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Farmland Microclimate and Yield of Winter Wheat under Different Row Spacing

Xun Bo ZHOU[a], Shu Juan SUN[a], Guo Min YANG[a], Yu Hai CHEN[a], Peng LIU [a]

[a] *Agronomy College of Shandong Agricultural University, State Key Laboratory of Crop Biology, Taian, 271018, P.R. CHINA*

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Corresponding author: Yu Hai CHEN, e-mail: yhchen@sdau.edu.cn, Tel: +(86) 538 824 22 26
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ABSTRACT

To gain new insights into the underlying mechanisms responsible for farmland microclimate and yield of winter wheat under different row spacings [row spacing: 7 cm (RS7); 14 cm (RS14); 24.5 cm (RS24.5); 49 cm (RS49)], field experiments were conducted at Taian, China. Between the hours 13:00 and 14:00, low values of relative humidity (RH) and air temperature at 5 cm above the ground for the various row spacings were obtained. The average RH of RS7, RS14, RS24.5, and RS49 was 91.0%, 90.3%, 85.7%, and 76.4%, respectively; the average air temperature were 22.6°C, 23.2°C, 24.3°C and 25.3°C, respectively. The soil temperature of RS49 was higher than those of RS7 and RS14. The maximum values of eddy thermal diffusivity was 0.07 $m^2 s^{-1}$, as well as sensible and soil heat fluxes, were obtained at 12:00 o'clock. The order of these parameters was similar to that of the air temperature, but opposite to that of the latent heat flux. The yield of RS49 was significantly lower than those of the other treatments ($P < 0.05$). The present study indicates that excessive row spacing may result in severe dissipation of energy. RS14 is the optimum condition under uniform planting density.

Keywords: Eddy thermal diffusivity; Heat flux; Soil temperature; Energy balance; Crop yield

İşlenebilir Arazi Mikrokliması ve Kışlık Buğdayın Değişik Sıra Arası Mesafesindeki Verimi

ESER BİLGİSİ

Araştırma Makalesi — Bitkisel Üretim
Sorumlu Yazar: Yu Hai CHEN, e-posta: yhchen@sdau.edu.cn, Tel: +(86) 538 824 22 26
Geliş tarihi: 28 Şubat 2012, Düzeltmelerin gelişi: 03 Nisan 2012, Kabul: 24 Nisan 2012

ÖZET

İşlenebilir arazi mikrokliması ve kışlık buğdayın değişik sıra arasındaki [sıra arası: 7 cm (RS7); 14 cm (RS14); 24.5 cm (RS24.5); 49 cm (RS49)], işlem basamaklarını daha iyi anlayabilmek için Taian, Çin'de tarla denemeleri yapılmıştır. Çeşitli sıra aralıklarında yerin 5 cm altındaki derinliklerde, saat 13 ve 14 arasında daha düşük bağıl nem ve sıcaklık değerleri elde edilmiştir. Ortalama bağıl nem RS7, RS14, RS24.5 ve RS49 için sırasıyla %91.0, 90.3, 85.7 ve 76.4 bulunmuştur. RS49'un toprak sıcaklığı, RS7 ve RS14'kinden daha yüksek olmuştur. Toprak ısı akışının yanı sıra en yüksek termal difüzyon katsayısı 0.07 $m^2 s^{-1}$ olup bu değer saat 12'de ölçülmüştür. Bu parametrelerin sıralaması hava sıcaklığı parametrelerinin sıralamasına benzer olmuş ancak gizli ısı akışı parametrelerinin sıralamasının tam tersi bir durum göstermiştir. Sıra arası 49 cm olduğu durumdaki uygulamanın diğerlerinden belirgin bir şekilde daha düşük olmuştur ($P < 0.05$). Araştırma sonuçlarına göre, sıra arası mesafesinin artması, enerji kaybında büyük kayıplara yol açtığını göstermiştir. Düzgün bir bitki dağılımı için en uygun koşullar açısndan sıra arası mesafenin 14 cm olduğu belirlenmiştir.

