About the Role of Turbulence in an Intercropping System

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Original Research Article

ABSTRACT

Aims: It was analysed the role of turbulence in the interaction between the atmosphere and two types of cropping systems, a corn-soy intercrop and soybean monocrop.
Study Design: Experimental.
Place and Duration of Study: The crop experiment was performed between October 2010 and April 2011 at the Balcarce Integrated Research Unit - Agricultural Experiment Station of the National Institute of Agricultural Technology (INTA in Spanish) and the Faculty of Agricultural Sciences at the National University of Mar del Plata (UNMdP in Spanish), while the meteorological experiment was performed during January 2011.
Methodology: The crop experiment involved two spatial arrangements: a corn-soybean intercrop and a soybean monocrop. For two days intensive measurements of the three components of air velocity were obtained with two three-dimensional wind-monitors (YOUNG GILL UVW 27005). One wind monitor was installed within the intercrop and the other in the soy monocrop arrangement.

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Micrometeorological data were analysed using the quadrant-hole methodology.

Results: Turbulence intensity inside the intercrop canopy results greater than in corn and soybean monocrop canopies. Air ejections associated to turbulence interaction with the canopy occurred more frequently than sweeps. However, sweeps were responsible for 57-60% of momentum flux, while ejections were responsible for only 27 to 30%. Also, around 50% of momentum was transported by eddies whose size is associated with a quadrant hole greater than 5 on both types of crops.

Conclusion: The interaction of turbulent eddies with the intercrop-canopy could benefit its environmental inner conditions.

1. INTRODUCTION

In the last three decades, numerous intercropping and mixed cultivation studies have been realized. [1] reintroduced the intercropping concept to intent to reproduce the dynamic of an unmanaged pasture. He proposed interplanting different crops representing various functional groups with an ecological point of view to increase the resilience of the entire system to variation in climate and water supply. Such systems were expected to have greater resistance to pests and other natural disturbances. Other authors have studied the advantages and disadvantages of this type of agriculture. They focused on the selection of crop combinations with different maturity dates (or different periods of high resources demand) [2,3.4,5]; the effects of plant density and/or crop design [6,7]; the effects of crop shading, restricting photosynthetically active radiation (PAR); competition for nutrients and water use [8,9,10,7]; disease and pest control [11,12]; biomass production and CO_2 emissions [10,7,13].

[10] found that wheat, corn and soybean monocrops in the southeastern region of the Argentine Humid Pampas (37°S) captured only 20-30% of annual PAR and transpired 44-72% of annual precipitation. In addition, these authors found that for corn-soy and sunflower-soy intercrops the production of the tallest species was reduced by 20% and that the production of soy was decreased by approximately 40%. These results potentially indicate that studies in this region have not yet properly quantified resource competition versus crop design.

The use of resources in agricultural systems is strongly linked to the system energy and soil water availability, which are derived from the radiation, energy and hydrological balances. [14] studied the effect of microclimate on a corn-soy intercrop system using several meteorological variables, including incoming solar radiation, relative humidity and temperature of the air inside the canopy. They observed that environmental conditions in the intercropping system were significantly improved, with temperatures at heights of 30 and 70 cm in the intercropping system being higher during the day and lower at night, but with less relative humidity. Greater short-wave radiation intensity was observed for the corn plants inside the canopy, which resulted in an enhancement of the photosynthesis. For corn, plant biomass and yield were higher in the intercrop relative to the monocrop. Although this study examined meteorological variables within the complex plant canopy, it did not address the processes that characterize scalar transport or the modification of the vertical profiles of wind, temperature, vapor pressure or carbon dioxide concentrations.

Turbulence is the primary transport mechanism of properties in the surface layer and is closely related to crop architecture [15,16]. A large portion of turbulence at the canopy top results from eddies developed at the canopy scale [16]. The transport of properties associated with turbulence inside and just above the canopy is quite different [17,18.19]. Many descriptions of turbulence in homogeneous canopies have been done [20,21], especially for crops and boreal and tropical forests. [16] summarized some of this information and indicated that the normalized momentum flux or shear stress decreases quickly near the top of the canopy. This decrease resulted from drag interaction of air with plants. For monocrop systems, the normalized standard deviation of the horizontal wind component by the friction velocity (σ_u / u_*) takes on values of 0.75, 2.00 and 2.50 within, on top of and above the canopy, respectively, while for the vertical velocity (σ_w / u_*) takes on values of 1.00 and 1.25 on top and above the canopy, respectively.

