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Impact of Soil Heat Flux on Water Use of Quinoa

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Abstracts

A field study was conducted in the winter season of 2017 at the Agricultural Experimental Station of Wadi Suder, south Sinai (D.R.C.), to evaluate the effect of soil organic matter and applied irrigation water on soil thermal conductivity, soil heat flux consequently on soil evaporation , actual water evapotranspiration (ETa) and water use efficiency (WUE) of quinoa yield(chenopodium quinoa willd). Theoretical water evapotranspiration (ETo) was calculated for each treatment using Penman-Monteith equations. Water use efficiency (WUE) was calculated as a result of cumulative improvement for studied parameters. The results reveal that soil thermal conductivity increases by24, 26 and 65% as increasing of applied water, organic matter and their interaction, respectively. While, soil heat flux correlated significantly with all treatments and soil heat conductivity. Generally, the increases were 71, 86 and 232% for organic matter, applied water and inter action, respectively. Whereas, soil heat flux increase by 0.02 mj/m^2/day as a result of increasing thermal conductivity by 9.33 cal/cm/s/ºc (each 1 cal/cm/s/ºc of thermal conductivity enhanced heat flux by 0.002 mj/m^2/day). Evaporation from soil surface increase by 0.008 mm/day as heat flux increase by 0.021mjm^{-2}day, whilst, increasing soil heat flux (1mj/m^2/day) resulted in decreasing **Eta** by 1.81m^3/fed. Simultaneously data illustrates that increasing evaporation by 0.008mm/day led to decrease **Eta** by 8.92m^3/fed. Thus, water use efficiency WUE increases spontaneously by (136%) and (119%) for seed and straw yield, as soil heat flux increased by 0.021mj/m^2/day, respectively. From the aforementioned data, we advise by using irrigation treatment 80% coupled with 1% organic matter which save about 20% from main applied water this ratio will increase seed yield by 402kg (36%). Also, at drought condition the farmer can use irrigation treatment 60% whereas save about 39% (675m^3) if it use under the same organic matter (1%) which could enhance seed yield by 27%.

Key wards: Soil heat flux (G), thermal conductivity (λ), Evaporation, water use efficiency (WUE).

Introduction

The amount of thermal energy that moves through an area of soil in a unit of time is the soil heat flux or heat flux density. The ability of a soil to conduct heat determines how fast its temperature changes during a day or between seasons ***(Thomas & Robert 2005).***
Soil heat flux (G) is important in micrometeorology because it effectively couples energy transfer processes at the surface (surface energy balance) with energy transfer processes in the soil (soil thermal regime). This interaction between surface and subsurface energy transfer processes has led to detailed investigations of soil heat flux for a wide variety of agricultural applications.

The magnitude of *G* as a component of the surface energy balance varies with surface cover, soil moisture content, and solar irradiance. Daytime peak hourly values of *G* for a bare, dry soil in midsummer could be in excess of 300Wm^{-2} ***(Fuchs & Hadas, 1972).*** By contrast, hourly *G* for a moist soil beneath a plant canopy, residue layer, or snow cover will often be less than ±20 W m^{-2}. Surface soil heat flux typically represents 1 to 10% of *R*n for growing crops (***Baldocchi et al., 1985; Clothier et al., 1986)***
Soil heat flux density could be measured using one of four methods (flux plate, calorimetric, gradient, or combination) ***(Thomas and Robert 2005)***. Therefore, this study aimed to calculate soil heat flux (G) by using the gradient one which Fourier's Law is applied $G = -\lambda \, \Delta T/\Delta z$ Where λ is the thermal conductivity of the soil (W m–1 K–1) and $\Delta T/\Delta z$ is the vertical temperature gradient (K m–1) of the soil layer, ***(Hillel, 2004).***

Thermal conductivity is the quantity of heat transferred through a unit area of the conducting body such as soil in unit time under a unit temperature gradient. The thermal conductivities of specific soil constituents differ widely. Hence the space-averaged thermal conductivity of a soil depends on its mineral composition and organic matter content as well as the volume composition of water and air ***(Hillel, 2003 and Abu-Hamdeh & Reeder, 2000).*** These properties often vary between soils, spatially at the soil surface for the same soil, between layers within a soil, and over time.

The thermal conductivities of wet soil porous particles increased with increasing temperature in contrast to the behavior of dry beds and this Increase was attributed to a greater thermal conductivity of water as well as to the temperature-dependent equivalent thermal conductivities arising from steam diffusion ***(Ssing et al 1997& Clothier,et al 1986)***.