Anahtar sözcükler: Termal difüzyon; Isı akışı; Toprak sıcaklığı; Enerji dengesi; Bitki verimi

1. Introduction

Cultivation of plants in crop communities introduces competition, which arises when the immediate supply of a single necessary factor falls below the combined demands of all plants. A plant that is sufficiently close to another can modify the latter's soil or atmospheric environment and thereby decreases the latter's rate of growth. Several researchers found that row width could influence the structure and yield of crop population (Eberbach and Pala 2005; Zhou et al 2010 & 2011). The main factors for competition are light, water, nutrients, and weed. Some approaches, such as early sowing, higher planting density, straw mulching, and improved fertilization have been used to increase crop yield (Cooper et al 1987; Anderson 1992; Philip & Mustafa 2005). Although these approaches are effective, there may be other superior methods. The primary purpose of determining the appropriate application of row spacing (RS) is to increase crop yield and to optimize crop population (Hill et al 2006; Zhou et al 2007).

Wheat is the main cereal crop in China. The Huanghuaihai Plain is one of the most important grain production areas in China. This region is an alluvial-flood plain and sub-humid continental monsoon zone in northern China, with an annual accumulated temperature (≥ 0°C) of 4,800°C, annual average rainfall of 600 mm, cumulative radiation dose of more than 5,200 MJ m^{-2}, and non-frost period of more than 200 days. In northern China, farmers grow winter wheat (*Triticum aestivum*) as the only cereal crop from October to May. The climate during the growing season is dry (precipitation of less than 200 mm), creating a moist lower atmospheric boundary layer in an otherwise dry climate. Regional advection is expected to play a role in surface-layer exchange processes (Lee et al 2004; Uçan et al 2007, Zhang et al 2008).

Environmental protection is one of the priorities as stated in the new Chinese agricultural policy. A compromise between the need to maximize yield and profit and an adequate use of resource is therefore required to reduce the negative effects of cultivation on the environment. Evaluating the response of crops to micro-habitat combined with RS can help identify the best allocation of available resources among crops in farms to maximize profit. The aims of the present study were (i) to evaluate the effect of RS on energy balance for wheat cultivated in a warm-temperate continental monsoon climate; and (ii) to analyze the effects of farmland microclimatic factors on wheat yield.

2. Materials and Methods

2.1. Site description

The present research was conducted at the experimental farm of Shandong Agricultural University, Taian (36°09' N, 117°09' E), in northern China. The site is representative of the main winter wheat-growing region of the Huanghuaihai Plain. Long-term average (1971 to 2008) rainfall and temperature are 696.6 mm and 12.8°C, respectively, whereas rainfall is approximately 200 mm from October to May. The total rainfall was 558.2 mm in 2006, 765.5 mm in 2007, and 627.5 mm in 2008. The soil was a silt loam with the average SOM of 16.3g kg^{-1}, N 92.98 mg kg^{-1}, P 34.77 mg kg^{-1}, K 95.45 mg kg^{-1}, and pH of 6.9.

2.2. Experimental design

Experiments were conducted during the growing seasons from October to June from 2005 to 2008. The present study was part of the continuous winter wheat-summer soybean [*Glycine max* (L.) Merr.] rotation experiment of the authors; post-summer soybean plants were hand-harvested and their stubbles were removed. Winter wheat (*T. aestivum* cv. Shannong 919) was hand-planted with a density of 4.08×10^6 plant ha^{-1} on October 15, 2005, October 6, 2006, and October 10, 2007. Before sowing, 280 kg ha^{-1} of diammonium phosphate, 280 kg ha^{-1} of urea, and 126 kg ha^{-1} of potassium sulfate were applied. The experiment consisted of four planting patterns under rainfed conditions: row spacing×plant spacing was 7 cm × 7 cm (RS7, a uniform grid pattern); 14 cm×3.5 cm (RS14); 24.5 cm×2 cm (RS24.5); and 49 cm×1 cm (RS49). Each experimental plot was 3 m×3 m in size and replicated thrice in randomized block designs. Seedling thinning was done by hand 5 d after wheat emergence to obtain the same final population density (2.04×10^6 plant ha^{-1}). The crops were harvested on June 9, 2006, June 5, 2007, and June 13, 2008. Yields were measured on 2 m^2 plots. Weather data were collected from the Taian Agrometerological Experimental Station located 500 m east of the experimental site. Monthly rainfall data during the winter wheat-growing seasons (October to June) are listed in Table 1.

During the experiment, diurnal soil temperatures between 8:00 and 18:00 hours at soil depths of 5, 10, 15, and 20 cm were measured on selected sunny days at the heading stage. Between 8:00 and 18:00 hours, relative humidity and air temperature were measured using dry and wet bulb thermometers every hour at heights of 5, 20, and 50 cm above the ground level.