The transport of the turbulent kinetic energy towards the inner region of the crop canopy was observed [22]. This transport was the primary consequence of the interaction of different sizes eddies with plants [18,23].

In this preliminary study, there was quantified the momentum transport characteristics for two types of crop arrangement: an intercrop and a monocrop system. The aim has been to produce a brief description of the environmental conditions that promote the transport of properties, momentum and scalars, within the canopy. Conditions associated to larger eddies at a corn-soy and a soybean system were considered.

2. METHODOLOGY

2.1 Data Collection

A field experiment was used in which the turbulence characteristics inside the roughness sublayer [17] associated with the different crop-plants spatial arrangement was evaluated. The crop experiment was performed between October 2010 and April 2011 at the Balcarce Integrated Research Unit - Agricultural Experiment Station of the National Institute of Agricultural Technology (INTA in Spanish) and the Faculty of Agricultural Sciences at the National University of Mar del Plata (UNMdP in Spanish), while the meteorological experiment was performed during January 2011. The crop experiment involved two spatial arrangements: a corn-soybean intercrop and a soybean monocrop. An intermediate cycle maize hybrid was sown in the intercropping system, while and adapted soybean cultivar was used for the intercrop and monocrop system.

A randomized block experimental design with three replications (Fig. 1) was used in a field of 50 m x 90 m, surrounded by weeds of about 0.3 to 0.5 m high. Subplots of intercropping and monocropping systems were of 25 m x 15 m. The intercrop plot treatments included 7 corn plants and 24 soy plants per linear meter. A row spacing of 0.52 m was used for both species. The corn was sown in mid-October, and the soy was sown approximately 30 days after the corn sowing. All rows were fertilized with potassium (P) during sowing. When the corn reached the phenology stage V4 according to [24], rows were fertilized with nitrogen (N). Plant phenology was recorded weekly. Soy growing stages were classified according to the [25] phenology scale. The crop orientation was N-S and they developed in rain-fed conditions.

2.2 Conventional Meteorological Data

In December 2010 there were installed at the field a wind monitor (YOUNG RM), a net radiometer (REBS Q7.1) and a thermo-hygrometer (VAISALA HMP45C) at 3.2 m high above the ground (h_1). Hourly mean values for each variable were stored in a Campbell Scientific 21X data logger. In January 2011, intensive measurements of the three components of air velocity were obtained with two three-dimensional wind-monitors (YOUNG GILL UVW 27005) (Fig. 2). One wind monitor was installed within the intercrop and the other in the soy monocrop arrangement. These
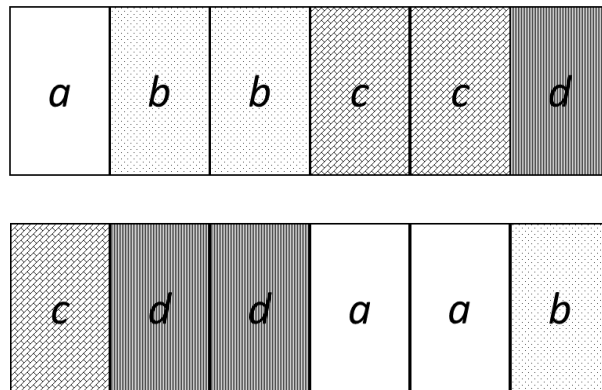

Fig. 1. Experiment configuration by randomized blocks and their repetitions. m: maize row, s: soybean row. a: 2 m:3 s; b: m monocrop; c: 1 m:2 s; d: s monocrop

anemometers, composed by three orthogonal arms with propellers, recorded the three wind components (*u, v, w*) at a temporal resolution of one second. The anemometer arms were positioned to record each wind velocity component using the meteorological coordinate system (u > 0 from the west, v > 0 from the south and w > 0 vertically from the ground). The lowest arm was positioned at 1.2 m (*h*) high. At the intercrop treatment, the arm corresponding to component *u* was physically obstructed by the corn plants. Therefore, only days with a general flow direction coincident with the *v* component (parallel to crop rows) of the wind were considered for the study. During the experiment two days met the former conditions (January 25 and 28, 2011, from now on J25 and J28). On both days, measurements of the 3-D wind components were made between 07:30 and 16:00 h (LT). The prevailed stability conditions were unstable. On the selected dates, the sun raised 2 to 4 minutes before 06:00 h (LT). The height of the crop was 2.1 m (*h_m*) for the corn and 1.0 m (*h_s*) for the soy.

