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Soil compaction, moisture content and pupal burial depth as a new control strategy of peach fruit fly *Bactrocera zonata* (Diptera: Tephritidae)

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Abstract:

Peach fruit fly (PFF) *Bactrocera zonata* (Saunders) (Diptera: Tephritidae) is one of the most deleterious tephritid flies of horticultural crops worldwide. Since PFF spends a part of its life cycle in the soil as pre-pupae and pupae, the effects of soil texture (clay, loamy and sandy soil) on larval burrowing depth and pupal burial depth (0, 1, 2, 4, 8, 12, 16, 20 and 24 cm) on emerging adults of PFF were studied. Moreover, the effects of both compaction and moisture (SM) of a sandy-loamy soil on adults' emergence rates of PFF as well as soil hydraulic properties were investigated. Soil compaction was tested at three compaction levels (without-, moderate- and severe-compaction; corresponding to an increase in bulk density by 0.0, 11.0 and 22.0%, respectively) at three levels of moisture content (air dry soil, 20 and 80% of water content at field capacity) against PFF pupae. Results indicated that the extremely burrowing depth of PFF larvae was 4 cm in clay soil, and 5 cm in both sandy and loamy soils. In inversely proportional to pupal burial depth, the emerging flies relied significantly on both pupal depth and soil type. In addition, emerged flies' rates were negatively affected more by SM than soil compaction. Furthermore, emerged flies correlated positively related with the total soil porosity (%), quickly drainable pores and slowly drainable pores. Additionally, soil compaction altered soil hydraulic properties (i.e., total and air porosity, saturated hydraulic conductivity and water retention curve) by reducing the portion of macro pores and increasing micro pores. The study concluded that moderate soil compaction can be significantly suppressed the PFF population and enhanced soil hydraulic properties; therefore, soil compaction could be an important approach in integrated pest management (IPM) against PFF.

Introduction

Fruit flies (Diptera: Tephritidae) are the most harmful insect pests of horticultural crops throughout the world, including the peach fruit fly (PFF) *Bactrocera zonata* (Saunders) (Diptera: Tephritidae). This pest has become widespread in Egypt and active throughout the year, except during the cooler months, particularly January (El-Minshawy *et al.*, 1999; Hashem *et al*., 2001; Draz *et al*., 2002; OEPP/EPPO, 2005; El-Gendy and El-Saadany, 2012 and El-Gendy and Nassar, 2014). It has a wide range of hosts, i.e. vegetable and fruit crops (El-Gendy, 2017), causing an estimated damage of 190 million €/a year (FAO/ IAEA, 2000). Current control methods of this pest heavily rely on the aerial application of malathion, bait sprays, or ground cover sprays of potent organophosphorus pesticides (Roessler, 1989). However, globally, there is an increasing awareness of the risks of chemical pesticide residues. For this reason, there is a desperately need to produce chemical free food, which would be achieved through the organic farming. Therefore, the agriculture control practices will play an essential role in the control of these pests.

As Tephritid fruit flies stages of pre-pupae and pupae subsist in the soil habitat, therefore, they are subjected to several different abiotic variables; soil texture, porosity, density, temperature and moisture that influence pupal mortality and malformation flies (El-Gendy and AbdAllah, 2019). It has been previously reported that soil texture and moisture significantly affected pupal survival rate of *B. tryoni* (Hulthen and Clarke, 2006), adult emergence of *Anastrepha ludens, A. oblique* (Montoya *et al*., 2008) and *B. zonata* (El-Gendy and AbdAllah, 2019).

In light textured soils, rain and/or irrigation water creates preferential paths, resulting in a rapid water movement, low water retention, excessive drainage, high air permeability and aeration conditions and high O_2 availability (Wei and Durian, 2014 and Shipitalo *et al*., 2000). Such soil could be an excellent environment of the growth of PFF. Since, the macro-pores are the most dominant; such pores facilitate larval movement and penetration to greater depths (Dimou *et al.,* 2003). However, altering the pore size distribution in light soils (by reducing total porosity and the portion of macro-pores), usually led to changes in soil hydraulic and retention properties, soil density and penetration resistance which in turn might affect the PFF. To do so, one of the means is soil compaction. Soil compaction causes a reduction in most related soil physical properties; total porosity and macro-pores (quickly drainable pores (QDP), infiltration rate and hydraulic conductivity but also, increases the portion of micro-pores (slowly drainable pores, SDP). Moreover, compaction alters the shape of the soil water retention curves (Zhang *et al*., 2006). Varallyay and Lesztak (1990) reported that if the macro-pores volume of compacted soil was half that of un-compacted soil, the air permeability and infiltration rate will be reduced dramatically.