2.3. Computation and statistical analyses

Eddy thermal diffusivity, as well as sensible, latent, and soil heat fluxes, were calculated by using the following equations (Weng et al 1981): The energy budget at the land surface is given by

$$R_n = H + E + G \tag{1}$$

where R_n is the net radiation; H is the sensible heat flux; E is the latent heat flux; and G is the soil heat flux.

Eddy thermal diffusivity was calculated using the following equation:

$$K(z) = \frac{k^2(u_2-u_1)}{\ln\left|\frac{z2}{z1}\right|}\left(1+\frac{T_1-T_2}{(u_2-u_1)^2}\ln\left|\frac{z_2}{z_1}\right|\mathrm{z}\right) \tag{2}$$

where K(z) is the eddy thermal diffusivity at height z; k = 0.38 is constant; z_1 = 5 cm and z_2 = 50 cm; T_1, T_2 and u_1, u_2 are air temperature and wind speed at 5 and 50 cm, respectively; and Z is the height between z_1 and z_2. In the present study, z = 20 cm.

Sensible heat flux was calculated by

$$H = -\rho CpK\frac{\partial T}{\partial z} \tag{3}$$

where H is the sensible heat flux (W m^{-2}); ρ = 0.00129 g cm^{-3} and Cp = 1.008 J g^{-1} $°C^{-1}$ are constants; K is the eddy thermal diffusivity; and ∂T/∂z is the lapse rate.

After conversion, Equation 3 appears as follows:

$$H = \frac{5\rho CpK_{(0.2)}(T_1-T_2)}{\ln\left|\frac{z2}{z1}\right|} \tag{4}$$

where $K_{(0.2)}$ is the eddy thermal diffusivity at 20 cm; and T_1 and T_2 are the temperatures at 5 and 50 cm, respectively.

Latent heat flux was determined using the following equation:

$$E = \frac{5\rho LK_{(0.2)}(q_1-q_2)}{\ln\left|\frac{z_2}{z_1}\right|} \tag{5}$$

where L is the vaporizing latent heat (J g^{-1}) and q is the air specific humidity (g kg^{-1}).

Soil heat flux was calculated by

$$G = \frac{Cm}{\Delta t}\left(S_1 - \frac{k}{10}S_2\right) \tag{6}$$

where G is the soil heat flux of 0–20 cm soil profiles in Δt time; Cm is the soil volume heat capacity (J cm-3 °C-1); k is the conduct temperature ratio (cm2 s-1); Δt is the interval between two observation hours; and S1 and S2 are the temperature variations in 0–20 and 10–20 cm soil profiles, respectively.

The data were analyzed by SPSS 16.0, and least significant difference tests were used. Effects

Table 1-Monthly rainfall (mm) for the winter wheat growth seasons
Çizelge 1-Kışlık buğdayın yetiştirilme dönemindeki aylık yağış miktarları (mm)

Season	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Total*
2005/2006	4.6	5.4	3.8	4.7	7.8	0.0	23.5	77.0	0.6	127.4
2006/2007	5.3	14.2	9.5	0.0	2.1	46.7	15.2	118.8	0.7	212.5
2007/2008	17.3	8.0	16.5	4.0	4.8	17.7	57.7	44.7	6.4	169.9

are considered significant in all statistical calculations if the *P* values are ≤0.05 (Mishra et al 2001).

3. Results and Discussion

3.1. Diurnal air relative humidity

For the different row spacings, a low relative humidity (RH) was obtained at 5 cm above the ground at approximately 13:00–14:00 hours (Figure 1). The RH in 2005/2006 was evidently lower than those in 2006–2008. The difference in RH can be attributed to the low amount of rainfall in 2005/2006 (127.4 mm). For rainfed winter wheat, the average RH of RS7, RS14, RS24.5, and RS49 were 91.0%, 90.3%, 85.7%, and 76.4% in 2005–2008. The RH of RS49 was evidently lower than those of the other row spacings; moreover, the RH of RS7 was approximately equal to that of RS14.