Fig.2. UVW anemometer. Photograph by María Gassmann

Turbulence is usually studied using statistical tools based on the Reynolds decomposition rules [17]. Due to the low temporal resolution of measurements for turbulence studies, the decomposition proposed by [26] was used. They supposed that the wind velocity fluctuation *u'_i* defined at the Reynolds decomposition could be expressed as:

$$u'_i = u'_{iL} + u'_{iS} \qquad (1)$$

where *u'_{iL}* represents the perturbation due to large-scale eddies of turbulence and *u'_{iS}* represents the contribution of the smaller ones. Fluctuations were calculated as $u' = u - \overline{u}$, where $\overline{u}$ is the 15-min averaged wind value. The small-scale fluctuation was removed by the digital filter provided by the distance constant of the UVW propellers (1 m). [26] used a sampling frequency of 1 Hz to explore time series of turbulence searching for specific structures in the air flow around a canopy. The methodology supposed that turbulent structures, usually called coherent structures, explain the major part of the near-surface turbulent kinetic energy, with large heterogeneous and anisotropic vortices. Eddies in the small and large scale were practically uncorrelated.

2.3 Atmospheric Turbulent Structures

Mean and standard deviation of the wind components from 1-s measurements were calculated every 15 minutes. Because the wind direction was from the north or the south on the selected days, the observed *v*-wind component was considered as the mean horizontal wind velocity. To avoid confusion, a horizontal rotation was implemented so that mean wind direction would be consistent with the *u* component of the mean wind in a micrometeorological coordinate system.

To detect the presence of turbulent structures near the canopy, the quadrant-hole analysis was applied to the wind components [18]. The quadrant method [27,28] consists of the decomposition of the turbulent shear stress into four quadrant events. This method has mostly been applied to smooth-wall turbulent boundary layers, vegetated canopies and wind tunnel models [28,18,29,30]. It allows for a description of the role of air sweeps and ejection into the canopy related to the turbulence-canopy interaction and the consequent momentum transport in the vertical direction. The technique is based on the integration of the probability density function of the covariance between the

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horizontal and vertical components of the wind ($\overline{u'_L w'_L}$), known as the turbulent vertical transport of momentum [31]. The quadrant method, which was developed by [32], has been used by numerous authors to describe the interaction of turbulence with obstacles in the atmospheric boundary layer [28,15,33].

The Reynolds stress ($\overline{u'_L w'_L}$) associated to larger eddies at the surface layer can be decomposed for each quadrant of a Cartesian coordinated system as the joint probability of u_L and w_L perturbations:

Quadrant 1 (Q_1) $u'_L > 0$ and $w'_L > 0$ (+)
(outward interactions)

Quadrant 2 (Q_2) $u'_L < 0$ and $w'_L > 0$ (-)
(ejections)

Quadrant 3 (Q_3) $u'_L < 0$ and $w'_L < 0$ (+)
(inward interactions, microfront)

Quadrant 4 (Q_4) $u'_L > 0$ and $w'_L < 0$ (-)
(sweeps)

The vertical transport of momentum can be described as follows:

$$\overline{u'_L w'_L} = \overline{u'_L w'_L}_1 + \overline{u'_L w'_L}_2 + \overline{u'_L w'_L}_3 + \overline{u'_L w'_L}_4 \quad (2)$$

The friction velocity is defined as:

$$u_*^L = \sqrt{-\overline{u'_L w'_L}} \quad (3)$$

The number of events per quadrant provides information about its relative contribution to the momentum transport. Because of the time-lag of wind measurements (1s), the contribution of the observed events is limited by this resolution, therefore only the role of the larger eddies would be described.

The correlation coefficient of u and w (R_{uw}) measures the momentum transport efficiency in units of velocity variance [16] and according to [34] its value allows to know if fully developed turbulence conditions were achieved. For monocrops, typical values are approximately -0.32 outside of the canopy and approximately -0.5 inside it.

As pointed out by [16] the role in the momentum transport of coherent structures is recognized by a major contribution in Q_2 and Q_4. Following [18] the stress fraction function contribution is defined as:

$$S_{i,H} = \frac{\langle u'_L w'_L \rangle_{i,H}}{\overline{u'_L w'_L}} \quad (4)$$

Where I refers to the quadrant number (1, 2, 3, 4) and H is the hole size measured as $H = |u'_L w'_L| / |\overline{u'_L w'_L}|$. The size of the hole H gives information about the relative importance of short-lived events with high values of $|u'_L w'_L|$, producing a fifth region of analysis in the plane (u'_L, w'_L). The increment in the magnitude of H points out the importance of events with larger values of $|u'_L w'_L|$ within each quadrant.