Basically, soil compaction dramatically affects soil porosity, pore size distribution, air porosity and water retention properties, as a result adult emergence rates of PFF might be also affected. However, there is no comprehensive study has investigated the impact of soil compaction on adult emergence rates of PFF. Therefore, the goal of this study was to investigate the impact of different levels soil compaction (moderate and severe) at different water content on adult emergence rates of PFF as well as some soil physical properties (Total porosity, pore size distribution, and hydraulic conductivity). A further objective was to study the impact of soil types; clay, loamy and sandy on pupal behavior, as well as the impacts of the pupae burial depth in these soil types on emerging adult flies’ percentages.

Materials and methods

The experiments were carried out in the Laboratory of Eradication of the peach fruit fly at Damanhour, El-Beheira Governorate, Egypt. Whereas, the effect of soil compaction on soil physical properties was determined in the soil science laboratory, Department of Natural Resources and

Agricultural Engineering, Faculty of Agriculture, Damanhour University, Damanhour, Egypt.

1. Mass rearing technique:

The mass rearing technique of PFF was conducted under laboratory conditions according to El-Gendy (2002) and described by El-Gendy and AbdAllah (2019).

2. Soil characteristics used:

Three soil samples were collected from the districts of Rashid, Damanhour and Abo-Homos, El-Beheira Governorate, Egypt. Soil samples were passed through 2 mm sieve and air was dried, then sifted and autoclaved for 24hr. at 80°C before being used (Hennessey, 1994). The main soil physical and chemical properties are presented in Table (1).

Table (1): Physical characteristics of the three tested soils.

Soil type	**Particle size distribution (%)**				**T .P (%)**	**B.D (g/cm^3)**
	Grave(l)	**Sand**	**Silt**	**Clay**		
Sandy	1.26	97.30	1.46	1.24	33	1.5
Loam	2.24	50.45	29.8	19.75	44.8	1.44
Clay	1.83	35.5	24.16	40.34	56.7	1.32

T.P: Total porosity.
B.D: Bulk density.

3. Effect of soil texture on pupation depth of *Bactrocera zonata*:

Three types of air-dried soil; sandy, loamy and clay soils were tested against PFF larvae burrowing using black polyvinyl chloride (PVC) columns (7 cm height and 8 cm in diameter, sealed from the bottom, with a fine metal mesh used, and fixed in a petri-dish, 15 cm diameter). The columns, in three groups; each group was filled with one type of the tested soils up to 6 cm. Each soil type was replicated ten times; each replicate involved twenty matured larvae (pre-pupae stage) that could pop on soil surface. Soil columns were immediately covered with muslin cloth and randomized distributed on the shelves in the rearing room. Two days later, the pupae were looked for in the soil with ice cream stick, depth (distance to the surface, cm) of each discovered pupa was measured. Pupation percentages against each depth were calculated.

4. Effect of pupation depth (Burial depth) on the emergence of adults *Bactrocera zonata*:

Black PVC columns (8 cm in diameter) and transparent jars (1L) were used. The columns were consisted of two parts; the bottom part was 6 cm in height (sealed in the bottom and fixed in a petri-dish as described above), and the upper part was either 4, 8, 12, 16, 24 or 20 cm (according to the tested pupal depth). Nine soil depths, for each soil type (Sandy, loamy and clay), were tested against PFF pupae in five replicates. Twenty healthy pupae (seven-day-old) were gently placed in the center of soil surface of column-bottom part. Then, the upper part of tube was fixed above the bottom part, and gently packed with the same soil type for nine heights; 0, 1, 2, 4, 8, 12, 16, 20 and 24 cm. The upper part of the column opening was connected to the hole of the Jar, which were fixed by the silicon material. Columns were randomly distributed in the rearing room on the shelves. The numbers of emerged flies were recorded, and the adults' emergence rate was calculated using the formula: Adults' emergence rate = [(Number of adult's emergence)/ (Number of tested pupae)]*100.

5. Effect of soil compaction on adult's emergence of *Bactrocera zonata*:

Since the sandy soil showed to be in compactable, and due to undesirable impacts of soil compaction on the clay soil properties (Botta *et al.*, 2006, 2008, 2009, 2010; Manuwa and Odubanjo, 2007; Odey, 2018 and Etana *et al.*, 2013), the effect of soil compaction on adult's emergence of PFF was investigated using a sandy loam soil (Table, 2).

Table (2): Main physical and chemical properties of a representative sandy- loam soil samples in the experimental site (0-30 cm depth).

Soil property	**Value**
Particle size distribution	
Sand (%)	70.2
Silt (%)	10.0
Clay (%)	19.8
Texture class	sandy- loam
Water retention points	
Saturation (%)	46.2
Field capacity (%)	21.6
PWP (%)	11.2
Available water (mm m^{-1})	104.4
Bulk Density (BD) (Mg m^{-3})	1.35
Total porosity (%)	46.2
Saturated Hydraulic Conductivity) (mm h^{-1})	72.21
Ece (dS m^{-1})	4.2
pH	8.15
OM (%)	1.17
$CaCO_3$ (%)	3.22

PWP and OM permanent wilting point, and organic matter. Electrical conductivity (ECe) measured in soil paste extract. Soil reaction (PH) measured in 1:2.5 soil suspension. Organic matter (calculated by multiplying the organic carbon content by a conversion factor of 1.724).