3.2. Diurnal air temperature

For the different row spacings, a high air temperature was obtained at 5 cm above the ground at 13:00–14:00 hours in 2005/2006, and at 13:00 hours from 2006 to 2008 (Figure 2). The air temperatures in 2005/2006 were evidently lower than those from 2006 to 2008. The difference in air temperature can be attributed to the climatic conditions during the different growing seasons. The air temperatures under the canopy and in the open are significantly correlated with solar radiation, the presence or absence of canopy leaves, and wind speed (Morecroft et al 1998). The order of average air temperature for rainfed winter wheat from 2005 to 2008 was as follows: RS14 < RS7 < RS24.5 < RS49, the values were 22.6°C, 23.2°C, 24.3°C and 25.3°C, respectively. The air temperature of RS49 was significantly higher than that of RS14 ($P < 0.05$).

3.3. Diurnal soil temperature

For the different row spacings at a soil depth of 5 cm, the diurnal temperature in the afternoon was higher than that in the morning. The maximum diurnal temperature from 2005 to 2008 was obtained at 13:00–15:00 hours (Figure 3). The characteristics of soil temperature were similar to that of air temperature under the various growing seasons. For rainfed winter wheat from 2005 to 2008, the order of average air temperature was as follows: RS14 < RS7 < RS24.5 < RS49 (17.4, 17.4, 18.5, and 21.3°C, respectively). The soil temperature of RS49 was higher than those of RS7 and RS14. Soil temperature can influence many processes in young forest stands, including growth and phenology of trees, water uptake, and nutrient mineralization (Devine & Harrington 2007). In contrast to vegetation indices, soil-surface temperature represents a variable that is reactive to both the overriding atmospheric and surface conditions (Santanello & Friedl 2003). The high soil temperature leads to the dissipation of energy and loss of nutrient, and it decreases crop yield.

3.4. Effects of row spacing on farmland microclimatic conditions

At the turbulent surface layer of the atmosphere, eddy diffusivities for all conserved scalars are normally assumed equal (Gavilán & Berengena 2007). When sources are not uniformly distributed, eddy diffusivities need not be equal, and the scalar fluctuations are imperfectly correlated (McNaughton & Laubach 1998). Row spacing can provide a physical barrier between the soil and the atmosphere, and consequently improve heat conditions at the soil surface. Figure 4 is based on the data at the heading stage from 2005 to 2008. The order of eddy thermal

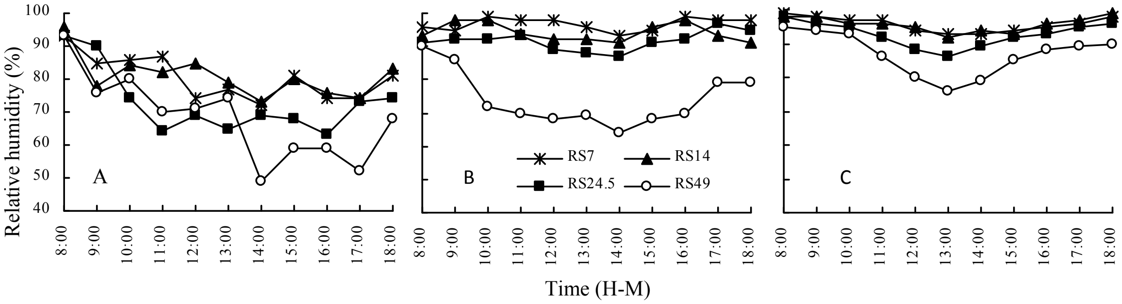

Figure 1-Diurnal air relative humidity (5 cm above ground) for four row spacings of winter wheat. A, B and C is 2005/2006, 2006/2007 and 2007/2008 seasons, respectively

Şekil 1-Kışlık buğdayın dört sıra arası mesafesinde günlük hava bağıl nemi (toprak seviyesinin 5 cm üstü). A, B ve C şekilleri sırasıyla 2005/2006, 2006/2007 ve 2007/2008 dönemlerini göstermektedir