(Farouki, 1986), found an increase in either the saturation or dry density of a soil will result in an increase in its thermal conductivity. Also, thermal conductivity increased with increasing soil density and moisture content, ***(Kathleen et al. 2009).***

Agricultural management practices including irrigation, drainage, and tillage have the potential to affect the thermal properties of soils and therefore soil thermal regime. In particular, the effect of tillage and crop residue management on soil heat flux has been the subject of several studies ***(Richard and Cellier, 1998 & Sauer et al., 1998).*** Tillage loosens the surface soil, although some local compaction also may occur. Lower soil bulk density generally translates to lower λ, thus, lower *G* has been observed in tilled soil as compared with un-tilled or compacted soil ***(Richard & Cellier, 1998)***. Crop residue has a low thermal conductivity and, whether lying on the soil surface or incorporated into the soil by tillage, may inhibit heat transfer into the soil. Residue layers also have a shortwave reflectivity that is higher than most soils and provide a barrier to vapor flow ***(Sauer et al., 1997).***

Thus, soils with a large proportion of the surface covered by crop residue as mulch tend to have higher water contents, lower temperatures, and lower *G*. Such changes in soil thermal regime, of course, have implications for the surface energy balance and evaporation.

Irrigation scheduling is one of the factors that influence the agronomic and economic viability of small farmer. It is important for both water savings and improved crop yields. The type of soil and climatic conditions have a significant effect on the main practical aspects of irrigation, which are the determination of how much water should be applied and when it should be applied to a given crop. Other important elements should also be considered, such as crop tolerance and sensitivity to water deficit at various growth stages, and optimum water use. Water shortage is a serious problem affecting plant growth and yield in the Mediterranean region ***(Souza et al., 2004)***.

Improving food crop production in the arid and semiarid regions. Influenced by multiple abiotic stresses, by strengthening a diversified crop production and introducing new climate-proof crops and cultivars with improved stress tolerance such as quinoa (chenopodium quinoa willd). Deficit irrigation strategy (DI) has been widely investigated as a valuable and sustainable production strategy in dry regions. By limiting water applications to drought sensitive growth stages, this practice aims to maximize water productivity and to stabilize, rather than maximize, yields ***(Geerts and Raes, 2009)***. Benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water ***(English and Raja, 1996)***. Quinoa (Chenopodium quinoa Willd.) comes from the Andean highlands of South America, It has a high nutritional value of protein, vitamins and minerals ***(Jensen et al.,2000)***, and it is drought and frost resistant crop ***(Garcia et al., 2003; 2007; Jacobsen et al.,2009***, ***Jacobsen et al., 2005; 2007; Bois et al.,2006)***, and salt ***(Jacobsen et al., 2001; Jacobsen, 2009).***

Thus, this study aims to explain the relationship between (1) thermal conductivity and soil organic matter and quantity of irrigation water, (2) soil thermal conductivity and heat flux, (3) heat flux and soil evaporation (4) heat flux and evapotranspiration (5) impact on water use efficiency.

Materials and methods

The field experiment was carried out in winter season of 2017/2018 and in split design in which the main plot was represented by three levels of composted farmyard manure application rates, i.e.0.0, 0.5 and 1 %. Sub-main plots were represented by three levels of irrigation water 60, 80 and 100% with three replicates for each treatment. Thus, the experimental design is as follow: (3 rates for farmyard manure) x 3(irrigation water levels x 3(replicates) =27 plots. After soil preparation, plots were divided into (5 lines/ plot) and sown by quinoa after seeds infuse in water for about twenty four hours, at (14 pits / line) at 15 th November 2017.

Field Measurements:

Soil thermal conductivity and heat flux measured monthly and calculated by Fourier, law according to ***(Hillel, 2004)***. Soil evaporation was determined according to ***(Richard et al., 1990)***. Organic matter (O.M) was determined as well as organic carbon (O.C) according to ***(Jackson,** 1973)* where, O.M % = O.C %*1.72. The electrical conductivity determined using 4075Conductivity TDS meter described by ***(Jackson, 1973)***. The pH values of soil solution were determined by 3010 pH meter According to ***(Black,** 1983)*.The initial physical and chemical properties of Wadi Suder soil, farmyard manure and irrigation water shown in table (1).

Three irrigation water amounts (ETc) were obtained from the product of the potential evapotranspiration (ETo) by crop coefficient for every stage of quinoa then multiplying by 0.6, 0.8 and1.0 (i.e., (**Q1)** 100%, (**Q2)**80% and **(Q3)**60%). The ETo was calculated from Penman-Monteith equation **Allen et al. (1989).**

Table 1. Physical and chemical properties of initial soil, organic manure and irrigation water.

