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ORIGINAL PAPER

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MICROCLIMATIC CONDITIONS AND PHYSICO-CHEMICAL PROPERTIES OF SOIL IN INTENSIVE ECOLOGICAL VEGETABLE CROP ROTATION IN HIGH TUNNEL

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ABSTRACT

In 2014–2015 at the experimental station of the University of Agriculture in Kraków, situated in Mydlniki near Kraków, Poland, experiments with intensive crop rotation in a high tunnel were conducted. The objectives concerned microclimatic zones in the tunnel and the yield and quality of butterhead lettuce (spring), cucumber (summer), and butterhead lettuce (autumn). Besides the properties of the soil in the high tunnel, a crucial role was played by microclimatic factors. The measurements showed variations in solar radiation, temperature and air humidity depending on the zone in the tunnel and the weather. Higher temperature in the centre of the tunnel was conducive to obtaining greater yields of spring lettuce and cucumber. In the spring and summer periods, the amounts of dry matter and total sugars in the edible parts of the cultivated vegetables were higher in the eastern and central zones of the tunnel. In the autumn, with less solar radiation, the amount of sugars in lettuce leaves was greater in the western zone. There was observable influence of the location in the tunnel from which samples were taken for analyses (zonal effect) on some physical parameters of the soil (bulk density, water capacity, and water-stability index).

Key words: PAR radiation, temperature, soil, lettuce, cucumber, yield

INTRODUCTION

The use of high tunnels is still on the rise worldwide, especially in the production of horticultural crops [Lamont 2009]. The main countries where high tunnels are built and used are China and Japan, and in Europe, Spain and Italy [Figuier 2016]. Single and multi-span high tunnels of various shapes and dimensions belong to the category of "protected cultivation" and in the literature are very often mixed. In some countries with a temperate climate, the minimum height of a high tunnel is 1.5 m [Siwek and Libik 2012]. In a temperate climate, high tunnels increase soil and air temperature in every season, exclude rainfall and reduce the incidence of diseases, crop losses, and improve yield quality. They offer a cost effective way of prolonging the growing season and also allow small-scale growers to gain a market share in the niche market of "locally grown" produce [Hecher et al. 2014]. Low-cost, passive solar high tunnels seem to be ideally suited for growing high-value crops such as organic vegetables or fruits. Although plastic tunnels have the potential to offer many production benefits, soil quality management within these structures is particularly challenging and laborious as the work area is restricted [O'Connell et al. 2012, Rudisill et al. 2015]. It is possible, however, to make predictions of the microclimatic conditions by modelling [Reyes-Rosas et al. 2017].

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The main crops cultivated in high tunnels around the world are tomatoes, cucumbers and sweet peppers, lettuces and some flowers [Knewtson et al. 2010, Siwek and Libik 2012, Figuier 2016] for which the microclimate is adequate. The factors which determine the microclimatic conditions depend mainly on solar radiation. Depending on this factor, the temperature, air moisture and CO_2 level are determined [Boulard and Wang 2002, Hemming and Baeza-Romero 2018]. Every factor influences the plants separately and also affects the other factors. In high tunnels, the regulation of microclimate is performed in two directions: to diminish heat loss during the night and cold periods, and to reduce extremely high temperatures during hot seasons, which could cause irreparable damage to plants. A single tunnel protects sweet pepper only partially [Mydlarz et al. 1994], but a double-span tunnel has a more apparent influence on the microclimate, as the incidence of powdery mildew is lower [El-Aidy et al. 2007].

In vegetable cropping systems, a lack of crop rotation within these structures leads to serious problems such as soil-borne diseases, high soil salinity, poor soil structure, decreasing microbial diversity, and consequently reduced crop yields [Rudisill et al. 2015].

The aim of this study was to conduct an assessment of microclimatic and soil conditions in a single tunnel and determine their influence on the growth, quantity and quality of yield of some vegetable species in an ecologically managed high tunnel.

MATERIAL AND METHODS

Study site. The experiments were conducted in 2014–2015 at the experimental station of the University of Agriculture in Kraków, situated in Mydlniki near Kraków, Poland. The climate of the station, located in southern Poland (N51°13', E22°38'), is humid continental (Dfb) according to Köppen's classification. The soil type is a Fluvic Cambisol, according to the classification of the World Reference Base for Soil Resources [2015].

Experimental design. The experiment was established in 2014 and repeated in 2015 in a single, ecologically managed (since 2013), Farmer STN 070 high tunnel measuring 7 m in width, 30 m in length and 3.2 m in height. Ventilation in this structure was through the doors only. In the late autumn of 2013, the soil in the tunnel was fertilized with cow manure (30 t ha^{-1}).