The term in angle brackets represents a conditional average defined using a fraction function $I_{i,H}$:

$$I_{i,H} = \begin{cases} 1 & if (u'_L, w'_L) \in Q_i \\ 0 & if (u'_L, w'_L) \notin Q_i \end{cases} \quad (5)$$

as follows:

$$\langle u'_L w'_L \rangle_{i,H} = \lim \frac{1}{T} \int_0^T u'_L w'_L(t) \, I_{i,H}(t) \, dt \quad (6)$$

The fraction function is used for analyzing the relative contribution of each quadrant to the magnitude of momentum transport above the crop.

3. RESULTS AND DISCUSSION

3.1 Meteorological Conditions during the Study Period

Meteorological conditions on J25 and J28, 2011, were analyzed (Fig. 3). On J25, the predominant wind direction at h_1 was from the north. On J28, the wind was from the north until 03:00 hours (LT) and then turned to the south for the remainder hours of the day (Fig. 3a). In both cases, the predominant wind direction outside of the canopy was parallel to the crop rows. Wind intensity was weak to moderate on both days (Fig. 3b). However, the wind was more intense in the morning and afternoon of January 28.

The intensity of the net radiation indicated that both days were sunny (Fig. 3c). However, cloud cover increased during the afternoon of J25, and a weak cold front produced some precipitation on J26. The turn in wind direction at 06:00 hours (LT) on J28 was accompanied with a significant temperature drop in comparison to the temperature observed on J25 (Fig. 3d).

3.2 Wind Components Statistics

Despite there was only considered the contribution of the larger eddies, the intercrop σ_u^L / u_*^L and σ_w^L / u_*^L values were similar to those summarized by [35] above a monocrop corn canopy on J25 and on top on J28 (Table 1). Measurements were taken inside the canopy (z/h_m = 0.6 m), so these results put on evidence that the turbulence inside the intercrop results more intense than inside a maize canopy. Soybean values measured above the top of the canopy (z/h_s = 1.2 m) presented lower values except on J28 for σ_u^L / u_*^L. The correlation coefficient showed that well above the soybean canopy R_{uw} assumed values of the inner canopy according to bibliography [16] on J25 while on J28 values correspond to that observed above the canopy. Similar results are obtained for the intercrop but with the days exchanged.

It was realized an independent sample comparison of the values (σ_u^L / u_*^L) and (σ_w^L / u_*^L), treated as means with unequal (and unknown) population variances (Welch's t-test, [36]) to identify differences between crops design and time of the day. Comparison was made for each day between de monocrop and intercrop systems, and for the morning and the afternoon separately. Results showed that for each date, considering the two periods and two cropping systems, the mean values were different with a 95% of confidence (Table 2).
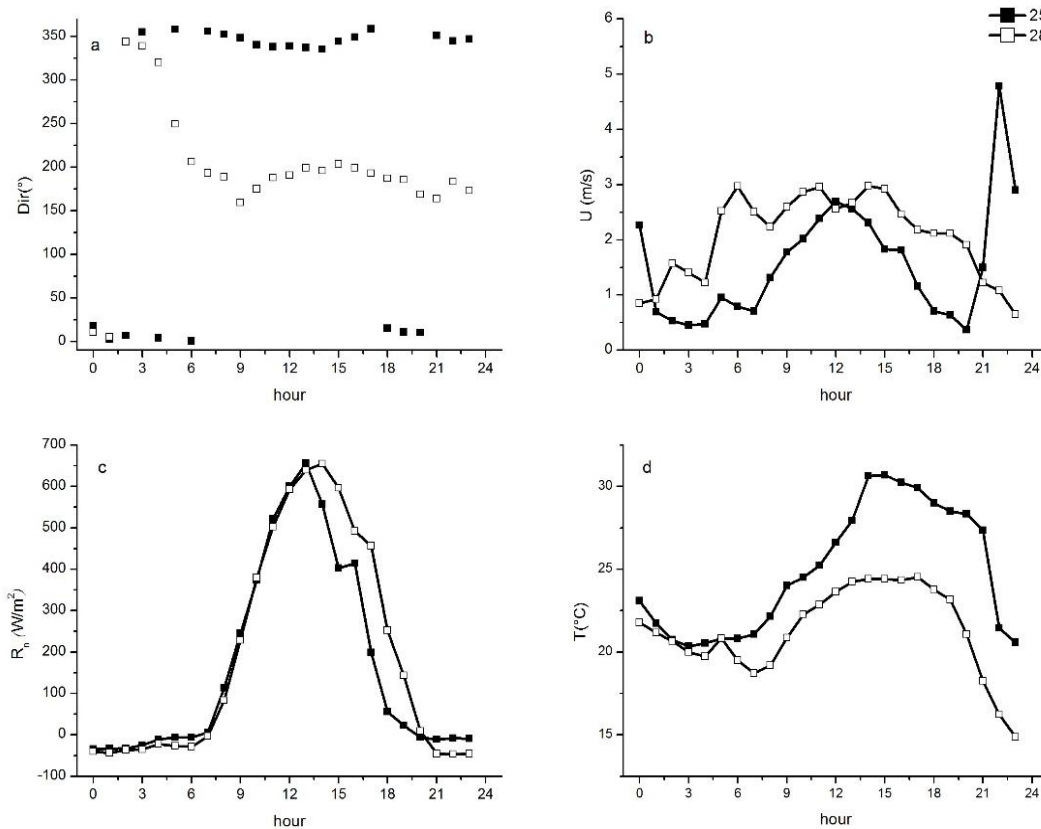