Physical properties	Particle size distribution				soil thermal conductivity cal/cm/s/°c	Bulk density
	Sand	Silt	Clay	Texture class		
	85	7.02	7.98	L.S	9.5	1.53
Chemical properties	$CaCO_{3\%}$	ECdS/m	pH	CEC meq/100g soil	OM%	
	51.9	10.4	7.9	2.8	0.25	
Farmyard manure	C%	N%	C:N	P ppm	K ppm	OM%
	23.5	1.9	12:1	17.5	125	40.42

Irrigation water	Soluble cations and anion meq/l										
	Na	Ca	Mg	K	Cl	CO_3	HCO_3	SO_4	SAR	ECdS/m	pH
	45.6	24.9	4.9	0.44	55.8	-	1.9	19.03	9.6	7.24	7.55

$$E\,To = \frac{0.408\Delta(Rn-G) + y\dfrac{900}{T+273}\mu_2(es-ea)}{\Delta + Y(1+0.34\mu 2)}$$

Where:

ETo	= reference crop evapo transpiration	{mmday $^{-1}$}
Rn	= net radiation at crop surface	{Mjm^{-2} day^{-1}}
G	= soil heat flux density	{Mjm^{-2} day^{-1}}
T	= air temperature at 2m height	{°C}
U_2	= wind speed at 2m height	{ms^{-1}}
e_s	= saturation vapor pressure	{KPa}
e_a	= actual vapor pressure	{KPa}
{es-ea}	= saturation vapor pressure deficit	{KPa}
Δ	= slop vapor pressure curve	{KPa°C^{-1}}
Γ	= psychro metric constant	{KPa°C^{-1}}

The crop coefficient was assumed as0.4, 0.8, 1.1 and 0.7 for establishment, vegetative, flowering and ripening stages, respectively.

Table 2. Applied water m^3/f

Q	**ETc** $_{mm}$				**ETm m^3/f**	**Applied water m^3/f**
	In.	**Dev.**	**Mid.**	**Lat.**		
Q1	27.25	74.78	148.74	46.8	1250.22	1687.8
Q2	27.25	59.82	118.99	37.44	1000.18	1350.24
Q3	27.25	44.87	89.24	28.08	750.13	1012.62

Q1=100% Q2=80% Q3=60% In.= Initial stage Dev.= Development stage Mid.= Mid stage Lat.=Late stage

The recorded data were:

1-Plant productivity

Seed and straw yield (kg/ fed.) were calculated for Quinoa plants

2-Water consumptive use

0 **(Giriappa, 1983).**

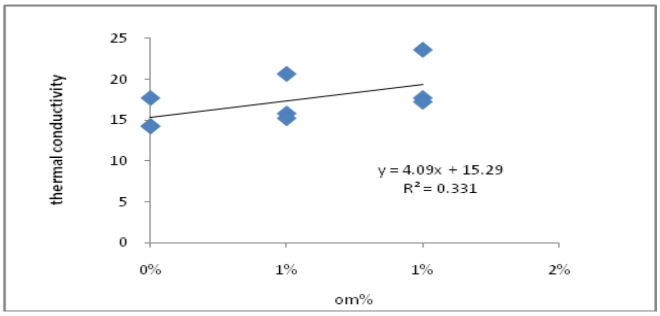
Results and discussion

Thermal conductivity:

The thermal conductivity of soil varies by composition of the solid fraction (mineral type, particle size, and amount of organic matter), water content, and bulk density ***(Abu-Hamdeh & Reeder, 2000)***. These properties often vary among soils, spatially at the soil surface for the same soil, between layers within a soil, and over time. So, entity of organic matter and applied water is desirable and momentous for its impression on thermal conductivity. Table (3) point out that thermal conductivity increased by 24, 26 and 65% as increasing of applied water, organic matter and their interaction. Figs. (1a&1b) illustrate the linear relation of simple and multiple regression of OM and applied water and coupled of them, where, y=15.29+ 4.09 x_1, y= 7.21 + 0.123x_2 and y = 5.36 + 0.12x_2 + 4.1x_1, where y, x_1 and x_2 are thermal conductivity, organic matter and applied water, respectively. The simple and multiple correlations which assure these relations are: r=0.575*, r= 0.712* and R= 0.917*** for organic matter, applied water and interaction, respectively. From the coefficient values of organic matter and applied water, it seems that thermal conductivity increased by 0.123 and 4.09 for each excessive unit of water and organic matter.