After harvesting early butterhead lettuce and before planting cucumber in both years the soil was prepared with a rototiller to a depth of 13–15 cm and potassium sulphate and Bioilsa ecological N-fertilizer were applied. Before planting the lettuce aftercrop, the soil was cultivated again with a rototiller. During the two vegetation seasons, Humistar, NaturalCrop SL and Bio-algeen were used for supplementary feeding. Plant protection against downy mildew and spider mites was done with a garlic preparation and Septovital 200 SL, respectively. The plants were irrigated with a drip system – a plastic tubes with holes 20 cm apart.

The objectives of the experiment concerned the microclimatic zones in the high tunnel (determined by the distance from the doors):

1. butterhead lettuce (spring): planted 0–10 m and 10–20 m from the eastern entrance;
2. cucumber: planted 0–10 m and 10–20 m from the eastern entrance;
3. butterhead lettuce (autumn): planted in the eastern zone 0–10 m, central zone 10–20 m, and western zone 0–10 m (Tab. 1).

Microclimatic conditions. Soil temperature was recorded using HOBO autonomous sensors (Onset Corp., Bourne, MA, USA) located in the immediate vicinity of the plants in the separate zones. Temperature data were recorded at one-hour intervals over the course of the experiment and are summarized in the form of average values. In addition, measurements were taken before and after midday on two days with different weather conditions (on 16 May 2014 with full clear sky, and 21 May 2014 with full cloud cover) of photosynthetically active radiation (PAR) (spectroradiometer LI-COR 189B), air relative humidity and temperature (Hygromer A1, Rotronic AG), soil moisture (HH2 Moisture Meter), and CO_2 content of the air (Telaire 7001).

Yield analysis. The estimation of cucumber yield was done according to the Polish Standard PN-85/R-75359 by including healthy fruits of a regular shape, without disease symptoms and no mechanical or pest damage. The fruits were divided into three grades: pickling grade (8–10 cm in length), brining grade (10–15 cm) and salad grade (>15 cm). For but-

Table 1. Agrotechnical dates and spacing between plants during the two-year experiment with butterhead lettuce–
–cucumber–butterhead lettuce crop rotation

Species and cultivars	Year	Date of sowing	Date of planting	Spacing (cm)	Date of harvesting
Butterhead lettuce 'Veronique'	2014	24 January	4 March	40 × 30	29 April
Cucumber 'Bursztyn F_1'		1 April	6 May	80 × 50	2 June–31August
Butterhead lettuce 'Veronique'		12 August	3 September	30 × 30	27 October
Butterhead lettuce 'Mafalda'	2015	26 January	3 March	40 × 30	22 April
Cucumber 'Lazuryt F_1'		30 March	29 April	80 × 50	2 June–31August
Butterhead lettuce 'Mafalda'		12 August	3 September	30 × 30	28 October

terhead lettuce, the standard used was PN-R-7522. Dry weight and soluble sugars of fresh cucumber fruits from 3–5 harvests were determined in the laboratory. Dry weight was determined by drying samples at 92–95°C until a constant weight was obtained, measured with a Sartorius A120S analytical balance (Sartorius AG, Germany). Soluble sugars were determined by the anthrone method. For this analysis, plant material was mixed with 80% ethanol. After the addition of the anthrone reagent, samples were placed in a water bath for 30 min (100°C), cooled down to 20–22°C, and the absorbance was measured at 625 nm using a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., USA).

Physico-chemical soil analysis. Soil samples for analysis were collected from the 0–20 cm soil layer immediately after each cycle of rotation, i.e. after growing lettuce in the spring, cucumber in the summer, and lettuce in the autumn. Water resistance of soil aggregates, soil bulk density, water capacity, organic carbon content, as well as the levels of macro- and micronutrients in the soil were assessed.

To determine the physical properties, soil samples with undisturbed structure were collected using a 250 cm^3 Kopecky's stainless steel cylinder with perforated bottom. Soil bulk density and water capacity were determined according to Kopecky's procedures [Komornicki et al. 1991]. Soil aggregates were separated during wet sieving according to the procedures described by Yoder [Yoder 1936]. To measure the water resistance of the soil structure, 40 g samples of air-dry aggregates sifted through a sieve with a mesh diameter of 5 mm were weighed out, performing the determinations in six replicates. Each dry soil sample was subjected to a slow wetting pretreatment in deionized water for 5 min. The sample was then wet-sieved using a motor-driven holder for lowering and raising the sieves in a container of water. There were five size classes used: 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 for 20 min. The weight of soil on each sieve was determined by drying at 105°C and weighing. The water-stability index was calculated separately for each aggregate size class and for the 5 size classes combined. Aggregates separated on the 2.5 mm sieve were described as large macro-aggregates, those on the 1.5 mm sieve as medium macro-aggregates, and those on the 1 mm sieve as small macro-aggregates. The remaining aggregates retained on the 0.5 mm and 0.25 mm sieves were micro-aggregates.

