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Effects of plastic mulches and high tunnel raspberry production systems on soil physicochemical quality indicators

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A b s t r a c t. In horticulture, degradable materials are desirable alternatives to plastic films. Our aim was to study the impact of soil plastic mulching on the soil properties in the high tunnel and open field production systems of raspberry. The raised beds were mulched with a polypropylene non-woven and two degradable mulches: polypropylene with a photodegradant and non-woven polylactide. The results indicated that the system of raspberry production, as well as the type of mulching had significant impact on soil organic carbon stock, moisture content and water stable aggregate amount. Soils taken from the open field system had a lower bulk density and water stability aggregation index, but higher organic carbon and capillary water content as compared to soils collected from high tunnel conditions. In comparison with the open field system, soil salinity was also found to be higher in high tunnel, as well as with higher P, Mg, Ca, S, Na and B content. Furthermore, mulch covered soils had more organic carbon amount than the bare soils. Soil mulching also enhanced the water capacity expressed as a volume of capillary water content. In addition, mulching improved the soil structure in relation to the bare soil, in particular, in open field conditions. The impact of the compared mulches on soil quality indicators was similar.

K e y w o r d s: *Rubus idaeus*, degradable plastic, high tunnel, water stable aggregates, organic matter

INTRODUCTION

Interest in plastic tunnels for small fruit production has been increasing in Poland (Siwek and Libik, 2012). Season extension is not the only benefit which plastic tunnels offer to raspberry production. In most cases, this system increases yields of berry crops, improves quality, and decreases the incidence of some diseases, when compared with open field (OF) production systems (Demchak, 2009). Soil warming or avoidance of excessively high soil temperatures, along with soil protection against wind and rain are additional benefits of high plastic tunnel, as compared to open field production (Lopez *et al.,* 2009). What is more, the ground of the high tunnels (HT) in raspberry production may be covered with plastic mulch. This raises the root-zone temperature, controls weeds, prevents evaporation and reduces air humidity (Bushway, 2008). Black plastic is the overwhelming standard among raspberry growers worldwide. In open field production, plastic mulches protect soil surface from erosion processes by mitigating the impact of raindrops and slowing runoff, and, hence, their application preserves a good soil structure. A major limitation of using plastic mulch, however, involves disposal of non-degradable materials at the end of the growing season. In horticulture, degradable materials are, therefore, desirable alternatives to traditional plastic films (Kasirajan and Ngouajio, 2012).

Many physical, chemical and biological parameters have been used to define soil quality (Reynolds *et al.,* 2008). Askari and Holden (2015) indicate that evaluating and monitoring selected soil parameters, such as bulk density, organic carbon and aggregate size distribution, provide adequate management information on soil quality differences among the production systems. Indicators of soil quality can be defined as those soil properties and processes that display the greatest sensitivity to changes in soil function (Andrews *et al.,* 2004). In our study, we have chosen several important physical and chemical soil property indicators that readily change in response to soil management practices in raspberry production, in both high tunnel and open field conditions. These include properties

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which reveal direct influence on plant growth (*i.e.* soil pH and available nutrients concentration), and several indirect indicators of soil function (*i.e.* organic carbon content, the soil structure stability index and soil water capacity).

The study of aggregate stability has been valuable in assessing soil response to management practices and environmental changes (Barthès and Roose 2002; Lugato *et al.,* 2010; Six *et al.,* 2000). Aggregate stability is a crucial factor of a good soil structure and soil productivity. The soil structure directly affects crop yields through influence on water and air movement, root growth and biological activity. Aggregation is also an important process in soil organic carbon prevention and storage (Novelli *et al.,* 2013). Le Bissonnais (1996) defined four main mechanisms of aggregate breakdown in cultivated soils, such as slaking, breakdown by differential swelling, mechanical breakdown by raindrop impact and physic-chemical dispersion.

The formation and stabilization of aggregates are related to soil organic carbon dynamics. We hypothesize that soil covering with plastic and degradable mulches has significant impact on aggregate water stability and also on organic carbon changes. Earlier studies have shown (Domagała-Świątkiewicz and Siwek, 2013) that in vegetable production, mulching increases the amount of large water stable aggregates and organic carbon in soils. Soil organic carbon (SOC) is widely recognized as one of the key soil parameters in sustaining a good soil structure. SOC as a binding agent between primary and secondary mineral particles leads to an improved amount, size and stability of aggregates. Chaplot and Cooper (2015), similar to other researchers, underline that soil aggregation has the potential to increase organic matter stabilization in soils. Six *et al.* (2000) stress that the interaction between soil aggregates and organic matter is two way. *i.e.* organic materials stabilize soil aggregates and soil aggregates stabilize SOC. Breakdown of soil aggregates by raindrops impact or by water erosion encourage detachment and transport of labile fractions of soil organic matter, and also enhance the exposure of organic matter to oxidizing conditions (Schmidt *et al.,* 2011).