In this experiment, two factors were investigated; the main factor was soil compaction at three levels of soil compaction; C_0 (un-compacted; control), C_1 (moderate) and $C_{2,}$ (severe compaction), and the second factor was soil moisture at three levels (0, 20 and 80% of field capacity) with five replicates. Dark PVC soil columns (13 cm in height and 10 cm in diameter, Figure, 1) were used. Each soil column was divided into two parts; the lower part (4 cm height, bottomed sealed and fixed in a petri-dish, as referenced above), which contained un-compacted soil (bulk density; BD =1.35 Mg m^{-3}), and the upper part (9 cm height) contained the compacted soil. The exerted compaction was calculated using BD as an indicator. For control treatment, soil was moved into the upper portion of PVC columns at density of 1.35 Mg m^{-3}. Regarding the compaction treatments, soil was moved into the upper part of PVC columns and compacted in 8 cm height by applying appropriate blows of a hammer (5 kg mass and diameter slightly less than the diameter of the columns) to two compacted levels. The 1st level was 1.5 Mg m^{-3} (moderate, C1) and the 2nd level was 1.65 Mg m^{-3} (severe compaction, C2).

For all treatments, twenty healthy pupae (seven-day-old) were placed in a small hole (1×1×0.5 cm, L: W: D) in the center of the lower soil surface (un-compacted) of each column for all treatments. Then, the upper part PVC columns were closely attached to the lower part with silicone material. Once prepared, the compacted columns were watered to 20% or 80% of field capacity using drip irrigation system at fixed water discharge of 2 L h^{-1} as well as air dried soil columns were investigated. The upper part was covered with muslin cloths and tied with rubber band. The columns were randomized on shelves in the rearing room. Adults' emergence rate was calculated as above-mentioned formula.

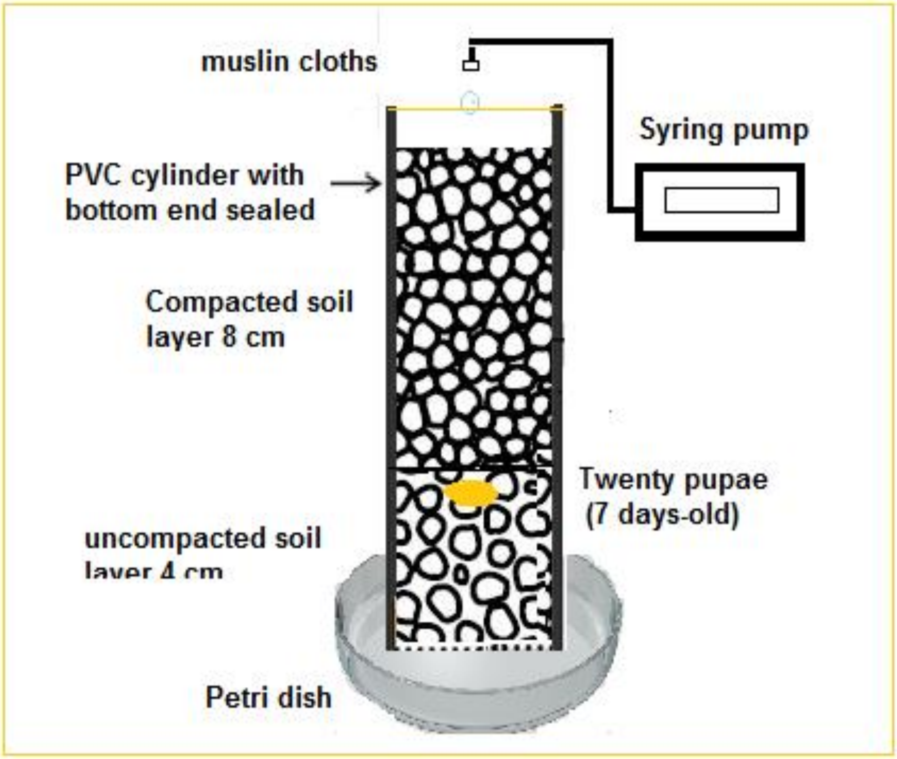

Figure (1): A schematic of the PVC column set-up. An emitter (Q= 2.0 L h^{-1}) is connected to a syringe pump. The PVC column has a height of 13 cm and a cross-sectional area of A = 78.5 cm^2. The soil packing has of 12 cm of soil; 8 cm of compacted soil and 4 cm of control soil).

6. Determination of soil water content at field capacity:

The soil water content at the field capacity of loamy-sand soil; compacted and un-compacted was determined by placing three columns sealed with muslin cloth from the bottom (representing each compaction treatment) in a saucer filled with water to allow soil saturation from the bottom. When the soils were saturated, the saucers were removed and excess water drained gravimetrically (overnight) until no drainage was observed from the columns (AbdAllah *et al*., 2019; Agaba *et al*., 2010; and Chen *et al*., 2003). Then soil samples were dried at 105 ºC and soil water content was calculated.