Organic carbon was determined by oxidation with potassium dichromate according to the procedures described by Tiurin [Lityński et al. 1976]. Determinations of available macronutrients (N, P, K, Mg, Ca and S) were made in 0.03 mol dm^{-3} CH_3COOH by the universal method, and soluble micronutrients (Zn, Cu, Mn, Fe, B) in 1 mol dm^{-3} HCl extracts according to the Rinkis method [Ostrowska et al. 1991]. In the extracts, the mineral components, except nitrogen, were determined by the ICP OS method (Teledyne Liman Labs). Mineral nitrogen as $N\text{-}NH_4$ and $N\text{-}NO_3$ was determined by the FIA (Flow Injection Analysis) method according to the procedures described in PN-EN ISO 13395 [2001].

Statistical analysis of results. Statistical calculations were performed with the Statistica 11 (StatSoft) program. The experimental factors were: the type of crop rotation in the tunnel – factor I (A), and the zone in the tunnel (sampling location: east, centre, west) – factor II (B). The interaction of both factors (A × B) was also calculated. The significance of differences between means was determined by Fischer's LSD test.

RESULTS AND DISCUSSION

Microclimatic conditions. Apart from soil properties, a crucial role in high tunnels is played by microclimatic factors. The conditions inside vary greatly depending on the construction of the tunnel, method of ventilation and physical characteristics of the covering film. The measurements showed large variations in the levels of solar radiation, temperature and air humidity. The air composition depended on the method of ventilation (Tab. 2).

Photosynthetic active radiation (PAR). Irrespective of the weather conditions, lower intensity of PAR was measured inside the tunnel than outside. An interesting result was the almost 50% higher PAR intensity recorded outside during the sunny day. Inside the tunnel, on the cloudy day, lower levels of radiation were recorded in the morning than in the afternoon. On both the sunny and the cloudy day, the amount of solar radiation in the range 400–700 nm was similar irrespective of the zone in the tunnel. In a different climate (Northern India), the difference in solar radiation between the inside and outside of a tunnel was 16–37% and depended on its height [Lodhi et al. 2013].

Air temperature. Inside the closed tunnel during the cloudy day at 10.00 hours, the mean temperature was 4.2°C higher than outside. In the afternoon, this difference increased, reaching 5.8°C. On the sunny day, despite ventilation, the air temperature inside exceeded 30°C. Its mean value was 3.1°C higher than outside, and in the centre of the tunnel there was no significant difference in comparison with the western zone. In both kinds of weather, lower air temperatures were recorded in the eastern zone. Larger differences in air temperature between the entrance and the centre had been obtained in a 1.5 m high tunnel, where its value greatly exceeded the maximum for the normal growth and development of sweet pepper [Mydlarz et al. 1994].

Relative air humidity. Inside the closed tunnel, during the cloudy day, the air relative humidity was 75–85%. Its level was similar to that outside, and after the increase in temperature, it decreased only slightly. During the sunny day, the level of air relative humidity was markedly lower (30–40%). In the afternoon on that day, its values got smaller as a result of temperature increasing. The results show that in poorly ventilated high tunnels high air humidity persists, and this persistence can have a negative influence on the generative processes and health of the plants. There were no significant differences among the zones. In the climate of northern India, the conditions in a tunnel closed during the night were such that in the early morning the relative air humidity was 5–6% lower than outside, and during the afternoon hours it was 12–18% higher [Lodhi et al. 2013].

Air CO_2 content. In the non-ventilated high tunnel during the cloudy day, a high concentration of CO_2 was measured, especially at 14.00 hours. In the ventilated tunnel during the sunny day, a lower CO_2 concentration was recorded, but the level was slightly higher or similar to that outside. Irrespective of the kind of weather, the concentration of CO_2 before noon was higher than the standard 300 ppm, both inside and outside. With a rise in temperature, the CO_2 level in the closed tunnel was markedly higher. On the sunny day, however, this correlation was reversed. A detailed investigation of the microclimate in a tunnel with similar ventilation and 1.5 m in height had shown that CO_2 levels in the centre and close to the entrance of the tunnel increased to 1400 ppm during the night and fell rapidly to a medium level (300 ppm) after sunrise, and depended on the intensity of PAR [Mydlarz et al. 1994].