We assumed that soil plastic degradable cover has an important role in protecting soil degradation, and can improve soil quality as characterized by properly selected indicators. The aim of our work was to assess the impact of the production system and biodegradable mulch treatment on several physical and chemical soil parameters, including the aggregate stability index.

MATERIAL AND METHODS

The field trial was conducted during 2011-2013, in high tunnel (HT) and open field (OF) production systems at the Fruit Experimental Station in Brzezna (49°36′12″N 20°36′52″E). The tunnel system was established in the autumn of 2010, in the Orchard Department of the Experimental Institute of Horticulture in Brzezna. The average atmospheric precipitation in this area is about 700 mm yearly, with the mean yearly temperature + 8.4°C. Rainfall in the winter season is about 30%, and in the summer season, about 70% (Fig. 1).

In 2011, the temperatures for the vegetation period of raspberries were near the average, while the rainfalls noted for 2011 were heavy, especially in July. The growing season of 2011 was colder, as the average temperature recorded between May and September was 17°C, compared to 18.5°C recorded in 2012 and 19°C in 2013. Higher precipitation (420 mm in 2011, as well as 320 and 380 mm in 2012 and 2013, respectively) was also noted. 2013 had an annual precipitation of 380 mm and maximum rainfall in June, which was beneficial for flowering and fruit setting. Favourable climatic conditions (low precipitation and relatively high temperatures) were also recorded before the harvest.

The study was carried out on the basis of a completely randomized split-plot design, with a production system as main-plots replicated four times, and with plastic and degradable covers in raspberry (*Rubus idaeus*) cultivar Polka acting as subplots. Two mulches commercially advertised as degradable, *i.e.* photodegradable polypropylene (PP photo.) and experimental spun-bond, polylactic acid-based mulch (PLA), were compared to black polypropylene non-woven mulch (PP) and bare ground control. The typical single tunnel installed in 2010, has a width of 4.5 m and a height of 3 m, and is made of polyethylene film on a steel pipe structure. Each combination was represented by 20 plants (four replicates of five plants). The plants were grown on raised beds, in rows with a width of approximately 70 cm. In spring 2011, soil mulches were placed in the rows of plants. The plots were irrigated using a dripper line. Fertilizers (P, K, Mg) were incorporated during bed preparation, and in every year, in the spring, the nitrogen fertilizers were supplemented.

For soil site description, the granulometric analysis was performed by the aerometric method. This procedure is regulated by the PN-R-04032 (1998), standard published for the agricultural soil analysis in Poland. The data of particle-size fractions and textural soil classification for the experimental site in Brzezna is presented in Table 1.

Soil samples were collected from each replication by means of a soil core sampler, during the raspberry growth period, from soil depths of 0-20 cm. For bulk density,

Table 1. Soil particle size distribution under Polish Norm PN-372 R-04032 and textural classification (sandy loam)

Fraction	Particle size (mm)	Size fraction (%)
Sand	2.0-0.05	52
Silt	0.05-0.002	44
Clay	<0.002	4

Table 2. Soil moisture at the sampling moment, as well as soil physical properties of raspberry cultivation under plastic tunnel and open field conditions

Factor	Bulk density (g cm^{-3})	Soil moisture (kg kg^{-1})	Capillary water content %ww	Capillary water content %wv	%C	Water stability aggregates index (%)
2011	1.27 a	0.341 a	34.0 a	43.2 a	0.88 b	90.6 b
2012	1.25 a	0.331 a	33.2 a	40.4 a	0.81 a	90.6 b
2013	1.25 a	0.346 a	34.4 a	42.8 a	0.85 b	84.2 a
High tunnel	1.26 a	0.329 a	33.1 a	41.9 a	0.83 a	89.9 b
Open field	1.25 a	0.350 b	34.6 a	42.3 b	0.86 b	87.0 a
Control	1.26 a	0.328 a	33.1 a	40.3 a	0.80 a	86.3 a
PLA	1.25 a	0.343 a	34.4 a	42.6 b	0.86 bc	89.9 b
PP photo.	1.26 a	0.342 a	33.9 a	42.1 b	0.84 b	89.0 b
PP	1.26 a	0.344 a	33.9 a	42.3 b	0.89 c	88.7 b

PLA – polylactic acid-based mulch, PP photo. – photodegradable polypropylene mulch, PP – polypropylene mulch. Values in the same columns marked with different letters differ significantly (p = 0.05).