7. Effect of soil ccompaction on ssome physical properties:

Similarly, soil columns were prepared at a BD of 1.35, 1.5 or 1.65 Mg m^{-3} to represent soil compaction treatment (C0, C1 and C2). Then total porosity, air porosity, saturated hydraulic conductivity, and pore size distribution were determined.

The pore size was calculated from the water retention curves using the following equation (Marshall *et al*., 1996):

$r = \rho wgh = (2\gamma \cos\alpha)/ \psi$

where r is the mean equivalent cylindrical radius of the pores (m) at a given matric potential ψ (Pa); γ is the surface tension of water (72.75 mJm^{-2} at 20 °C); α is the contact angle between the water and the pore wall, which was assumed to be zero; ρw is the density of the water (0.9982Mg m^{-3} at 20 °C); g is the acceleration due to gravity (9.80 m s^{-2}); and h is the matric suction (m) applied to drain the water.

The pores size distribution was classified to quickly drainable pores (QDP) (> 30 µ), slowly drainable pores (SDP) (30-9 µ), water holding pores (WHP) (9-0.2 µ) and fine capillary pores (FCP) (< 0.2 µ), according to De Leenheer and De Boodt (1965). Delineated pore size distribution was calculated as percentage of total porosity.

8. Saturated hydraulic conductivity:

Measurements of fluid flow through a soil provide a meaningful description of compaction, because the fluid conductivity is related (Odey, 2018). Saturated hydraulic conductivity was measured according to (Moutier *et al*., 2000). A plastic cylinder (20 cm height with a diameter of 7 cm) with a fine metal screen at the bottom were used to determine the hydraulic conductivity of control and compacted soil using three replications for each treatment. The soil was packed in the cylinder at a BD of 1.35, 1.5 and 1. 65 Mg m^{-3} and covered with a filter paper to reduce soil surface disturbance. Soil cylinders were saturated by capillary rise using tap water (0.5 dS m^{-1}). After the saturation process from the bottom, the flow direction was reversed, and a constant pressure head of 4 cm was applied in the top of soil cylinder. The leachate was collected, and hydraulic conductivity was calculated.

9. Statistical analysis:

The number of pupae from each depth level of each soil type was converted into percentages. The data were normalized by an arcsine square root transformation and a linear regression was used to determine the relation between larvae burrow depth and soil type. Data of pupae burial depth in soil types and adults' emergence of PFF, as well as soil compaction and WSCL on adults' emergence of PFF were converted into percentages and normalized by an arcsine square root transformation and analyzed using IBM SPSS Statistics (Version 22.0). Mean values were compared using Tukey at significance level 0.05.

Results and discussion

1. Effect of soil type on larval burrowing depth of *Bactrocera zonata*:

The variations in pupation depth levels of PFF as shown in Figure (1) relied only on burrowing depth of larvae among the tested soil types; sandy, loamy and clay (F=109.96, df=5, p=0.000), however, a significant interaction between soil type and burrowing levels (F=32.38, df=10, p=0.000) was recorded. In the sandy soil, the larvae pupated mostly on soil surface (1st level, 0-1 cm) with 44.89% of total pupated flies of all soil levels, whereas the highest pupation level in clay and loamy soils was the 3rd level (>2-3 cm) with respective percentages of 60.65 and 45.00% of total pupated flies within each soil type. The larvae burrowed in sandy and loamy soils deeper than those in clay soil, up to 5 cm in sandy and loamy soils and to 4 cm in clay soil; beyond the 4th level of clay soil and the 5th level of sandy and loamy soils no pupae were found. The drilling of PFF larvae in the soil was significantly in a negative relation to soil texture in case of both sandy (r=-0.84, p=0.0001) and clay soil (r=-0.59, p=0.009), and non-significant in loamy soil. Results also stated that, according determination coefficient, the sandy soil texture was more effective on pupation depth levels than clay and loamy soil (sandy; R^2=0.8738, clay; R^2=0.1393, loamy; R^2=0.1201).