Parameters of soil quality in the tunnel. Soil analyses performed after growing cucumber showed a systematic decrease in the organic carbon content of the soil in the tunnel and also an increase in soil bulk density in relation to the beginning of cultivation in April 2014 (Tab. 3).

The cumulative water-stability index for soil aggregates, calculated as the sum of fractions with diameters 0.25–5.0 mm, was 89.7% in the spring (lettuce). After growing lettuce in the autumn, which closed the crop rotation cycle (butterhead lettuce–cucumber–butterhead lettuce) in the tunnel, the water resistance of soil aggregates, which is a measure of soil structure stability, amounted to 78.5% (Tab. 4). Soil aggregation, as well as soil structure, is essential for soil functioning and productivity. Aggregates resistant to water can physically stabilize soil organic matter and protect it from decomposition [Six et al. 2002]. Soil aggregate dynamics are influenced by many factors, including soil biota, root growth, soil chemistry, environmental and agronomic conditions [Bronick and Lal 2005]. The reason for the decrease in the resistance of soil structure to water might have been a decrease in the level of organic matter, which is a binder of soil particles. The breakdown of soil aggregates, especially macro-aggregates, resulted, in turn, in the acceleration of mineralization of organic matter and a decrease in centrations of nitrogen and phosphorus as well as high levels of magnesium, potassium and sulphur (K_2SO_4 fertilization).

An intensively managed tunnel requires that the demanding main crop plants are supplied with nutrients in the form of organic fertilizers every year. As a result, the soil is maintained in good culture and its humus content gradually increases. After fertilizing the soil with manure in the autumn of 2014, the bulk density of the soil in the tunnel measured in the spring after lettuce cultivation was 1.25 g cm^{-3}, and after cucumber cultivation it significantly increased to the value of 1.35 g cm^{-3}. At the end of the growing season, af-

Table 2. Some microclimatic factors in different zones of the high tunnel on a cloudy day (21 May 2014) and a clear-sky day (16 May 2014)

Microclimatic factors		Tunnel				Outside			
		cloudy day		sunny day		cloudy day		sunny day	
		10.00	14.00	10.00	14.00	10.00	14.00	10.00	14.00
PAR (μ mol m^{-2} s^{-1})	east	329	587	1510	1550	–	–	–	–
	centre	325	588	1530	1490	434	646	2240	2070
	west	324	568	1555	1540	–	–	–	–
Air temp. (°C)	east	15.1	18.4	29.6	31.6	–	–	–	–
	centre	16.0	18.5	32.0	34.0	11.6	12.6	28.6	30.0
	west	16.5	18.4	32.8	34.3	–	–	–	–
Relative air humidity (%)	east	87	76	42	30	–	–	–	–
	centre	84	75	38	33	92	92	31	34
	west	88	74	36	32	–	–	–	–
CO_2 (ppm)	east	1274	1645	493	389	–	–	–	–
	centre	1058	1530	548	406	478	1063	470	402
	west	1046	1257	570	409	–	–	–	–

Table 3. Physical properties and organic carbon content of the soil under butterhead lettuce–cucumber–butterhead lettuce crop rotation in the tunnel, 2014

Species	Bulk density (g cm^{-3})	Water capacity (% w/w)	Water capacity (% w/v)	Organic carbon (%)
Lettuce (spring)	1.17 ±0.02	39.6 ±1.8	45.7 ±1.3	1.34
Cucumber	1.24 ±0.07	31.0 ±1.7	38.4 ±1.8	1.33
Lettuce (autumn)	1.28 ±0.07	37.7 ±3.2	47.0 ±1.6	1.24

Table 4. Water stability of soil aggregates (mean values and standard deviation at p = 0.05) under butterhead lettuce–cucumber–butterhead lettuce crop rotation in the tunnel, 2014

Species	% of aggregates with dimensions (mm)					
	5.0–2.5	2.5–1.5	1.5–1.0	1.0–0.50	0.50–0.25	∑ 0.25–5.0
Lettuce (spring)	19.8 ±2.1	17.1 ±0.8	19.3 ±3.2	21.2 ±1.9	12.4 ±1.7	89.7
Cucumber	11.1 ±2.0	10.0 ±2.9	12.2 ±1.0	27.4 ±3.9	21.9 ±0.9	82.7
Lettuce (autumn)	12.8 ±1.6	11.4 ±0.2	10.4 ±0.9	23.1 ±2.4	20.8 ±2.9	78.5

Table 5. Soil reaction (pH), salt concentration (EC, mS cm^{-1}) and macroelement content (mg dm^{-3} of soil FW) after cultivation in the tunnel with butterhead lettuce–cucumber–butterhead lettuce crop rotation, 2014