Fig. 3. Variability in hourly meteorological observations on January 25 and 28, 2011:
a) wind direction, b) wind velocity, c) net radiation and d) air temperature

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**Table 1. Mean values of dimensionless turbulent variances and correlation coefficients for *u*
and *w* wind components in corn-soy intercrop and soy monocrop systems**

	Noon	σ_u^L / u_*^L	σ_w^L / u_*^L	$-R_{uw}$
25 - inter	Before	2.61	1.53	0.26
	After	2.67	1.36	0.31
25 -soy	Before	1.84	1.12	0.49
	After	1.91	1.07	0.49
28 - inter	Before	2.07	1.11	0.46
	After	1.91	1.09	0.49
28 -soy	Before	3.75	1.10	0.25
	After	4.11	1.32	0.19

3.3 The Interaction of Turbulence with Vegetation

There were analyzed 22 and 23 15-minute records of wind component measurements on J25 and J28, respectively, with the quadrant-hole technique. Fig. 4 addresses the contribution to a shear stress of each quadrant (1, 2, 3 and 4). The "0" value identifies the hole size H considered. For various periods $S_{2,0}$ and $S_{4,0}$ take values above 0.5 while $S_{1,0}$ and $S_{3,0}$ were predominantly lower than 0.5, especially after 15:00 h. Searching between 15:00 to 16:15 h, it was found that the interactions components ($S_{1,0}$ and $S_{3,0}$) of the shear stress were smaller in magnitude than the other momentum components (ejections and sweeps), and the inward interactions were less intense than the outwards. Observations made at z/h_m = 0.6m in the intercrop reveled mean values of $(S_{1,0} + S_{3,0})/(S_{2,0} + S_{4,0})$ of 0.27 (J25, intercrop), 0.23 (J25, soybean) and 0.19 (J28, intercrop). These
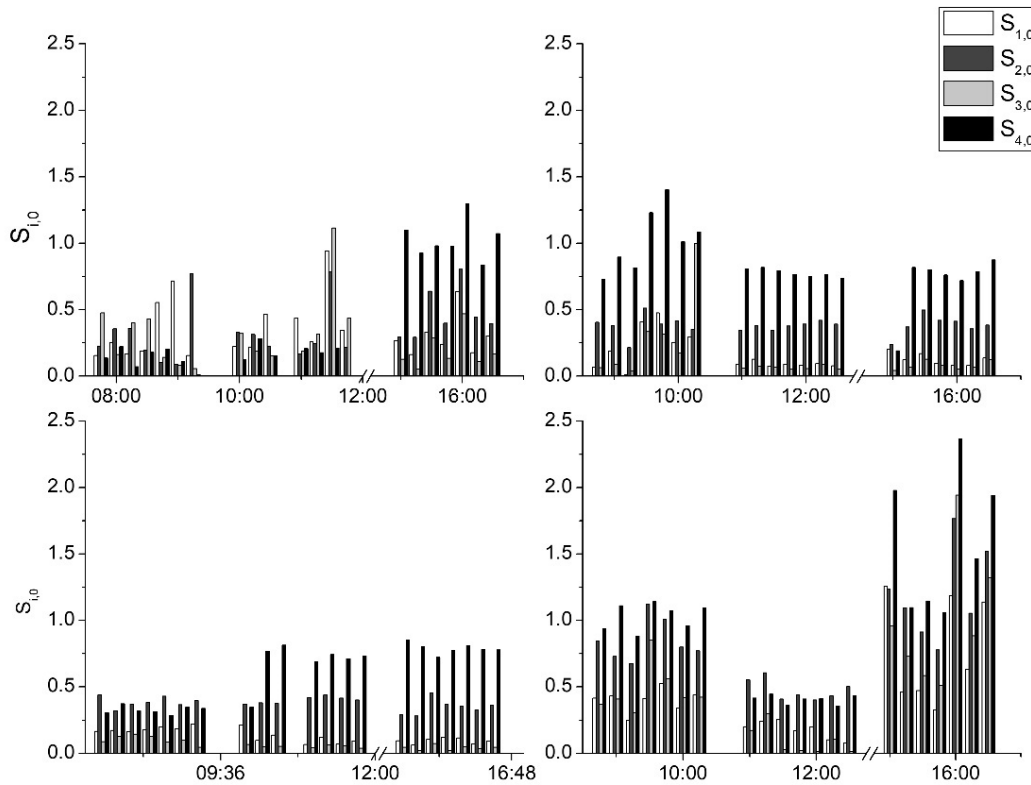