Table 3. Percent of classes of soil water stable aggregates (mm) in soils of raspberry cultivation under plastic tunnel and open field conditions

Factor	Percent of water stabele aggregates (mm)				
	4.0-2.5	2.5-1.5	1.5-1.0	1.0-0.5	0.5-0.25
2011	20.9 a	18.2 c	16.4 c	21.9 b	13.2 a
2012	21.1 a	17.0 b	14.5 b	23.5 c	15.8 b
2013	21.4 a	14.7 a	12.1 a	18.5 a	17.4 c
High tunnel	21.8 b	16.5 a	14.4 a	22.1 b	14.9 a
Open field	20.4 a	16.7 a	14.3 a	20.4 a	15.9 b
Control	23. 1 b	16.6 ab	12.9 a	18.3 a	15.3 ab
PLA	20.7 a	16.6 ab	14.7 b	22.3 bc	15.5 b
PP photo.	19.5 a	15.9 a	14.7 b	21.4 b	16.6 c
PP	21.1 a	17.6 b	15.1 b	23.1 c	14.4 a

Explanations as in Table 2.

undisturbed samples from the depths of 0-10 were collected by means of a Kopecky cylinder with a volume of 250 cm^3. Soil cores were weighted, wetted (for capillary action) and dried at 105°C. Soil aggregates were then separated by wet-sieving, using Yoder procedures (Yoder, 1936). Aggregates from undisturbed 0-20 cm bulk soil were collected at each of data plots, with four replicates. Aggregates (<5 mm) were obtained by dry sieving of the bulk soil. Each sample (40 g of dry aggregates) underwent slow wetting pre-treatment in deionised water for 5 min. The sample was subsequently wet-sieved using a motor-driven holder lowering and raising sieves in a container of water. Five size classes were used, *i.e.* 0.25, 0.5, 1.0, 1.5 and 2.5 mm. The stroke length was 5 cm and the sieving frequency was 5 cycles cm^{-1} for 20 min.

Soil pH was measured at a soil to water ratio of 1:2. Soil organic carbon (SOC) was determined using the dichromate oxidation method (Ostrowska, 1991). The available form of macronutrients and sodium was determined in 0.03 mol dm^{-3} CH_3COOH by means of the universal method. The extractable form of boron was measured in 1 mol dm^{-3} HCl extractan. The available forms of nutrients were determined using the inductively coupled argon plasma atomic emission spectroscopy ICP-OES technique (ICP-OES).

Statistical analyses enabled comparing the main effects and interactions of the production systems (HT and OF), the types of mulch and years. All data was subjected to variance analysis using the three-way (three-factor) ANOVA system. All means were separated using Fisher least significant difference test (LSD) (p = 0.05). Main effects were presented in Tables 2-4, and interactions between factors in Figs 2-3.

Data on yield and crop quality were evaluated and presented in a separate publication by Król-Dyrek and Siwek (2015).

Table 4. Soil acidity (pH), electrical conductivity (EC mS cm^{-1}) and P, K, Mg, Ca, S-SO_4 (mg dm^{-3} of fresh soil), Na, and B (mg kg^{-1} d.m.) in soils of raspberry cultivation under plastic tunnel and open field conditions

Factor	pH_{H_2O}	EC	P	K	Mg	Ca	S-SO_4	Na	B
2011	6.51	0.11	32.1	87	110	1039	14.1	21.5	0.04
2012	7.16	0.14	22.9	84	165	1268	38.5	26.0	0.14
2013	6.92	0.11	22.8	79	105	849	13.4	16.2	0.35
High tunnel	7.89	0.17	40.9	71	161	1472	25.8	29.8	0.30
Open field	5.84	0.07	11.0	96	92	633	18.2	12.7	0.06
Control	6.90	0.12	25.6	75	121	1039	19.1	22.1	0.15
PLA	6.92	0.11	25.2	74	122	1081	19.1	17.6	0.18
PP photo.	6.95	0.12	29.3	105	139	1107	26.3	25.8	0.20
PP	6.70	0.14	23.7	79	124	981	23.5	19.3	0.18

Explanations as in Table 2.