Species	pH_{H2O}	EC	$N\text{-}NH_4$	$N\text{-}NO_3$	Ca	K	Mg	P	S
Lettuce (spring)	7.53	0.25	0.64	25.0	1143	48	122	49.0	25.7
Cucumber	7.61	0.15	4.00	12.2	1099	404	123	31.3	285
Lettuce (autumn)	7.66	0.16	2.78	15.6	1168	216	152	40.8	186

Table 6. Physical properties and organic carbon content of soil in the tunnel, depending on crop rotation and sampling location, 2015

Species	Zone	Bulk density (g cm^{-3})	Water cap. (% w/w)	Water cap. (% w/v)	%C	∑water stability (%)
Lettuce	west	1.32 a	36.2 a	47.6 a	1.48 a	91.9 a
	centre	1.25 a	37.5 a	46.8 a	1.41 a	90.5 a
	east	1.18 a	39.6 a	46.7 a	1.45 a	90.8 a
Mean		1.25 A	37.7 B	47.0 B	1.46 A	91.1 A
Cucumber	west	1.31 a	39.5 b	51.6 b	1.40 a	87.8 a
	centre	1.36 a	36.8 b	48.2 ab	1.64 a	91.5 b
	east	1.38 a	32.1 a	44.5 a	1.39 a	93.3 c
Mean		1.35 B	36.1 B	48.1 B	1.49 A	90.9 A
Lettuce	west	1.20 a	33.0 a	39.7 a	1.40 a	89.0 a
	centre	1.25 b	31.1 a	38.8 a	1.51 a	94.7 b
	east	1.25 b	31.8 a	39.7 a	1.34 a	95.9 b
Mean		1.23 A	31.9 A	39.4 A	1.41 A	93.2 B

Small letters indicate the significance of differences between the means for tunnel zones (east, centre, west) and capital letters between the means for the species. Means marked with the same letters do not differ significantly at p = 0.05 (Fisher's LSD test)