2. Effect of pupation depth and soil type on adults' emergence of *Bactrocera zonata*:

Percentages of emerging PFF flies outside the soil depended significantly on both pupal burial depth and soil type (burial depth; F=98.57, n=8, p=0.0001, soil type; F=139.21, n=2, p=0.0002). In addition, a significant interaction was recorded between burial depth of pupae and soil type on emerging flies (F=26.01, n=16, p=0.0000). As shown in Figure (2), the rate of emerging flies outside different soil types was inversely related to the burial depth of pupae within the soil type (loamy: r=-0.93, p=0.000, clay: r=-0.91, p=0.000, sandy: r=-0.84, p=0.000). The highest percent of the emerged flies was recorded in the first burial depth (zero cm) of all tested soil types with more emergent in loamy soil (98.33%), followed by clay (96.67%) and sandy (96.66%) soils, respectively. The emerged flies decreased gradually with the increasing of pupal burial depth to record the highest emergency at 24cm depth in sandy soil by 60% compared with 33.3 and 25% in clay and loamy soils. In sandy land, the overall average of emerging flies was greater (70.85%) than loamy (64.99%) and clay (59.44%) soils. The pupation depth was more effective than soil type on the adults emergence percentages (pupation depth: F=61.48, df=1, p=0.0000, soil type: F=8.45, df=1, p=0.0047) with 43.7 and 9.67%, respectively, with a significant combined effect (soil depth: F=73.30, df=1, p=0.0000, soil type: F=16.19,df=1, p=0.0001) by 52.22% of the total effects on emerging flies according to determination coefficient (R^2).

3. Effect of soil compaction on adults' emergence of *Bactrocera zonata*:

At SM of 80%-FC, no flies were emerged from the compacted soil at compaction levels of C0 (un-compacted soil), C1 (moderate soil) and C2 (severe soil). The same trend was obtained at SM of 20%-FC in both C1 and C2 compaction. However, in C0 at SM of 20% of FC and air-dried soil, the emerged flies were 40.0 and 81.66%, respectively, as shown in Figure (3). The percentages of emerged PFF, found to be significantly different based on soil compaction and SM (soil compaction; F=67.20, df=2, p=0.000, SM; F=335.03, df=1, p=0.0001), followed by a significant interaction between them (F=67.20, df=1, p=0.0001). Emerged flies were negatively in a significant partial relation with soil compaction level (r= - 0.61, p=0.004) and SM (r= - 0.80, p=0.000). In parallel, the percentages of emerging flies found to be significantly affected more by SM than soil compaction level (SM; F=33.29, df=1, p=0.000, soil compacting; F=10.71, df=1, p=0.004). According to R^2 values, 61.8 and 36.1% of effects on adult emergence out of the soil results to SM and soil compacting, while 74.65% results from their combined effects (F=30.45, df=2, p=0.000). Side by side, the results in Table (3) show that the increased soil compaction level (BD) caused a significant decrease in the total porosity (TP) to be 38 and 32.3% compared with 46.2% for C0, un-compacted soil. As well, a significant decrease in quickly drainable pores (QDP), slowly drainable pores (SDP) and Ksat with proportional increasing to soil compaction level, while a significant increase was observed in water holding pores (WHP) and fine capillary pores (FCP). The observed changes in pore size distribution were soil correlated with the emerged flies of PFF; the emerged flies correlated negatively with FCP (r=-0.57*), while they related positively with the total soil porosity (%) (r=0.57*), QDP (r=0.59*), SDP (r=0.55*), Ksat (r=0.59**).

Table (3): Total porosity, pore size distribution as a percentage of total volume, of the studied soil samples at the two bulk densities.

Soil bulk density (BD) g/cm^3	Pore size distribution as a percentage of total volume						
	Total porosity (%)	Quickly drainable pores (QDP) > 30 µm	Slowly drainable pores (SDP) (30-9) µm	Water holding pores (WHP) (9-0.2) µm	Fine capillary pores (FCP)< 0.2 µm	Ksat	Water content at FC
1.35	46.2	25.3	8.32	6.26	6.32	32.14	21.6
1.5	38	15.3	6.22	8.32	8.22	16.75	20.4
1.65	32.3	10.32	4.3	8.3	9.4	10.33	19.6

The present findings elucidate that the burrowing depth of PFF larvae downwards the soil show to be affected by soil type, the highest mean pupation depth was 2-3 cm in both clay and loamy soils, and 0-1 cm in sandy soil. Obtained results are in agreement with the results of Montoya *et al*. (2008) in which they found that the most larvae of *A. ludens* (Loew), and *A. obliqua* (Macquart) (Diptera: Tephritidae), burrow in the loamy-sand soil by 1.0 to 2.0 cm depth. Dimou *et al*. (2003) reported that the deepest mean of pupation depth of *B. olive* was 3.2 cm. Furthermore, Jackson *et al.* (1998) found that in a dry sand soil, most pupae of *B. dorsalis* occurred at 0–5.5 mm depth. Also, on *A. oblique,* a few numbers of larvae and rarely of pupae occurred on the clay-loam soil surface. Interestingly, in all tested soil textures, no pupae of PFF were found deeper than 5 cm. Similarly, in sand-loam soil a rarely pupae of *A. obliqua* (1 pupae) found higher than 5 cm depth (Hodgson *et al*., 1998). In a clay-loam soil, no pupae of *A. oblique* were found at deeper than 2 cm. However, on *Carpomyia incompleta* Becker (Diptera: Tephritidae), the highest pupation depth was about 5 cm (Risk *et al.*, 2013).

