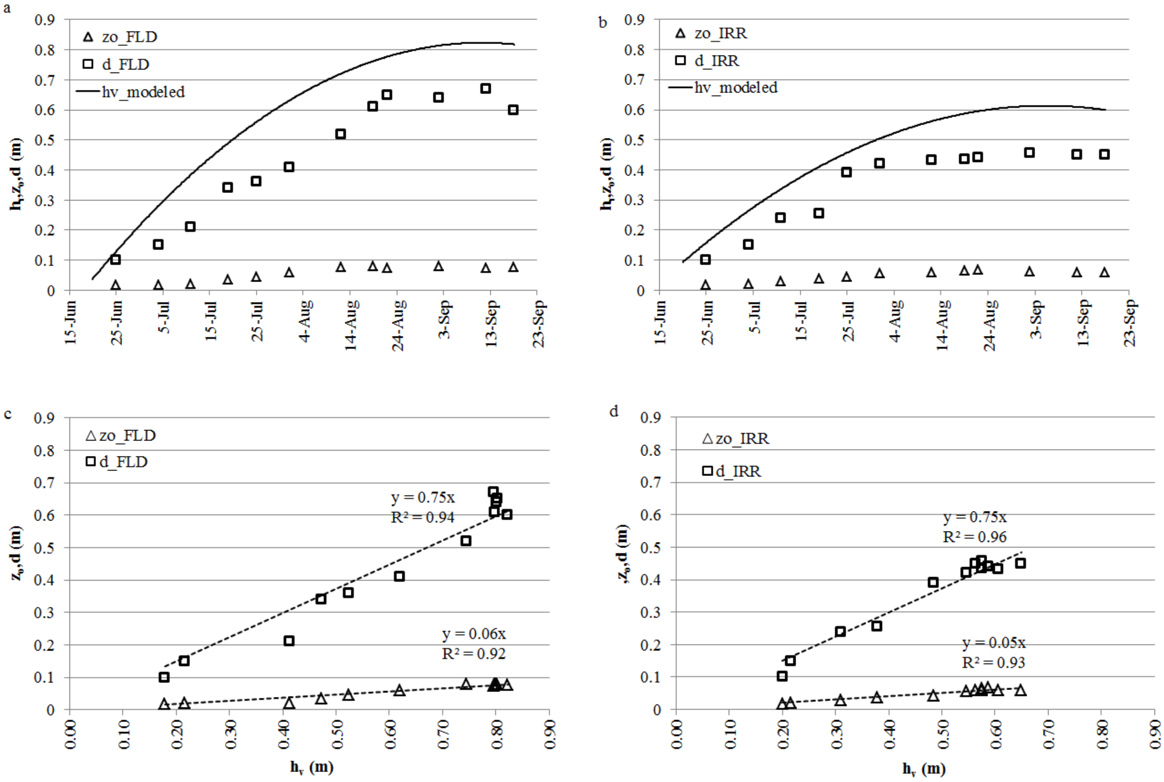

Fig. 3. Changes in crop height (h_v), displacement height (d), and roughness length (z_0), during the whole growing season for the IRR and FLD irrigation treatments (a and b), and regression analysis between d or z_0 and h_v for the two treatments (c and d)

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Tab. 1. Overview of the selection criteria for the application of the Martano (2000) method

Method	Variable	Selection criteria	Reference
Martano (2000)	u_i	$\overline{u} - 4\sigma_u < u_i < \overline{u} + 4\sigma_u$	Gao et al. (2003)
	$\overline{u}$	$\overline{u} > 1.5\ [ms^{-1}]$	Graf et al. (2014)
	z_m/L	$-2 < \frac{z_m}{L} < 2$	Sozzi et al. (1997)

Tab. 2. Comparison of z_o and d relations with h_v observed in this study with those in other works.

Author	z_0	d	Cultivation typology	Note
Nikaradze (1933) quoted in the work of Hansen (1993)	0.08 to 0.15 h_v	-	In crop not specified	-
Tanner and Pelton (1960) quoted in the work of Hansen (1993)	log z_0 = a + b log hv	-	Evaluated over different crops	Tanner and Pelton (1960) a = -0.883 b = 0.997 Sellers (1965) a = -1.385 b = 1.417 Kung (1963) a = -1.24 b = 1.19
Stanhill (1969) quoted in the work of Hansen (1993)	-	log d = 0.973 log h_v – 0.1536	Evaluated over different crops	-
Monteith (1965) quoted in the work of Hansen (1993)	-	0.63h_v	Evaluated over different crops	-
Thom (1972) quoted in the work of Jacob and Boxel (1988)	$z_0 = k\,(h_v\text{-}d)$	-	Evaluated over different crops	Monteith (1973) for generic crops k = 0.41 Thom (1972) for a wheat crop

				$k = 0.37$ Seiger (1974) for a dense crop $k = 0.28$ Moore (1974) for generic crops $k = 0.26$ +/- 0.07 Shaw and Pereira (1982) obtained by their crop model $k = 0.29$
Jacob and Boxel (1988)	$z_0 = k (h_v\text{-}d)$	$0.75h_v$	Maize crop	$k = 0.25$
Foken (2008)	$0.1h_v$	$2/3\ h_v$	Evaluated over different crops	-
Graf et al. (2014)	$z_0 = 0.06h_v + 0.02$	$d = 0.82h_v + 0.17$	Wheat crop	-
Gao et al. (2005)	-	¾ hv	Rice paddy	
This study	$0.06\text{-}0.05h_v$	$0.75h_v$	Rice (paddy and aerobic)	-