Table 3. Soil thermal properties and evaporation affected by organic matter and applied water.

Farmyard. manure	Irrigation Treatments	Thermal Conductivity Cal/cm/s/ºc	Heat flux mJ /m^2/day	Evaporation Mm/day
	100%	17.66	0.0164	0.007
0.0%	80%	14.26	0.0107	0.004
	60%	14.21	0.0088	0.003
	100%	20.60	0.0222	0.009
0.5%	80%	15.77	0.0124	0.005
	60%	15.20	0.0119	0.0048
	100%	23.54	0.0293	0.012
1%	80%	17.66	0.0156	0.0063
	60%	17.20	0.0155	0.0063



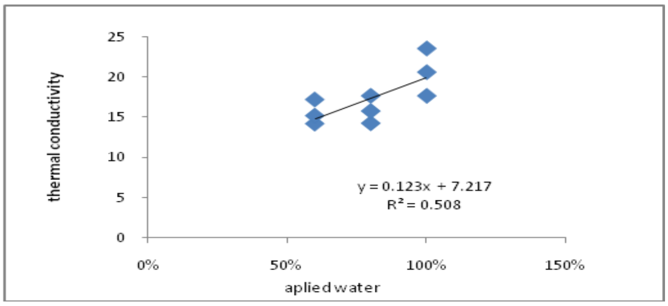


Fig. (1a) thermal conductivity affected by applied water and organic matter

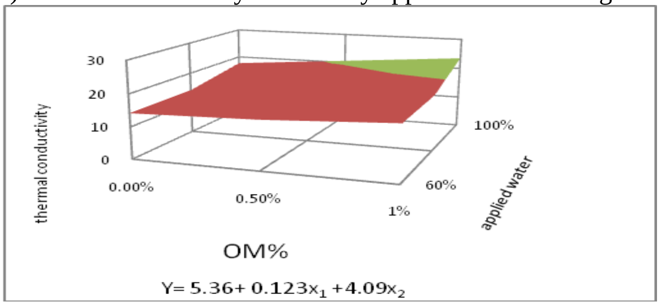


Fig. (1b) thermal conductivity affected by coupled of applied water and organic matter

Heat flux:

Measurement of soil heat flux density involves the measurement of soil temperature and one or more soil thermal properties (thermal conductivity or heat capacity), and possibly soil water and organic matter content. Wherever, soil with low heat capacity, organic matter, water content lower in its thermal content and conductivity consequently heat flux, therefore, this treatise aimed to study the relation of soil heat flux with soil organic matter, applied water and directly thermal conductivity. Table (3) declare that soil heat flux increased by 71, 86 and 232% organic matter, applied water and inter action, respectively. Whereas, soil heat flux increase by 0.02 mj/m^2/day as a result of increasing thermal conductivity by 9.33 cal/cm/s/ºc (each 1 cal/cm/s/ºc of thermal conductivity enhanced heat flux by 0.002 mj/m^2/day). Figs (2a&2b) come to emphasize these relations which show linear relation between thermal conductivity and heat flux and the complementary effect of organic matter and water on heat flux. The simple correlations were, r= 0.550*, r= 0.716* and r= 0.994*** for organic matter, applied water and thermal conductivity, by the same sequence. This means that thermal conductivity has superiority on

applied water followed by organic matter. From the previous data we can conclude the following:
1:-Soil heat flux increased by increasing soil organic matter which causes enhance for both soil moisture and soil heat capacity.
2:- According to Fourier' law soil heat flux correlated mathematically with thermal conductivity so, heat flux increased as thermal conductivity increase.

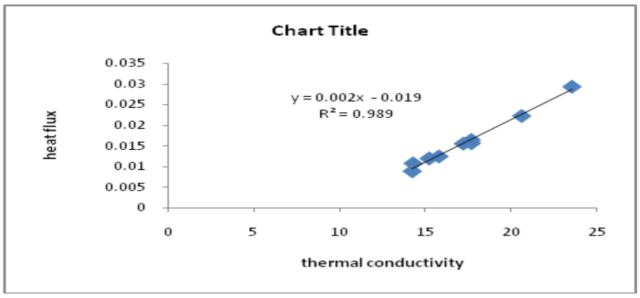


Fig (2a) heat flux affected by thermal conductivity.