In the present studies, emergence of PFF flies was found to be affected more by the burial depth than soil type. Furthermore, percentages of adults emerging out of the soil were negatively correlated with pupal burial depth. This might be attributed to soil weight that may restrict the movement of newly emerged flies through their orienting outwards the soil. These results are in the same line with those results that indicated the emergence rate of adult flies was negatively correlated with pupal burial depth of *C. incomplete* (Risk *et al.*, 2013) and *B. oleae* (Rossi) (Diptera: Tephritidae) (Bachouche *et al*., 2018). On the other hand, soil texture of clayey, sandy loam and sandy clay loam soils has a highly significant impact on the rate of adults emergence of *B. oleae* (Bachouche *et al*., 2018).

The present findings also clarify that emerging rates of PFF adults outside the soil negatively influenced more by SM than soil compaction. The results reveal the highest rate of emerged flies, 81.67%, attained at the control soil-air-dried soil, which decreased with the increasing of SM, to reach 0 % of emerged flies at 80% moisture at the same soil compaction level. These results are in line with Hou *et al.* (2006), who reported that the pupae of *B. dorsalis* (Hendel) (Diptera: Tephritidae) were unable to survive at soil moisture of 80, 90, and 100%, of FC while emergence rates exceeded 90% at the conditions of 10–60% moisture levels. In contrast of our results, El-Gendy and AbdAlah (2019) reported, at 90%-FC, higher percentages of adult emergence of PFF in un-compacted soil of sandy and clay. The inconsistency among results might be attributed to the variation in the soil texture. Regarding the soil compaction on percentages of emerging flies outside the soil, the present findings show no flies of PFF emerged in moderate or severe compacted soils at low, (20% FC), or high MS levels, (80% FC). The suppression effect of soil compaction on the emerging of flies outside the soil may attributed to the shortage of O_2 as a result of reduced total porosity and macro-pores of the compacted soil (Mosaddeghi *et al*., 2007). The soil compaction changes the pore size availability and distribution which generally leads to the reduction of the proportion of large pores and affects the movements of larger soil fauna (Nawaz *et al*., 2013).The change in pore space restricts root growth, and the gas exchange necessary for plant growth and yield (Odey, 2018 and Weber and Biskupski, 2008). In addition, due to the increase in penetration resistance of compacted soils, the burrowing abilities of the emerging adults is reduced (Baize and Jabiol, 1995).

Soil porosity strongly inversely correlate with penetration resistance: a decrease of porosity is generally associated with an increase of penetration resistance. It is well established that low levels of oxygen increase development time and mortality of *Drosophila melanogaster* Meigen (Diptera: Drosophilidae) (Peck and Maddrell, 2005). However, Cammack *et al.* (2010) mentioned that the soil compaction had no significant effect on the orientation (vertical or horizontal) of puparia of *Lucilia sericata* (Meigen) (Diptera: Calliphoridae) in the soil. Un-expectedly, the emerged flies of PFF, few numbers, changed their behaviour and oriented deeply downwards the un-compacted soil layer to rim of the bottom cover. This may be result to inability of flies to penetrate the compacted soil.

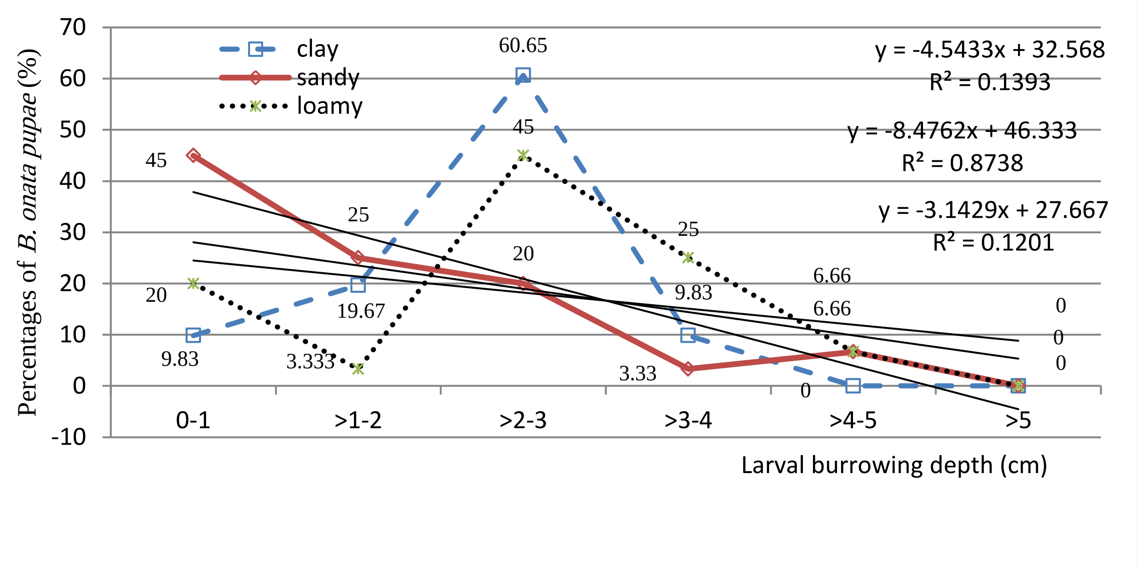

Figure (1): Relationship between soil type and percentages of pupation depth of *Bactrocer zonata*. LSD. For clay soil=7.44, LSD. For sandy soil=7.84, LSD. For loam soil=7.84.