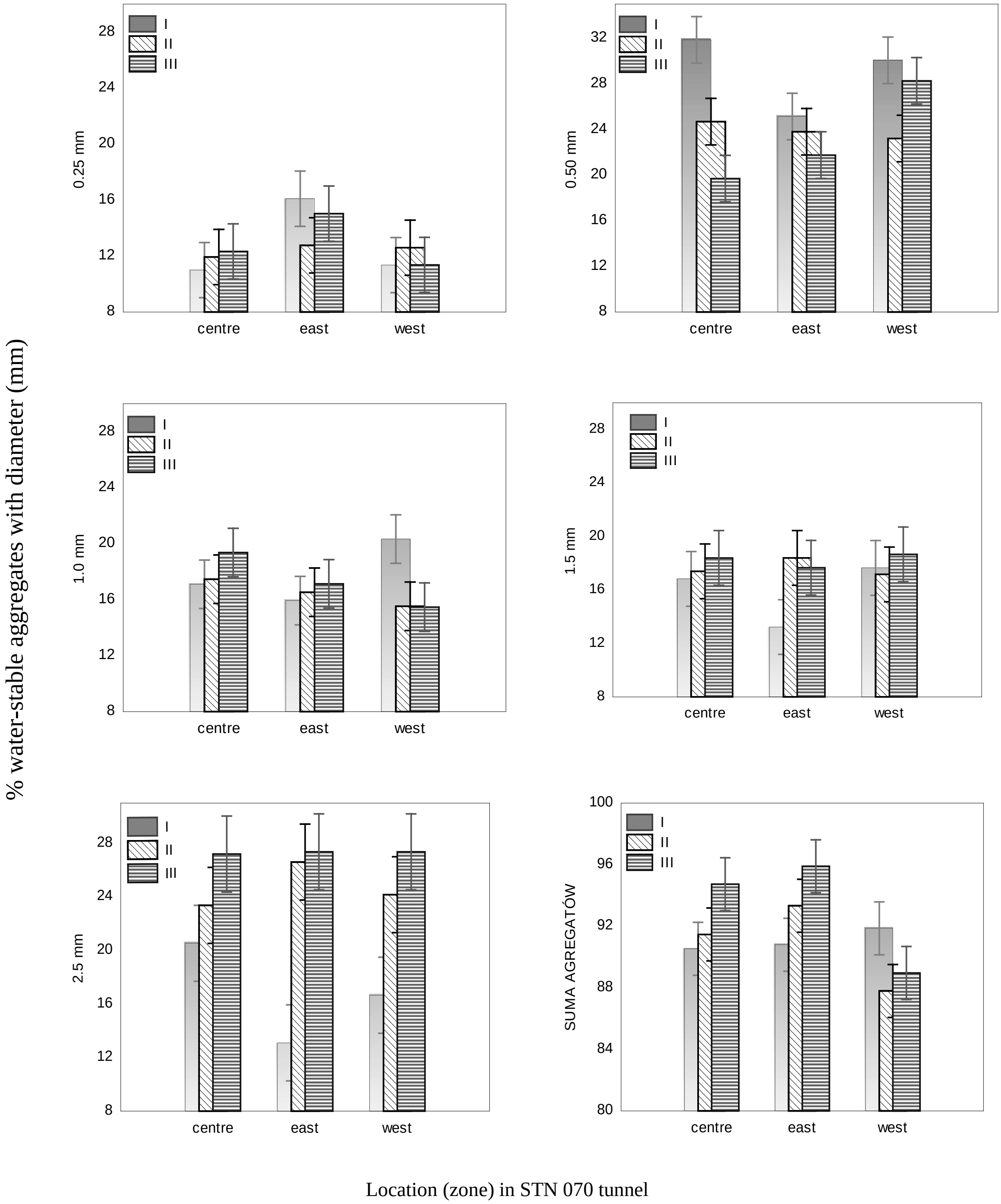

Fig. 1. Effect of crop rotation (I – after lettuce grown in autumn 2014 – March 2015; II – after cucumber, September 2015; III – after lettuce, October 2015) on the amounts of water-stable aggregates in size fractions and the cumulative amount of water-stable aggregates in the soil in the tunnel. For the interaction of factors A × B (at $p = 0.05$), LSD = 3.78

Table 7. Percentage share of different size fractions of water-stable aggregates in the soil depending on crop rotation and location in the tunnel, 2015

Plot	Zone	Diameter of aggregates (mm)					
		5.0–2.5	2.5–1.5	1.5–1.0	1.0–0.50	0.50–0.25	∑ 0.25–5.0
Before cultiv.	west	16.7 ±0.9	17.7 ±1.8	20.3 ±2.9	25.9 ±2.1	11.4 ±1.7	91.9 a
	centre	15.3 ±0.8	14.2 ±1.8	17.7 ±2.3	30.3 ±2.5	12.9 ±2.6	90.5 a
	east	13.1 ±0.9	13.2 ±1.2	15.9 ±1.8	32.4 ±1.0	16.1 ±1.7	90.8 a
Mean before cultiv.		16.8 A	15.9 A	17.8 A	28.0 B	12.8 A	91.1 A
After cucumber	west	24.2 ±0.9	17.2 ±1.5	15.5 ±0.2	18.3 ±0.8	12.6 ±1.3	87.8 a
	centre	23.4 ±2.6	17.4 ±0.6	17.5 ±0.6	21.3 ±1.5	11.9 ±2.0	91.5 a
	east	26.6 ±1.5	18.4 ±0.1	16.5 ±0.2	19.0 ±0.6	12.8 ±1.5	93.3 a
Mean after cucumber		24.7 B	17.2 B	16.5 A	19.6 A	12.4 A	90.9 A
After lettuce	west	27.4 ±0.5	18.7 ±1.0	15.5 ±1.0	16.1 ±1.3	11.4 ±0.7	89.0 a
	centre	27.2 ±0.9	18.4 ±2.3	19.4 ±1.0	17.4 ±1.8	12.3 ±1.5	94.7 a
	east	27.4 ±0.3	17.7 ±1.8	17.1 ±1.3	18.7 ±0.54	15.0 ±0.9	95.9 a
Mean after lettuce		27.3 C	18.2 B	17.3 A	17.4 A	12.9 A	93.2 B
Mean – factor: zone	west	22.8 a	17.9 a	17.1 ab	20.1 a	11.8 a	89.6 a
	centre	22.0 a	16.7 a	18.2 b	23.0 ab	12.4 a	92.1 a
	east	22.3 a	16.4 a	16.5 a	23.4 b	14.6 b	93.3 b

Small letters indicate the significance of differences between the means for the tunnel zones (east, centre, west) and capital letters between the means for the species (crop rotation). Means marked with the same letters do not differ significantly at p = 0.05 (Fisher's LSD test). For the interaction of the two factors at p = 0.05, LDS = 3.78

Table 8. Soil reaction (pH), salt concentration (EC, mS cm^{-1}) and macroelement content (mg dm^{-3} of soil FW) of the soil in the tunnel, 2015