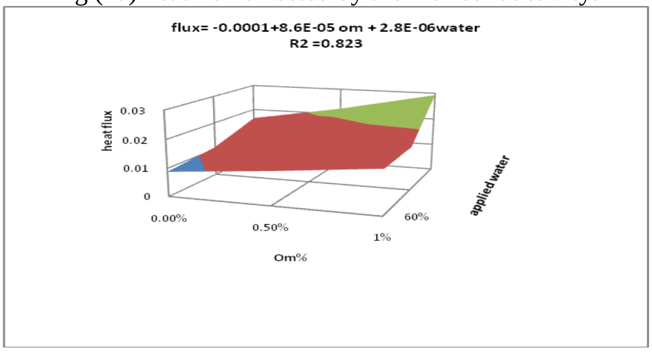


Fig (2b) heat flux affected by coupled of Om% and applied water.

Soil evaporation and actual evapotranspiration (Eta):

Evaporation is a process by which water changes to a vapor through the absorption of heat energy. It is that part of evapotranspiration which occurs directly from water or moist surfaces. Evapotranspiration is the term used for combined evaporation and transpiration. It is defined as the sum of the volumes of water used per unit area by the vegetative growth in transpiration and that evaporated from the soil. Soil heat flux plays the major role in calculated the two items. However, soil heat flux defined as latent heat flux, sensible heat flux and density heat flux, the first is called the latent heat for evaporation this mean that evaporation increase with increasing latent heat. Also, penman montith for calculating evapotranspiration involves heat flux (G) and net radiation in the equation. Whatever, tables (3&4) indicate that soil evaporation increase by 0.008 mm/day as heat flux increase by 0.021mjm^{-2}day, whilst, increasing soil heat flux (1mj/m^2/day) resulted in decreasing **Eta** by 1.81m^3/fed. On other side, the same table illustrates that increasing evaporation by 0.008mm/day led to decrease **Eta** by 8.92m^3/fed. Figs (3a, 3b &3c) come to assure these relations +whereas, its show the linear relation between these parameters and the simple correlations were, r= 0.94***, r= -0.621* and -0.618* for (heat flux & evaporation), (evaporation & Eta) and (heat flux & Eta), sequencely.

Table 4. Yield and consumptive water use efficiency.

Organic Mater %	Water Levels %	Seed yield Kg/f	Straw yield Kg/f	Eta m^3/f	Seed WUE	Straw WUE
	100	690	720	1300.85	0.530	0.55
0	80	621	661	1304.77	0.475	0.51
	60	558	608	1305.40	0.427	0.47
	100	1076	1106	1298.47	0.828	0.85
0.5	80	960	995	1303.04	0.736	0.76
	60	765	810	1302.28	0.585	0.62
	100	1304	1330	1296.14	1.010	1.03
1	80	1108	1150	1294.31	0.850	0.88
	60	995	1040	1293.80	0.769	0.80
Production limits		0.75: 1 ton/fed.				

Quinoa yield:

Quinoa yield comes as revenue of organic and applied water treatment and improved soil parameters whatever, table (4) point out that seeds yield increased by 82% as a result of organic matter increase, meantime, 23% and 133% attributed to applied water and the interaction, respectively. Also, Fig. (4) Assure these relations by showing the linear relation among seed yield and treatments. Meantime, the simple and multiple correlations were, r= 0.881**, r= 0.431 NS and R= 0.921 ***, for organic matter, applied water and the interaction, respectively. Although the non significance of applied water but when coupled with organic matter it show the significant effect and the multiple regression is $y=191.89 +154.9x_1 +7.6 x_2$ where y, x_1 and x_2 are seed yield, organic matter and applied water, respectively. Furthermore, there are three values of yield lie within the production limits of south Sinai soils (0.75: 1 ton/fed.), ***(guidance agrarian 2014)*** also, there are three values exceeds these limits by 7.6, 10.8 and 30.4%. Seemingly, the six values which lie in the production limits or above it come as a result of using all application water levels under 0.5 and 1% organic manure and it take the order(1% Om& 100% AW) > (1% Om &80%AW) > (0.5% Om & 100%AW) > (1% Om & 60%AW) > (0.5%Om & 80% AW) > (0.5% Om & 60%).

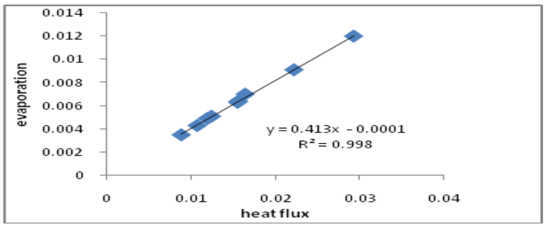


Fig. (3a) soil evaporation affected by heat flux.