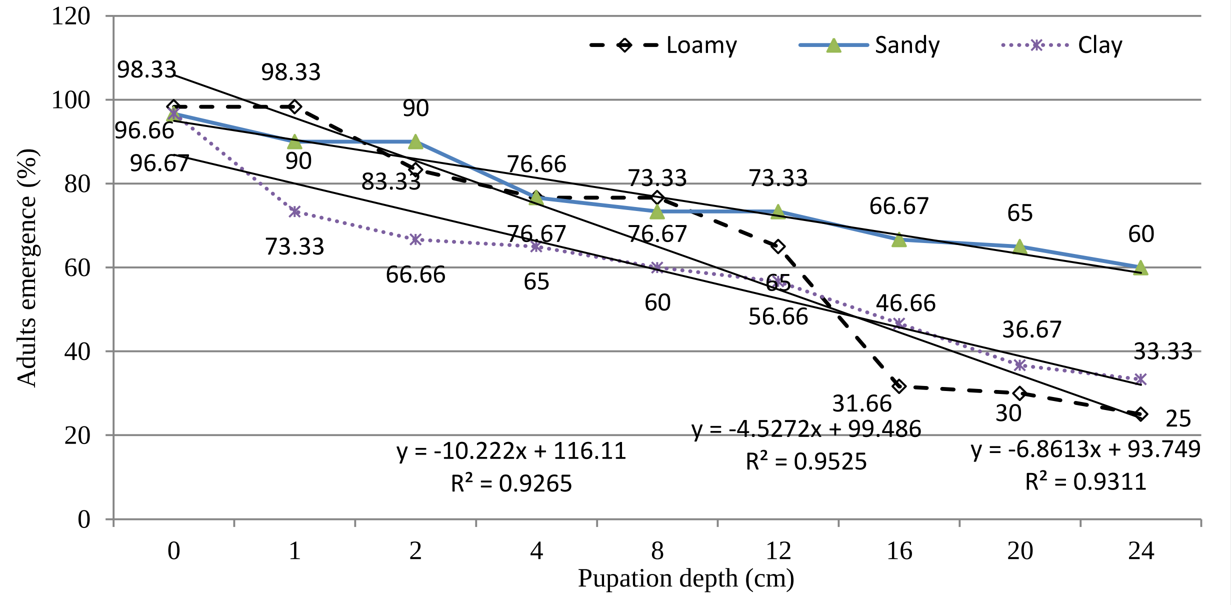

Figure (2): Adults emergence of *Bactrocera zonata* (%) and pupation depth (cm) in different soil types.

LSD. For clay soil=11.54, LSD. For sandy soil=13.31, LSD. For loam soil=10.98

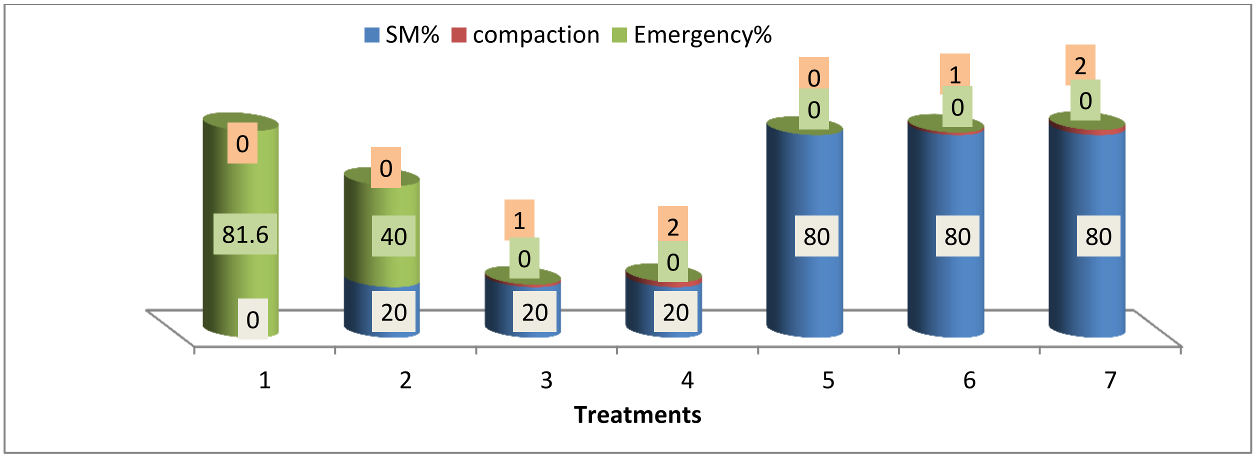

Figure (3): Relationship among sandy-loamy soil compaction levels, SM and emerged flies of *Bactrocera zonata*

LSD of Levels = 2.68. $LSD_{0.05}$ of RH% = 0.88, LSD of compaction = 0.72.