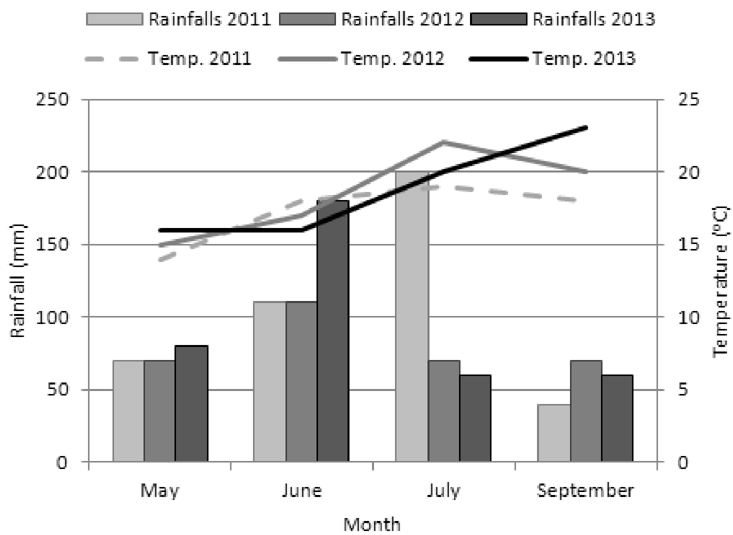

Fig. 1. Climatic conditions (data was obtained from the meteorological station in Brzezna).

RESULTS AND DISCUSSION

Soil texture has a significant influence on soil physical properties, as well as on aggregation. The soils in Brzezna Station, located in a mountain foreland region,, had been formed on a less-like, silty and very fine sand, and are classified as being leached brown soils. According to WRB classification (World reference base for soil resources 2014), these are considered as belonging to the Cambisols (Inceptisoles) category. The particle size analysis indicated sandy loam soil (Table 1).

Dry bulk density is the most frequently used parameter to characterize the state of soil compactness (Dexter, 2004; Håkansson and Lipiec, 2000; Reichert *et al.,* 2009). In the 2011 and 2013 seasons, the average soil bulk density (BD) of the test plots was 1.27 and 1.25 g cm^{-3}, respectively. The dry bulk density measured both for the open field soil and under high tunnel was similar (Table 2). However, a significant interaction between the year and the system of production was found (Fig. 2). In 2011, after the raised bed were formed, the soils in the OF system had higher bulk density than in the HT system (1.34 g cm^{-3} *versus* 1.20 g cm^{-3}, respectively). In the third year of the experiment, in the high tunnel system, higher BD values were noticed than under open field conditions (1.31 g cm^{-3} *versus* 1.19 g cm^{-3}, respectively). The mulch treatments had an insignificant effect on dry bulk density. However, in the first year of the study, all mulched soils in the OF system of production had lower BD values than in control soils, in contrast to the third year of the research (data not presented).

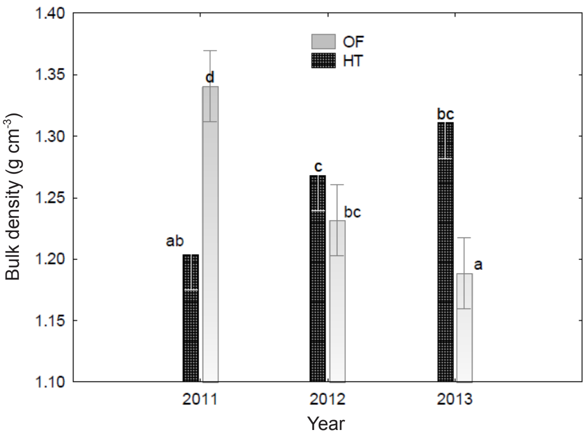

Fig. 2. Mean values (bars) and standard deviation (│ lines) of bulk density of soils in high tunnel (HT) and open field (OF) systems of raspberry production during the three-year period 2011-2013 (significant interactions for year x system of production: $LSD_{0.05}$ = 0.041).