Species	zone	pH_{H2O}	EC	$N-NH_4$	$N-NO_3$	Ca	K	Mg	P	S
Lettuce	east	7.72 a	0.37 a	1.33 a	4.10 a	1568 a	209 a	175 a	58 a	69 a
	centre	7.71 a	0.36 a			1384 a	135 a	156 a	57 a	54 a
	west	7.68 a	0.31 a			1354 a	225 a	159 a	56 a	69 a
Mean		7.70 A	0.35 B	1.33 A	4.10 A	1435 A	189 B	163 B	57 C	64 A
Cucumber	east	7.29 a	0.11 a	2.27 a	17.90 a	1444 a	207 a	153 a	42 a	29 a
	centre	7.35 a	0.10 a	5.54 a	37.10 a	1368 a	103 a	151 a	44 a	27 a
	west	7.26 a	0.13 a	5.74 a	24.40 a	1651 a	210 a	168 a	50 a	92 a
Mean		7.30 A	0.11 A	4.52 B	26.47 B	1487 A	173 B	157 B	45 B	49 A
Lettuce	east	7.62 a	0.17 a	2.53 a	5.40 a	1445 a	62 a	142 a	33 a	29 a
	centre	7.53 a	0.20 a	1.84 a	8.70 a	1430 a	70 a	141 a	30 a	43 a
	west	7.58 a	0.19 a	2.72 a	5.90 a	1300 a	65 a	125 a	28 a	27 a
Mean		7.57 A	0.19 A	2.36 AB	6.67 A	1391 A	66 A	136 A	30 A	33 A

Designations as in Tab. 7

Table 9. Microelement content (mg kg^{-1}) of the soil in the tunnel, 2015

Species	B	Cu	Fe	Mn	Mo	Zn
Lettuce	1.63	6.8	2049	200	0.04	48
Cucumber	0.44	6.7	2028	240	0.08	55
Lettuce	0.92	7.3	1632	193	0.08	56

After the autumn cultivation of lettuce, a significant increase in the 5.0–2.5 mm fraction (up to 27.3%) and an increase in the cumulative soil water-stability index were recorded (Tab. 7). In the central and eastern zones of the tunnel there was a tendency of the soil structure to increase its resistance to water (an increase in the cumulative water-stability index) in all the links of crop rotation (Fig. 1). This pattern was not found in the west of the tunnel, where there was a slight decrease in the total amount of water-stable soil aggregates during cultivation (Fig. 1).

The pH of the soil in the tunnel after the forecrop lettuce was slightly alkaline – pH 7.70, and during cultivation it did not change significantly with the concentration in the soil of calcium in the range 1391–1487 mg dm^{-3} and magnesium 136–163 mg dm^{-3} (Tab. 8). The concentration of basic nutrients (Ca and Mg) was high according to the guide values estimated using the universal method [Sady 2000]. A high level of Ca^{2+} and Mg^{2+} cations in the analyzed soils encouraged a high percentage of water-stable aggregates. Bivalent cations improve soil structure by binding clay particles and soil organic matter [Bronick and Lal 2005]. After cucumber cultivation, soil salinity significantly decreased from 0.35 to 0.11 mS cm^{-1}. During vegetative growth in the tunnel, changes were observed in the concentration of mineral nitrogen in the soil. The ammonium and nitrate nitrogen determined in the soil in March after lettuce cultivation was 1.33 and 4.10 mg dm^{-3}, respectively. After cucumber cultivation, the concentration of both nitrogen forms in the soil increased significantly, after which, in the final stage of cultivation (after autumn lettuce), it decreased again (Tab. 8).

The analyses demonstrated decreasing concentrations of available potassium in the soil in the tunnel. After the first link of rotation (lettuce), the potassium content was 189 mg K dm^{-3}, after the second link (cucumber) – 173 mg K dm^{-3}, and finally, after growing autumn lettuce (third link of crop rotation) – 66 mg K dm^{-3}. A similar trend was demonstrated for the phosphorus content in the soil (Tab. 8). The sulphur content in the soil did not change significantly during the growing season, decreasing from 64 mg dm^{-3} before to 33 mg dm^{-3} after the cultivation of lettuce. Statistical analysis showed that there was no significant effect of the location/zone factor in the tunnel on the macroelement content, pH and EC of the soil (Tab. 8).

After the cultivation of lettuce in the spring, the boron content was 1.63 mg B kg^{-1} of soil, and after cucumber cultivation its concentration dropped to 1/4 of the initial value, i.e. to 0.44 mg B kg^{-1} (Tab. 9). After the cultivation of lettuce in the autumn, the concentration of this element increased to a value of 0.92 mg B kg^{-1} of soil. The levels of the other microelements did not change significantly during the whole growing season.