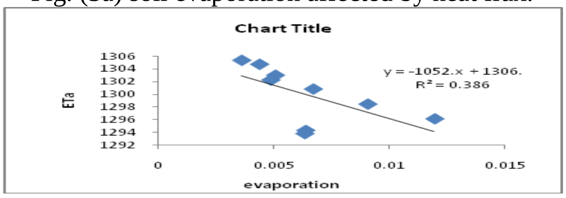


Fig. (3b) ETa affected by soil evaporation.

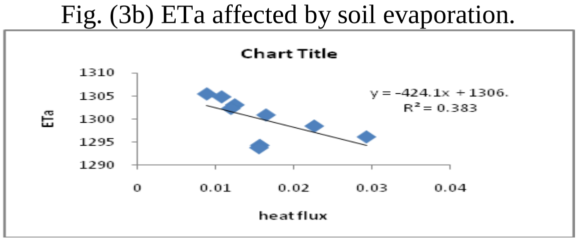


Fig. (3c) Eta affected by heat flux.

Heat flux relation with quinoa seed yield.

Soil heat flux affects on quinoa seed crop by indirect way where, raising heat flux means easiness energy translocation through rhizosphere and save the bio energy for all plant physiological process like, root elongation, nutrients uptake, water uptake and microbes activity. Whatever, the data shown in tables (3&4) illustrate that there is a significant relation between soil heat flux and quinoa seed yield. Thereon, when calculate the difference between the maximum and minimum values of heat flux and seed yield it obvious that increase soil heat flux by 0.0205 mj/m^2/day exceed seed yield by 746 kg /fed., means that (each 0.01mj/m^2 /day give 363 kg/fed.). Fig. (4b), show the linear relation between soil heat flux and seed yield and the simple regression. The simple correlation is 0.819**. These results agree with ***Samy(2001).***

Water use efficiency (WUE):

Improving water use efficiency requires a development of satisfactory means to estimate crop water requirements or evapotranspiration (ETo). Water use efficiency as cumulative study involves ETa and yield. Also, soil heat flux affects indirectly on WUE through impact on Eta and evaporation. Table (4) declares that seed WUE increase by 83, and 24% attributed to increasing organic matter and applied water, while, straw WUE raising reached 77 and 17% for organic matter and applied water, respectively. Meantime, tables (3&4) declare that increase soil heat flux by 0.021 mj/m^2/day resulted in increasing WUE 0.58 (136%) and 0.56 (119%) for seed and straw, respectively. Fig. (5), comes to emphasize the previous relation through the linear simple correlations which were, r= 0.430NS, r= 0.881** and 0.823** for seed WUE whilst, for straw WUE were, 0.407NS, r=0.891**and r= 0.813** with applied water, organic matter and heat flux. From studying these correlation values it seems that applied water has a non significant effect on seed and straw WUE but when it coupled with organic matter and heat flux the relation had been changed. So that, the values of multiple correlations were R= 0.982*** and R= 0.981*** for seed and straw WUE and the multiple regressions were: Y_1= 0.139+ 0.36x_1 +4.3x_2 +0.003x_3 and y_2= 0.2+ 0.35x_1+ 4.6x_2+ 0.003x_3. Where, y_1, y_2, x_1, x_2 and x_3 are seed WUE, straw WUE, organic matter, heat flux and applied water respectively.

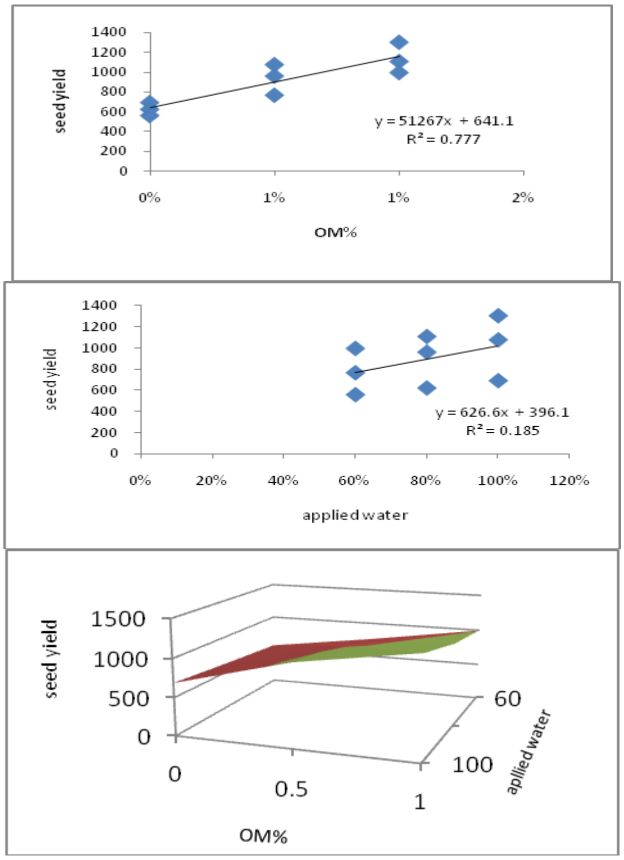


Fig.(4a). Seed yield affected by soil organic matter, applied water and their interaction.