According to the mean values for the three-year experiment period, moisture of the open field soils attained a value of 0.350 kg kg^{-1}, while that of the soils from the high tunnel had a value of 0.329 kg kg^{-1}. The higher moisture examined during soil sampling in the open field soil probably resulted from the additional amount of water from rainfall. This could also indicate a quicker soil water depletion in the HT system. This comes about by way of the roots of fast-growing plants with higher rates of transpiration, as in favourable conditions, plants produce higher biomass in tunnels than in open field conditions (data no shown). The soil covered with mulches also had slightly higher moisture than bare ground (Table 2). Raised beds, in contrast to level soils, usually have higher soil temperature, which promotes the loss of water from the uncovered soil (Tarara, 2000). Thus, it can be stated that mulching is the most effective way to minimize soil water evaporation. Ferus *et al.* (2009) point out that soil cover protects the soil from insulation and breaks the capillarity movement of water to the surface where it is evaporated. However, the porous structure of non-woven textile (PP, PLA) permits the cooling of soils through evaporation. Higher capillary water content was detected in 2011 and 2013, and lower in 2012 (Table 2). According to the mean values for the three years of the study, soils from the OF system of raspberry production had slightly higher capillary water content than soil from the HT system. Moreover, soil mulching enhanced the capillary water content expressed as volume water content. Dexter (2004), and Magdoff and Weil (2004) indicate a significant effect of organic matter content on water soil characteristics, especially for low-clay content soils. In the reference study, based on the mean values, soils taken from mulched plots had higher organic carbon content than that from the bare soil.

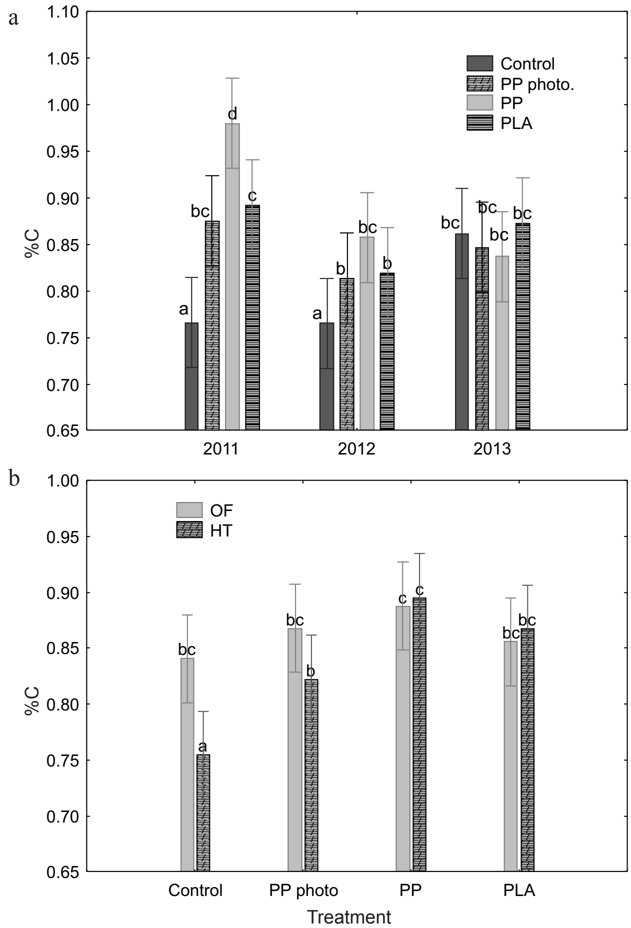

Fig. 3. Mean values (bars) and standard deviation (│ lines) of soil total carbon (%) of soils in high tunnel (HT) and open field (OF) cultivation systems under different treatments (control – bare soil, PP photo. – photo degradable polypropylene, PP – polypropylene, PLA – polylactic acid-base mulch) of raspberry production during the three-year period 2011-2013 (a – significant interactions: year x treatments $LSD_{0.05}$ = 0.069, b – system of production x treatments $LSD_{0.05}$ = 0.056). Figures with different letters within treatments are significant at p = 0.05.

The soil organic carbon (SOC) content in the tested soils ranged from 0.81 to 0.85% in 2012 and 2013, respectively (Table 2), and the production system affected the organic carbon amount in soils. Generally, a higher SOC content was found in the OF system (0.86%) as compared to the HT plots (0.83%). In addition, the mean values for 2011-2013 indicate that mulched soils had a significant more SOC amount than did bare soil control. The effect of significant interactions of year and treatments, and the system of production and treatments on organic carbon content in soils is shown in Fig. 3. In 2011 and 2012, all soils with cover treatments had higher soil organic carbon than bare soils. This pattern was especially observed for high tunnel soils (Fig. 3). In the third year of the experiment, differences between treatments were not statistically significant. Under open field conditions, mulching had no significant effect on organic carbon content in soils.