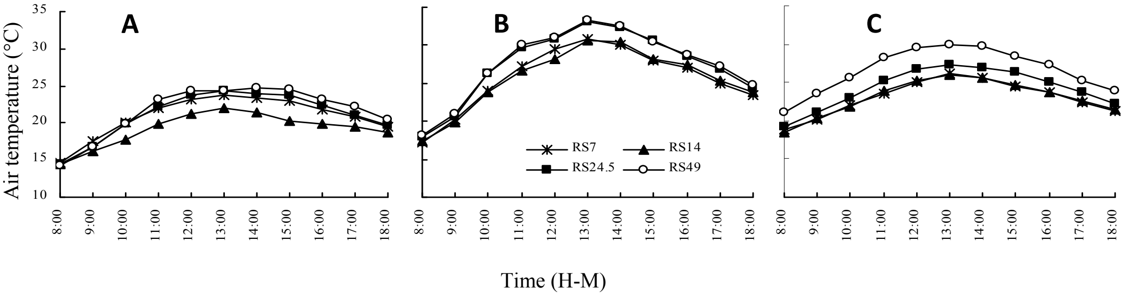

Figure 2-Diurnal air temperature (5 cm above ground) for four row spacings of winter wheat. A, B and C is 2005/2006, 2006/2007 and 2007/2008 seasons, respectively

Şekil 2-Kışlık buğdayın dört sıra arası mesafesinde günlük hava sıcaklığı (toprak seviyesinin 5 cm üstü). A, B ve C şekilleri sırasıyla 2005/2006, 2006/2007 ve 2007/2008 dönemlerini göstermektedir

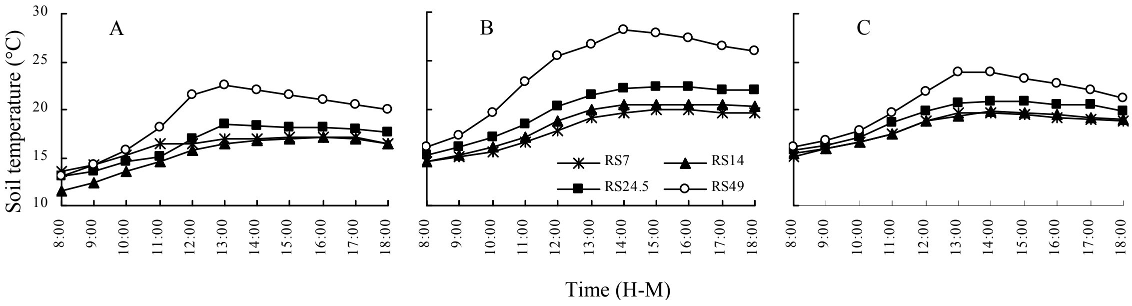

Figure 3-Diurnal soil temperature (5 cm depth) for four row spacings of winter wheat. A, B and C is 2005/2006, 2006/2007 and 2007/2008 seasons, respectively

Şekil 3-Kışlık buğdayın dört sıra arası mesafesinde günlük toprak sıcaklığı (5 cm derinlikte). A, B ve C şekilleri sırasıyla 2005/2006, 2006/2007 ve 2007/2008 dönemlerini göstermektedir