The dry soil bulk density and associated total porosity are the most frequently used parameter to characterize soil compaction and physical properties of soil (Panayiotopoulos *et al*., 1994 and Assouline, 2006 a, b). A significant reduction in TP of compacted soil was found as confirmed by the results of Botta *et al*., 2009; Hassan *et al*., 2007 and Kuncoro *et al*., 2014b). However, Several authors, Gebhardt *et al*., 2009; Kuncoro *et al*., 2014a and Vogeler *et al*., 2006, reported that, TP is not good indicator for soil compaction because it is not useful in characterizing compaction effects on storage and transport of water and air in terms of connectivity and continuity. In fact, at a given BD, for the same soil, the pore geometry and continuity can be different (Lenhard, 1986). For example, Marsili *et al*. (1998) found no difference in BD between treatments. The effect of soil compaction was confirmed by air porosity and pore system configuration, i.e. pore size distribution, and Ksat. This observation has been confirmed by Hillel (1998) in which they reported that, soil compaction affected pore diameter and continuity of macrospores that directly significantly affected soil hydraulic properties (Odey, 2018; *Soracco et al*., 2011, 2012, 2015; Lozano *et al*., 2014 and Etana *et al*., 2013).

The reduced Ksat of the compacted soil, observed in the current study, might be attributed to the reduction in macro pores, since compaction first reduce mainly large pores (Soracco *et al*., 2011, 2012, 2015; Odey, 2018; Abdollahi *et al*., 2014; Gebhardt *et al*., 2009; Marsili *et al*., 1998 and Lozano *et al*., 2014). Etana *et al.* (2013) found that macro-porosity and saturated and near-saturated hydraulic conductivity were smaller in the compacted plots. In contrast, Richard *et al.* (2001) found higher unsaturated Ksat in compacted soil than in un-compacted soil, while Zhang *et al.* (2006) found no significant differences between compacted and un-compacted soils. The inconsistency among results might be due to the differences in soil texture soil moisture and the level/severity of soil compaction. Similarly, Pagliai (1998) observed a significant correlation between hydraulic conductivity and maro-poresity in a loam soil compacted and un-compacted was observed. This observation stressed that the compaction in light textured soils is one of the most significant aspect not only to reduce water movement, in such soils, but also of environmental degradation, since the reduction of water infiltration may increase reduce the risk on nutrients lose to ground water.

The modification in water retention curves, due to soil compaction, was observed in several studies; since a decrease of water content at high matric potentials (from 0 to _10 kPa) and an increase of water content at low matric potentials (from _250 to _1550 kPa) were recorded (Ferrero and Lipiec, 2000). For example, Zhang *et al.* (2006) applied two levels of compaction at two silty loam sites and found that, at the two sites, at high level of compaction, the water content of the surface layer at tensions of <2 kPa and _8 kPa was significantly decreased. However, a slight effect occurs in the intermediate potential range. This reflects the fact that, under compaction, as the proportion of large pores decreases, the proportion of small pores increases (Assouline *et al*., 1997 and Van Dijck and van Asch, 2002) or remains unaffected (Matthews *et al*., 2010). Richard *et al.* (2001) showed that the decrease in the volume of pores retaining water between -5 and -20 kPa corresponds to a decrease in the volume of pores larger than 4 mm. In the same way, they attributed the increase in pore volume retaining water at potentials ranging between -20 and -80 kPa to increase in the volume of pores between 1 and 4 mm. They suggested that the increase in water retained at potentials between_20 and _80 kPa is due to the formation of relict structural pores being remnants of structural pores distorted during traffic and accessible only through the necks of textural (lacunar) pores (Richard *et al*., 2001).

It is concluded that, the results showed that no pupae of PFF were found beyond the 4th cm of clay soil and the 5th cm of sandy and loamy soils. The emerging flies relied significantly on both pupal depth and soil type, furthermore, emerged flies rates were negatively affected more by soil compaction and water content. Moreover, soil compaction reduced total porosity, air porosity and modified the pore system by increasing the proportion of larger pores and reducing the portion of micro pores, thus reduced saturated hydraulic conductivity. The reduced total and air porosity reduced O_2 availability and thus the number of emerging flies was significantly reduced. Generally, moderate soil compaction significantly suppressed the PFF population therefore soil compaction could be a win-win solution in light soils through enhancing soil hydraulic properties and as an effective approach in integrated pest management (IPM) against PFF.

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