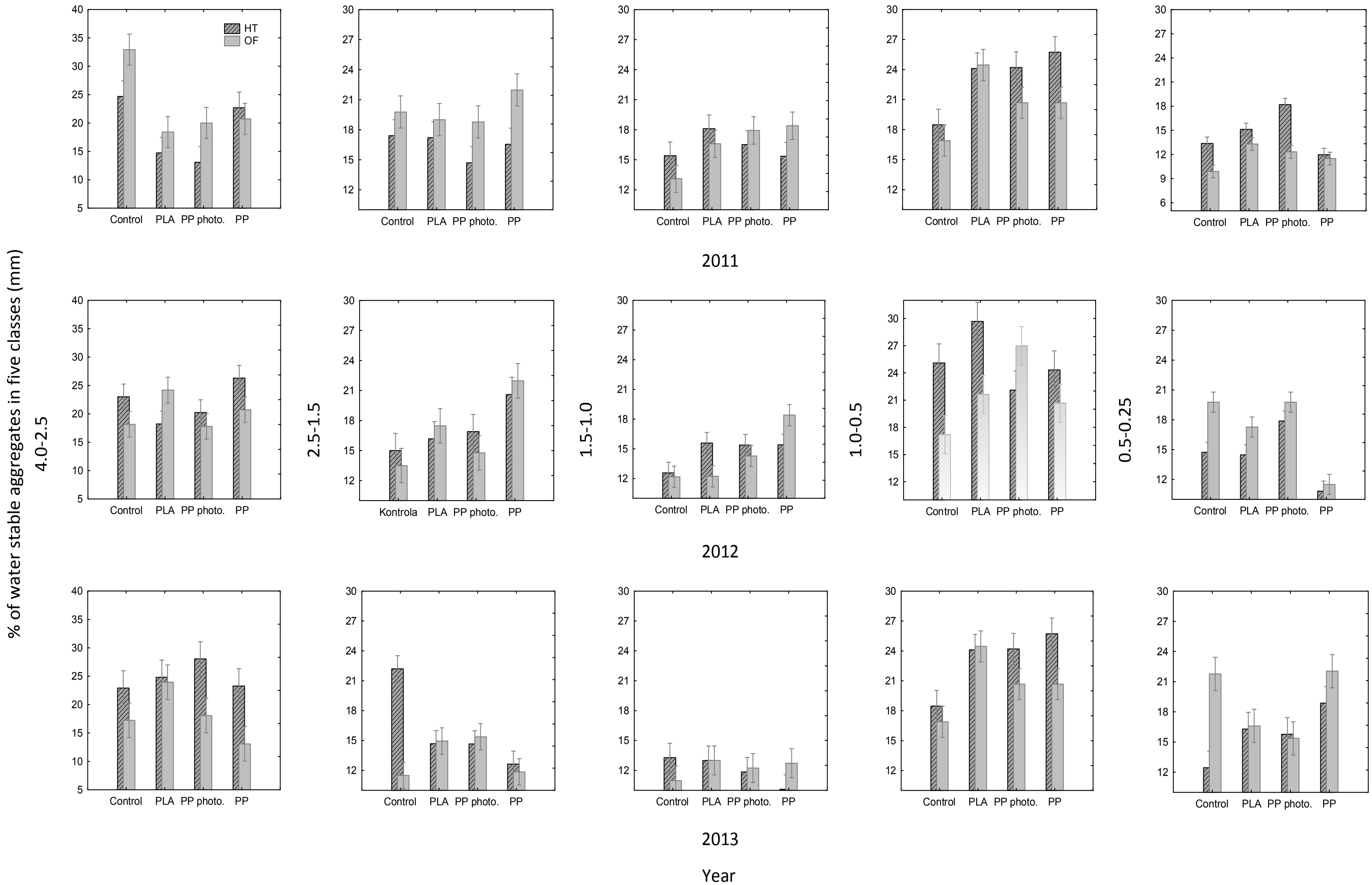

Fig. 4. Per cent of water stable aggregates of four classes (4.0-0.25 mm) in soils under different covers in high tunnel (HT) and open field (OF) production systems of raspberry, 2011-2013 (mean values – bars and standard deviation - lines).

The differences in C dynamics in the different soil management could be explained by means of the biological and biochemical mineralization hypothesis. As has been shown previously, soils from the HT system, particularly without cover, had lower moisture content than those under open field conditions. Possibly, the enhanced aeration stimulated greater microbial decomposition of organic carbon in soils. In contrast, higher temperatures under a plastic film tunnel during vegetative growth (Domagała-Świątkiewicz and Siwek, 2013; Siwek *et al.,* 2015) created more favourable conditions with regard to organic matter dynamics. The decomposition rate, similar to all chemical and biochemical reactions, is temperature dependent (Lützof and Kögel-Knabner, 2009). Indeed, Li *et al.* (2014) show that organic carbon, as well as higher microbial activity, is greater in high tunnel plots than in open field systems of tomato production.