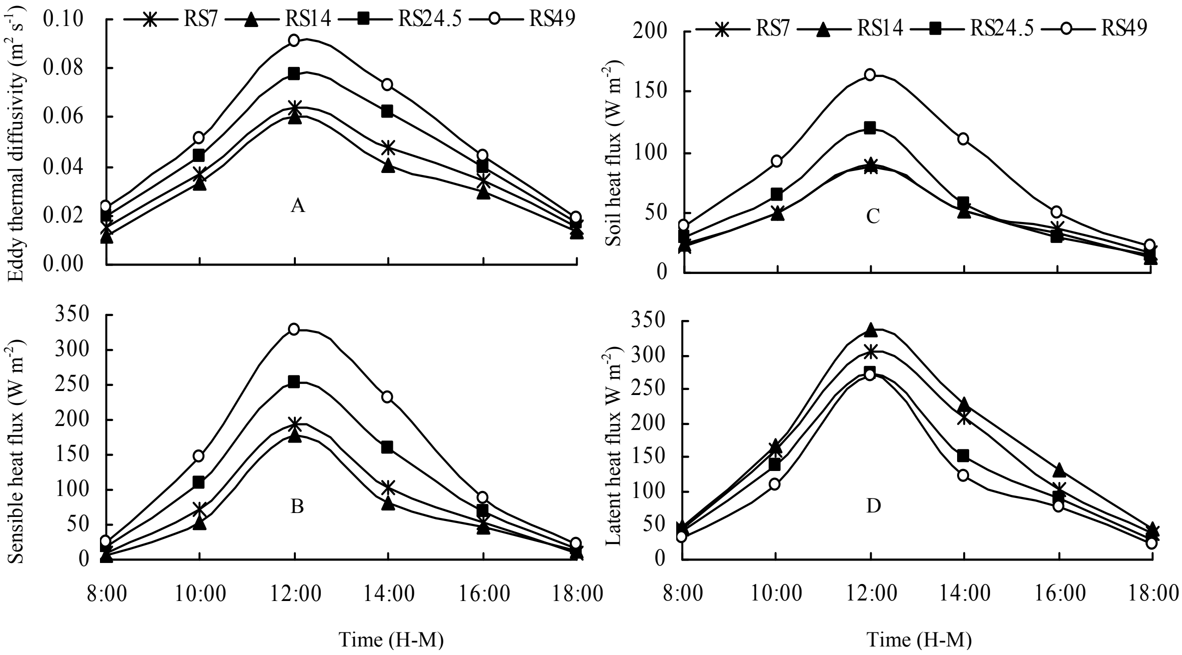

Figure 4-Effect of row spacing on eddy thermal diffusivity (A), sensible heat flux (B), soil heat flux (C) and latent heat flux (D) at heading stage of winter wheat. Data are average of 2005–2008 seasons

Şekil 4-Kışlık buğdayın başaklanma döneminde sıra arası mesafenin türbülanslı ısı difüzyonu (A), hissedilebilir ısı akışı (B), toprak ısı akışı (C) ve latent ısı akışı (D) üzerine etkisi

diffusivity, as well as of sensible and soil heat fluxes, was as follows: RS14 < RS7 < RS24.5 < RS49 (Figures 4 A, B & C); the order of latent heat flux exhibited an inverse trend (Figure 4 D). The soil heat flux was lower than the other two heat fluxes. The maximum heat fluxes of the different row spacings were measured at 12:00 hours. A variation in farmland microclimatic conditions can therefore be achieved by reducing or increasing row spacing under uniform planting density because vegetation partially covering the ground surface results in significant variations in the soil heat fluxes between interspace areas and underneath vegetation (Kustas et al 2000; Li et al 2008).

3.5. Effects of row spacing on net radiation

The surface energy balance describes the energy exchanges between the land surface and the atmosphere. The characteristics of land surface determine which energy transfer process will predominate, and these processes in turn will affect the variables of atmospheric state (Murray & Verhoef 2007). Net radiation did not evidently affect the yield during the course of the present study (Figure 5), and the R^2 value was only 0.293. However, for the average of the various row spacings, the equation of yield vs. net radiation was as follows: y (yield, kg ha^{-1}) = -2.9246x (net radiation, W m^{-2}) + 12210; R^2 = 0.9666. Increasing row spacing can therefore lead to a severe dissipation of energy. The average yield of RS7, RS14, RS24.5, and RS49 was 7521, 7686, 7336, and 6510 kg ha^{-1}, respectively, from 2005 to 2008. The yield of RS49 was significantly lower than that of the other treatments under rainfed conditions, and there was no the differences statistically in yields among RS7, RS14 and RS24.5 ($P < 0.05$).

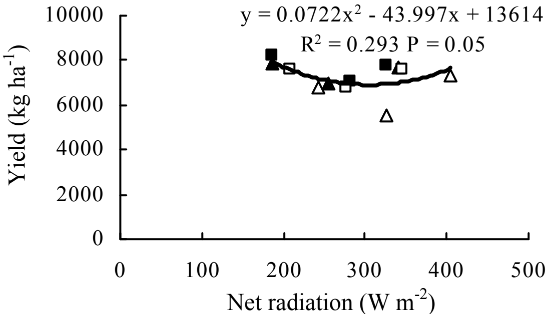

Figure 5-Regression of net radiation vs. yield for the rainfed wheat in 2005–2008
Şekil 5-2005-2008 yılları arasında kışlık buğday için net radyasyon ve verim arasındaki regresyon

4. Conclusions

The three-year study demonstrated that the yield of winter wheat under different row spacings was affected the most by RS, followed by microclimate factors, such as eddy thermal diffusivity, heat flux, air relative humidity, soil and air temperature. The yields of narrow row spacing are significantly higher than those of wide row spacing; moreover, row spacing affects energy balance. High yields of wheat can be achieved in northern China by reducing row spacing under uniform planting density conditions. The yields of RS7 were higher than those of RS24.5 and RS49, and this planting pattern is difficult to practice in the agricultural production for sowing seeds of tractor operation. Given these findings, RS14 is considered as the optimum condition in terms of yield and energy dissipation.

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