**Fig. 4. Absolute frequency of events per quadrant, which was used to study the turbulent transport of momentum. Left panel: J25, Upper: intercropping, Lower: soybean.
Right panel: J28: Upper: intercropping, Lower: soybean**

values were close to the values reported by [18] and [23] inside a corn canopy. The contribution of sweeps exceeded always ejections, with mean values of $S_{4,0}/S_{2,0}$ of 2.02 and 4.40 for soybean and intercrop respectively (J 25), and 2.23 on J28 (intercrop). These values are similar to the reported by [18] for corn but higher than those simulated by [23] with LES. The duration of ejection events was longer (around 45%) in both systems while sweeps events accounted for only 25 to 28% of the time [19]. Nevertheless, sweeps explained 57 to 60% of the momentum flux while ejections were responsible for 27 to 30%.

The stress fraction S_H decrease with the hole size H at a similar rate in the intercrop than in the monocrop (Fig. 4). [23] obtained that the decrease of the stress fraction was faster at the top of the corn canopy while it was slower inside it. Larger quadrant events guarantee intense momentum fluxes inside the canopy, although the total shear stress is larger at the canopy top. Around 50% of the shear stress is explained by events of large magnitude, with values of H from 5 to 8 in the intercrop and for H from 5 to 10 in the monocrop system. Larger events had less duration at both canopy types (Fig. 5). Then,

Table 2. Statistical t-test and degree of freedom (v) (after [36]) to compare (σ_u^L / u_*^L) and (σ_w^L / u_*^L) between mono- and intercropping system. Shaded cells: the null hypothesis cannot be rejected

Day	Noon	σ_u^L / u_*^L		σ_w^L / u_*^L	
		t	v	t	v
25 (inter/monocrop)	Before	29.8	13	22.8	13
	After	6.6	6	4.3	6
28 (inter/monocrop)	Before	18.1	22	1.9	25
	After	12.2	6	17.5	6