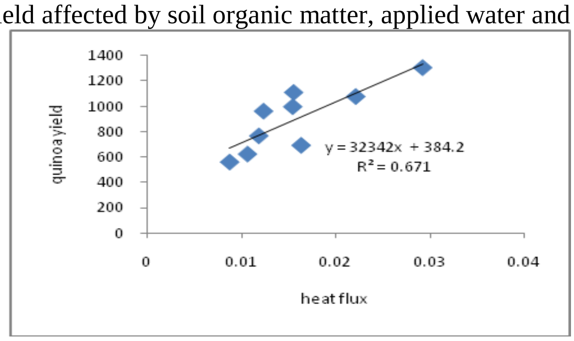
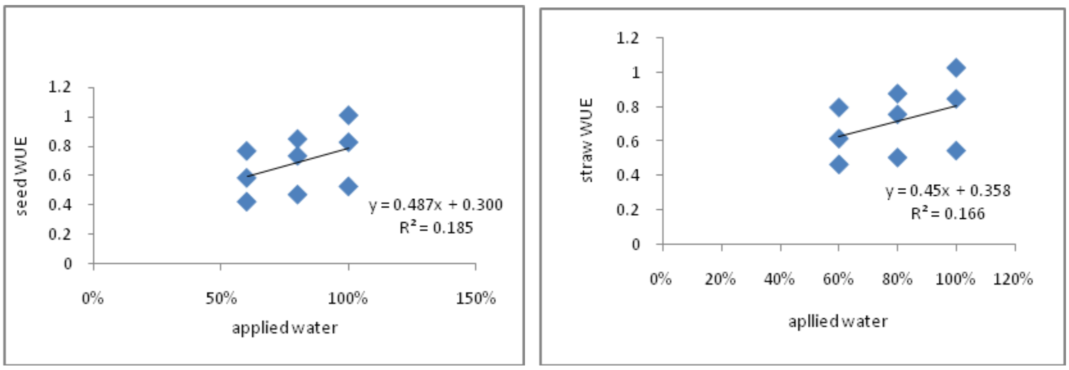