The annual soil carbon balance is controlled by two major processes, *i.e.* respiratory carbon loss and photosynthetic carbon improvement (Davidson and Janssens, 2006). Seasonal changes in weather conditions can have great impact on both processes, thus altering the source/sink behaviour of the system (Unger *et al*., 2010). Management practices, including film covering and mulching, also moderate moisture and temperature regimes in soils (Hunter *et al.,* 2012; Lamont, 2005; Moreno *et al.,* 2009), and can alter biogeochemical cycling of carbon. This can result in organic matter accumulation or mineralization. Moreover, the biological status of soils depends strongly on the soil physical and chemical conditions. The results of the study of Lerch *et al.* (2010) show a maximum enrichment of soil microbial biomass over soil organic matter of 3‰ under well-watered conditions. Magdoff and Weil (2004) indicate that increase in soil water content can also inhibit the air circulation that would stimulate rapid aerobic decomposition. Rey *et al.* (2017) suggest that sudden changes in soil moisture, rather than soil moisture itself, are the main drivers of soil carbon mineralization. In the presented study, mulched soils had higher capillary water capacity than bare soils.

Soil organic carbon content and organic matter supply are usually correlated to aggregate stability, as determined in other studies (Lugato *et al.,* 2010; Six *et al.,* 2000). In our study, the highest water stable aggregate (WSA) indexes (expressed as a sum of the water stable aggregate fractions of 0.25-4.0 mm) were found in soils in 2011 and 2012, and in the soils maintained *via* the high tunnel system as compared to open field conditions (Table 2). The upward trend in the WSA index during the experiment was observed especially in bare soil on the open field plots. Novelli *et al.* (2013) indicate that practices that keep soil covered protect it from the erosive forces that disrupt aggregation, while also building organic matter. In addition, management activities that disturb soil and leave it bare can result in a rapid decline in soil organic matter, microbial activity and aggregation stability (Elmholt *et al.,* 2008). In the presented study, there were significant differences among WSA indexes under various soil treatments. However, mulching enhanced the soil structure in relation to bare soils, in particular in OF conditions. Aggregates are susceptible to disruption by physical disturbances, such as dry-wet cycles and rainfall impact. Furthermore, incidents of rapid changes in soil moisture lead to the physical disruption of macro-aggregates, and to an increase in organic substrates available for decomposition by soil microbes (Denef *et al.,* 2001). The results of our study suggest that soil covering improves moisture and the soil structure by enhancing soil water-stable aggregate content. Indeed, several reports in literature indicate that aggregate stability is an appropriate indicator of soil susceptibility to water erosion and may be used to assess the effect of agricultural management (Barthès and Roose, 2012; Bronic and Lal, 2005).

In our study, macro-aggregates (2.5-4.0 mm) constituted 19.5-23.1% of water stable aggregates and varied significantly among the treatments and production systems employed (Table 3). The mean values obtained indicate slightly higher amounts of water stable macro-aggregates in tunnel soils, when compared to open field systems. However, in the first year of the study, open field soil revealed a higher content of macro-aggregates than tunnel soils, especially in the control treatment and under biodegradable mulches (Fig. 4). On average, in 2011-2013, bare soils contained more macro-aggregates than mulched soils. The mechanism proposed to explain these phenomena is that wet-dry cycles induce macro-aggregates to become slake-resistant (Denef *et al.,* 2001).

In the second and third year of the experiment, in the open field soils, mulched non-woven PLA showed significantly higher amounts of macro-aggregates than in the case of the control treatment. A similar result was seen in 2013, in the tunnel system, for soil under PP photodegradable mulch (Fig. 4). Aggregation is affected by soil organic carbon, biota, ionic bridging, clay and carbonates (Six *et al.,* 2004; Stamati *et al.,* 2013). Tisdall and Oades (1982) show that roots and fungi hyphae stabilize macro-aggregates (>250 μm diameter). In the study of Denef *et al.* (2001), in fungicide treated soil samples, no large macro-aggregates (>2 mm) were formed, whereas in soil samples without fumigation, 30% of the soil dry weight was composed of large macro-aggregates, and fungi represent the largest part of the microbial biomass. Consequently, macro-aggregation can be said to be controlled by soil management, as management influences the growth of plant roots, biota and the oxidation of organic carbon.