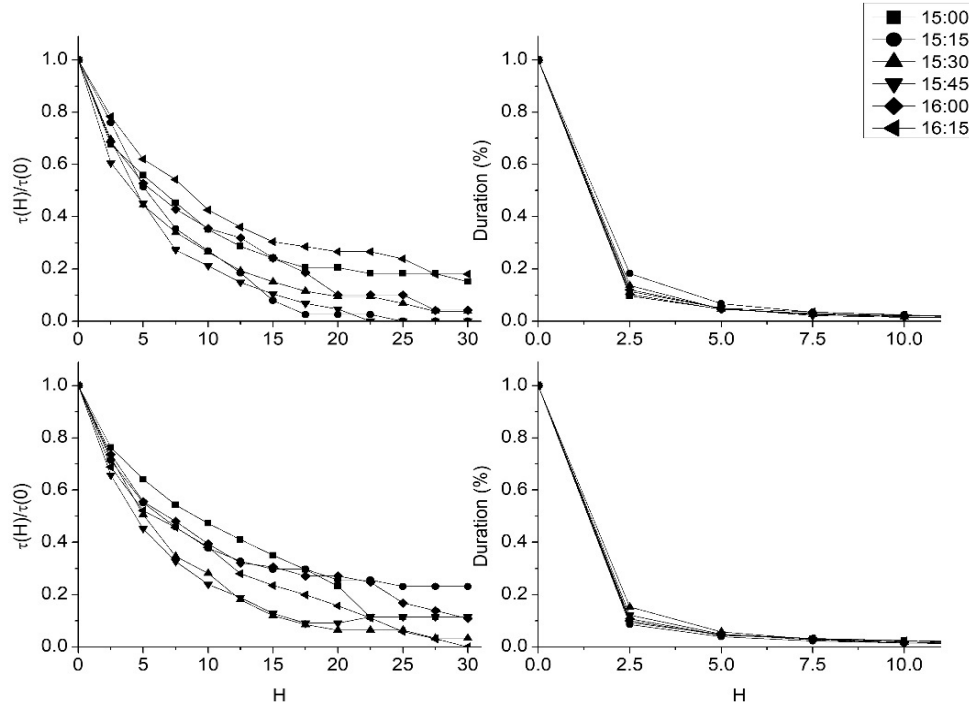**Fig 5. Left panels: Proportion of the sum of all four quadrant stress fractions for each hole size (τ(H)) relative to the momentum transport (τ(0)). Right panels: duration. Upper panels: intercrop. Lower panels: soybean monocrop**

smaller eddies produce a similar effect in the intercrop than that observed with larger eddies in the monocrop, improving ventilation conditions inside the intercropping system.
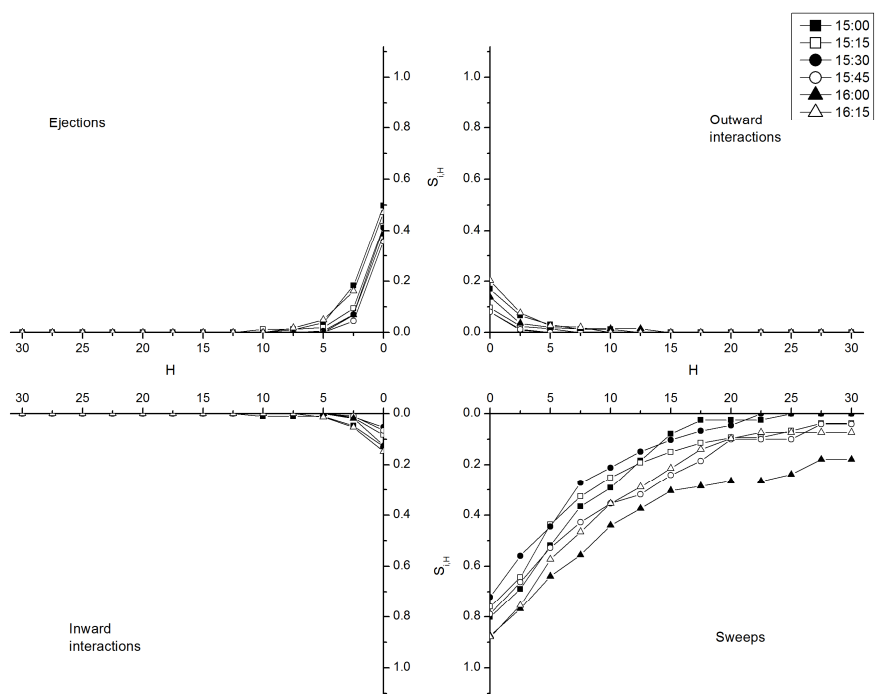