Fig.(4b) seed yield affected by soil heat flux



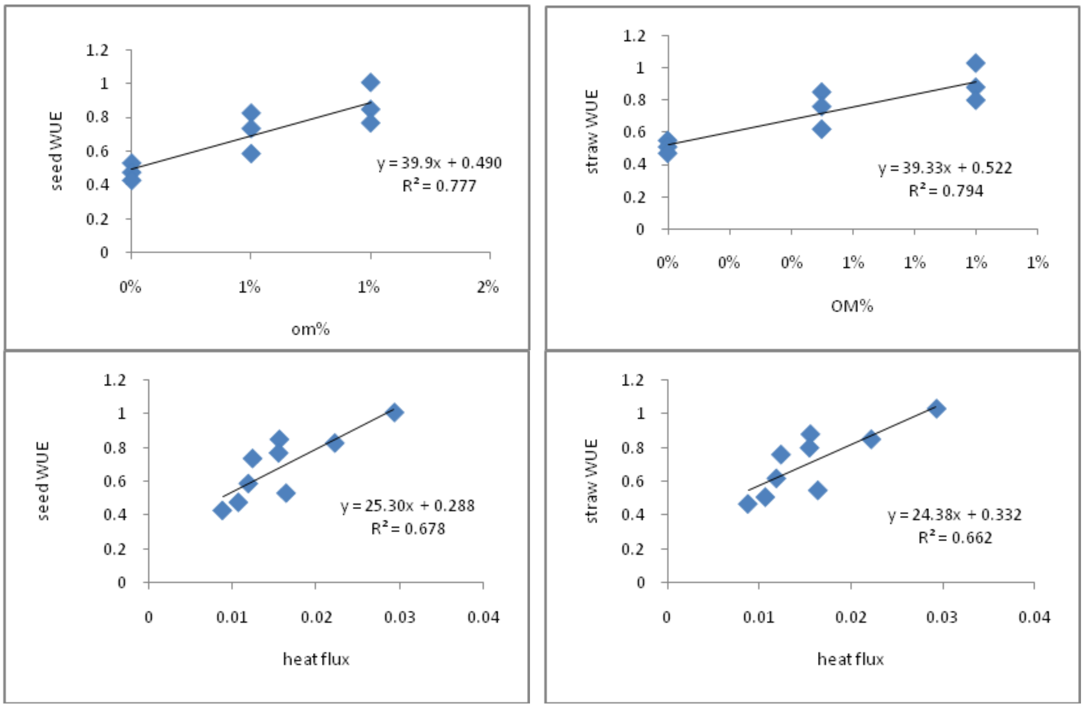


Fig. (5) WUE affected by applied water, organic matter and heat flux

Conclusion

Based upon results, the following can be concluded:

The effects of the applied treatments which improve most of studied soil characters terminally affect positively the crop yield parameters.

This complementally effect sustained over the studied successive season of cultivation with quinoa crop which indicate durability of these treatments in face of environmental and climatological conditions.

The obvious role of organic matter and irrigation water in producing crops has been detected with yield parameters, in which organic application had the major role in improving quinoa crop, ETa and WUE based upon it has the magnitude values of correlation. Whilst, organic matter and irrigation water led to increase thermal conductivity by mixing technique significantly effect on the all aforementioned studied parameters. Heat flux significantly and positively correlated with organic matter, irrigation water and thermal conductivity. So that, soil heat flux increase resulted in decrease Eta and increase soil evaporation, so that ETa decreases as evaporation increase. Water use efficiency for seed and straw yields come as the conclusion improvement of all parameter and heat flux cause the majority increase reach 139 and 119% for seed and straw yields followed by organic matter and irrigation water.

Eventually, from the aforementioned data we advise by using irrigation treatment 80% coupled with 1% organic matter which save about 20% from main applied water this ratio will increase seed yield by 402kg (36%). Also, at drought condition the farmer can use irrigation treatment 60% whereas save about 39% (675m^3) if it use under the same organic matter (1%) which could enhance seed yield by 27%.

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تأثير التدفق الحرارى للتربة على الإستهلاك المائى للكينوا

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مركز بحوث الصحراء

فى تجربة حقلية اقيمت فى شتاء 2017 فى محطة بحوث رأس سدر لتقييم تأثير المادة العضوية وكمبات مياه الرى على التوصيل الحرارى و الدفق الحرارى للتربة وبالتالى على معدل البخر والبخر نتح وكفاءة استخدام المياه لمحصول الكينوا . نظريا يتم حساب البخر نتح من معادلة بنمان مونتيث وتم حساب كفاءة استخدام المياه بناء على البيانات المتحصل عليها من التجربة. وقد اشارت النتائج الى:

زيادة معدل التوصيل الحرارى للتربة بنسبة 24و26و 65% بزايادة كميات ماء الرى والمادة العضوية والخلط بينهماعلى التوالى. وارتبط الدفق الحرارى معنويا بكل المعاملات المدروسة وحقق نسب زيادة بلغت 71و86و232 مع المادة العضوية والماء المضاف والتداخل بنهما على الترتيب. بينما زاد الدفق الحرارى بواقع 0.02 ميجا جول /م2/يوم مقابل 9.33 كالورى/ثانية/سم/درجة مئوية (كل 1 كالورى يقابله 0.002ميجا جول). ايضا زاد البخر بمعدل 0.008 مم /يوم مقابل 0.021 ميجا جول دفق حرارى فى حين زيادة الدفق هذه خفضت البخر نتح 1.81م3/فدان.

على الجانب الأخر ادت زيادة البخر السابقة لخفض البخر نتح 8.92م3/فدان ولهذا فإن كفاءة استخدام المياه تزيد تلقائيا بحوالى 136و119% للحبوب والقش على التوالى نتيجة للزيادة السابقة للدفق الحرارى .

ومن البيانات السابقة يمكن ان نوصى المزارعين بالرى بمعدل 80% عند 1% مادة عضوية وذلك حيث وفرت حوالى 20% من الماء المضاف عند 100% (196م3) عند استخدام هذه الكمية للرى عند 80% و 1% مادة عضوية اعطت زيادة محصولية (402 كج) اى 36% . كما ينصح باستعمال معدل الرى 60% تحت مستوى 1% مادة عضوية وتحت ظروف الجفاف (عجز مائى شديد) حيث وفرت حوالى 675م 3 وقد اعطت 27% زيادة فى المحصول عند استخامها فى الرى عند 60% من الماء المضاف و 1% مادة عضوية.