In the third year of our study, the PLA film was partially, to a rather low degree, degraded mechanically or slightly disintegrated. Progressive PLA decomposition resulting in the deterioration of polymer durability indicates that microorganisms can utilise it as a nutrient source. Macro-aggregates are formed around fresh organic residues which are subsequently incorporated and become coarse intra-aggregates particulate organic matter (Denel *et al.,* 2001).

Bronic and Lal (2005) demonstrate that large aggregates form in soils with high pH. Calcium (Ca^{++}) is one of the soil aggregating agents which could also improve aggregate stabilization (Dexter, 2004). In the presented study, soil pH was higher in the tunnel soils than in the open field soils. Briedis *et al.* (2012) show that liming brings about an accumulation of large aggregates in soils.

During the experiment, the mean amount of water-stable aggregates in diameters 2.5-1.5 mm and 1.5-1.0 mm significantly decreased, while aggregates with the size of >0.5 mm increased (Table 3). Disturbance activity during soil tilling and the forming of raised beds disrupt the existing aggregates, and the natural renovation of the soil structure and regeneration of network pores are a long-term process. The mechanisms that support soil structure restoration include drying-wetting cycles and freeze-thaw processes, as well as certain soil biological activities (earthworm activity and root growth). The three-year mean values presented in Table 3 indicate that soils from the OF system had higher amounts of micro-aggregates (0.5-0.25 mm) and lower amounts of macro-aggregates (4.5-2.5 mm) than that from the HT system. Generally speaking, this trend was not seen in 2011, but was noticed in 2012 and 2013 (Fig. 4). The water-stability of micro-aggregates depends on the persistent organic binding agents, and it appears to be a characteristic of the particular soil (Stamati *et al.,* 2013). Our results also showed higher amounts of organic carbon in soils under open field conditions. It can, therefore, be concluded that an increase in the water-stable micro-aggregate content of the studied soils was a direct result of an increase in the value of the organic carbon amount. Six *et al.* (2000) indicate that the physical protection of the particulate organic matter into micro-aggregates is caused by reduced diffusion of oxygen and decreased microbial activity of decomposers inside the smallest aggregates.

The soil acidity reaction was above pH 7.0 in the high tunnel soils and showed slight acidity under open field conditions (Table 4). Still, important differences among the treatments were not observed. According to EC values, the soils were classified as not-saline. However, soil salinity was found to be higher in the high tunnel system. Soil samples taken from tunnel plots had also higher P, Mg, Ca, S, Na and B content than soils from the open field system. High tunnel soils are not exposed to regular leaching from rainfall, and soluble salt accumulated over time from the application of hard water. Moreover, the high level of bivalent cations (>1000 mg Ca and >100 mg Mg dm^{-3} of soil) contributed to high water-stable aggregates content in the tunnel soils. Bivalent cations improve the soil structure through binding clay particles and soil organic matter, while a high pH value raises a negative surface charge on clay particles and flocculates dispersive clays (Dexter, 2004). Furthermore, increased pH often results in higher microbial activity and organic matter content. This, in turn, encourages aggregation (Briedis *et al.,* 2012).

CONCLUSIONS

The main conclusions on the use of plastic and degradable plastic mulches in high tunnel production systems are as follows:

1. Soils under mulches have a higher soil organic carbon amount than the bare soils. Soil mulching enhances the soil water capacity expressed as volume capillary water content.

2. The water stable aggregate index is higher in tunnel systems than under open field conditions, and under non-woven mulching than in uncovered soils. Generally, mulching improves the soil structure, in particular, under open field conditions. The film covering also prevents a decrease in the amount of large aggregates in soils in the following year of cropping, especially in the tunnel system of production.

3. The impact of the compared mulches on soil quality indicators is similar. Thus, degradable mulches can be recommended for raspberry cultivation, and for sustainable horticulture applications.

4. The tunnel production system prevents the leaching effect of rain; however, if drip irrigation is installed and utilized regularly, it is possible that elevated soil salinity and alkalinity (pH>7.0) can occur.

5. The results obtained may prove useful in designing sustainable cropping raspberry production systems. The study provided evidence that land use (systems of production and mulching practices) has an important impact on organic carbon stock, moisture content and water stable aggregate amounts in soils.

Conflict of interest: The Authors do not declare conflict of interest.

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