Fig. 6. Hole analysis for the afternoon intercropping data on January 28th
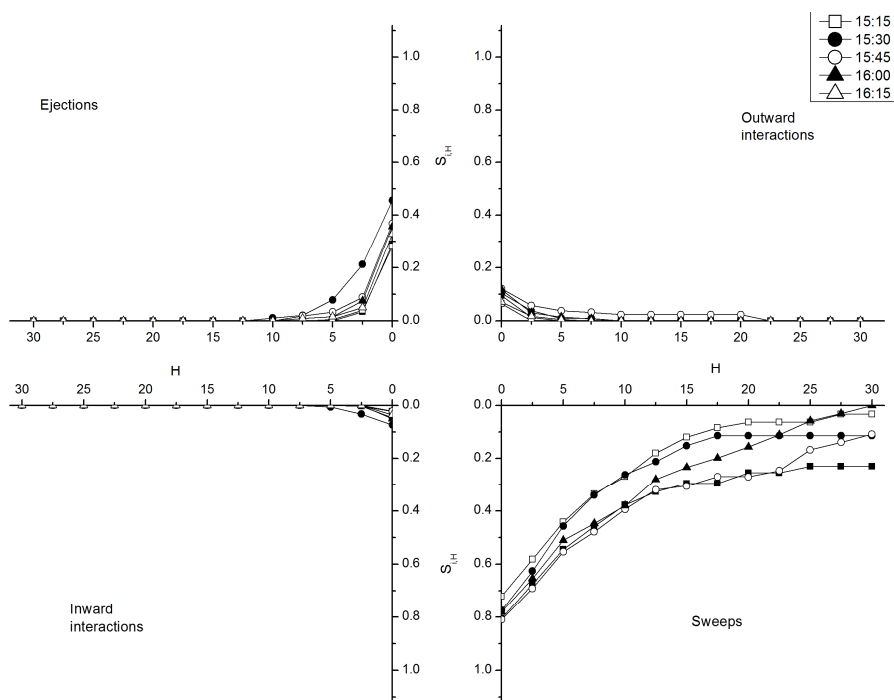

Fig. 7. Hole analysis for the afternoon monocropping data on January 25th

The importance of short-lived events of large magnitude was analyzed with the hole size analysis. Figs. 6 and 7 illustrated the stress fraction contribution by each quadrant at different times during the afternoon in the intercrop for J28 and the monocrop for J25. The same quadrant events trends are found for both crops during the development of organized turbulence. The interaction terms were relatively smaller than the others, while larger eddies had an important contribution of the momentum transport inside the canopy. Around 22 to 45% of the total stress is explained by sweeps events greater in magnitude than H = 10 (Fig. 6). Similar results are shown above the top of the soy monocrop (Fig. 7).

4. CONCLUSION

A preliminary analysis of the turbulence role in the roughness sublayers' momentum fluxes of mixed crop canopies was realized. Atmospheric turbulent conditions above a soybean canopy and inside an intercrop canopy promote the vertical transport of properties. The organized turbulence generated by the air-canopy interaction enhance momentum fluxes benefiting the environmental conditions above and inside the canopy and might improve the physiological response of mixed crops.

The characteristics of larger eddies over two crop surfaces, including a soy monocrop and a corn-soy intercrop, were studied applying the quadrant-hole size methodology for two days during which wind direction was parallel to crop rows. The momentum transport efficiency due to the interaction of larger eddies on both surfaces resulted similar, while their intensity for the intercrop results higher than for monocrop canopies. The quadrant analysis of the turbulence response at the intercropping canopy showed that sweeps are the main contributors to downward momentum transference inside the canopy. Around 50% of the shear stress is related to eddies with H values greater than 8. This fast-moving downward gust may transport temperature and humidity conditions from the top of the canopy within it, cooling and drying the environment inside the canopy. There was found also that the time duration of sweeps is less than the corresponding to ejection, but their contribution to the momentum flux was larger. During events, the total stress and duration decreased along with quadrant hole size. Near

the top of the soy monocrop similar results were found.

Short events of sweeps greater in magnitude than H =10 explained 20 to 45% of the stress of both cropping systems. The transport of momentum due to sweeps in the intercrop was of higher intensity than in the inner part of a corn canopy [23], providing a more efficient mechanism to plants ventilation. According to [37,38], the transport of scalars like temperature and humidity, are associated with sequences of ejections and sweeps that transfer properties through the roughness sub-layer. This finding implies that higher-intensity processes associated with larger eddies in the surface layer might result in an efficient mechanism of scalars transference inside a complex canopy as would be in the intercropping system. This mechanism potentially explains the results that were observed by [14]. In addition, improved ventilation of mixed canopy would reduce the high-moisture periods in the canopy and prevent the occurrence of conditions for plant disease infection.

On the other hand, stomatal resistance responds to wind speed increasing or reducing plant transpiration. According to [39] for stomatal resistance lower than 100 s/m (or conductance greater than 0.4 mol/m^2s), an increase of wind velocity increases plant transpiration. However, if stomatal resistance is greater than 100 s/m (or conductance lower than 0.4 mol/m^2s), the increase of wind velocity tends to reduce plant transpiration, favouring the control of water availability in the soil when atmospheric forcing is high. Therefore, the interactions between the contiguous atmosphere and plants of an intercropping arrangement could improve environmental conditions to plant development, due to better conditions for momentum and scalar fluxes at the top of the plant canopy. These conditions are important for crops growing in rainfed conditions.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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