Crop yield and quality

The yield of butterhead lettuce obtained in the spring shows that the plants closer to the entrance grew more slowly and reached a smaller mass (Tab. 10). On most vegetation days inside the closed tunnel the temperature was higher: in the centre the temperature difference was 3.1°C for the minimum, 4.4°C for the maximum, and 3.1°C for the mean soil temperature (Fig. 2a). The temperature had been the main reason for higher lettuce yields in the experiments by Wojciechowska and Siwek [2007] and Siwek et al. [2010].

The marketable yield of cucumber grown closer to the entrance in 2014 and 2015 was 3 and 10% lower, respectively, in comparison with the centre (Tab. 11). Non-marketable fruit comprised a very small part of the total yield, so it is not presented. The level of the yield was relatively high compared to the crop grown under

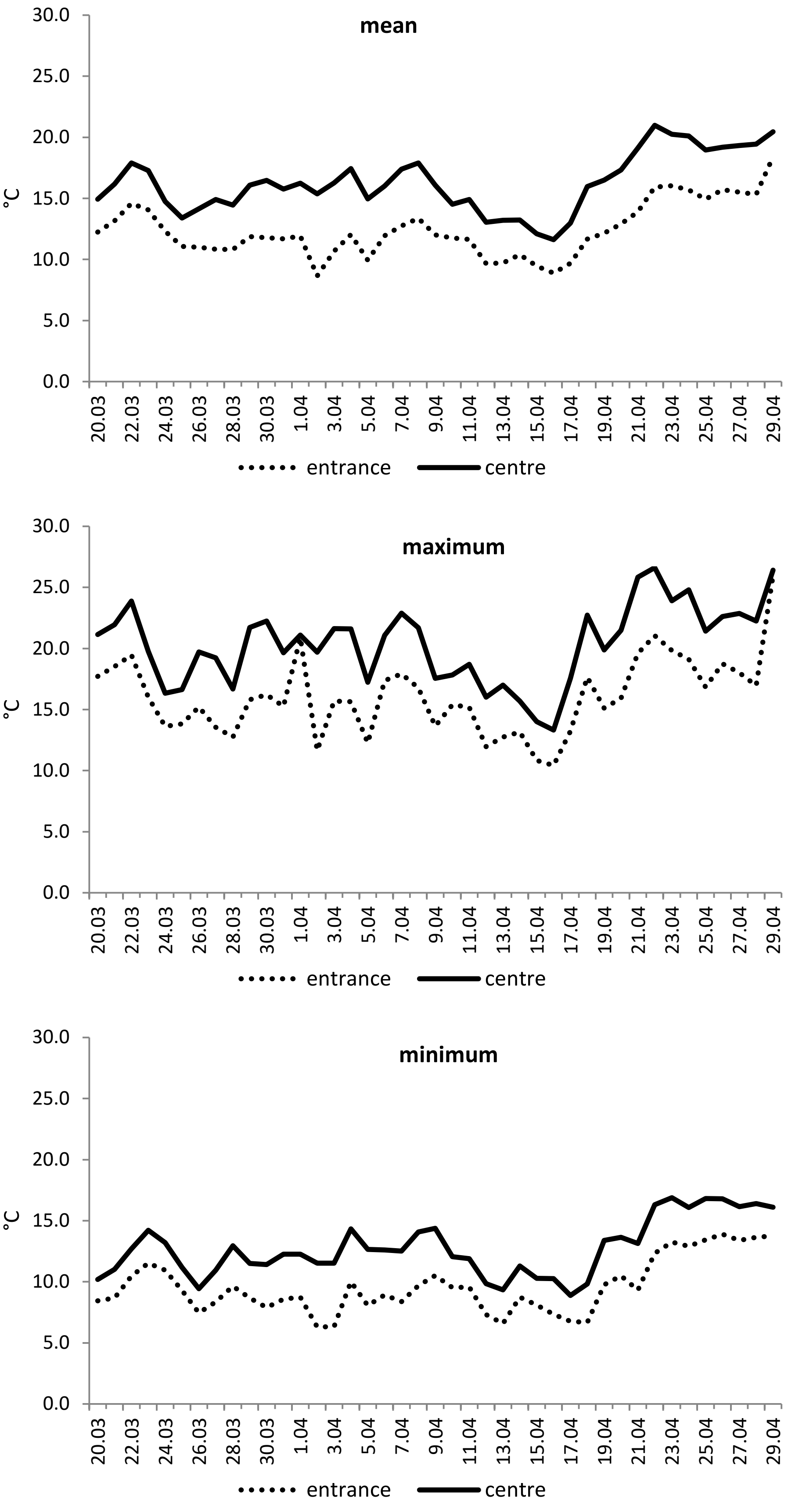

Fig. 2a. Soil temperature at the depth 10 cm in the high tunnel during early lettuce vegetation, 2014

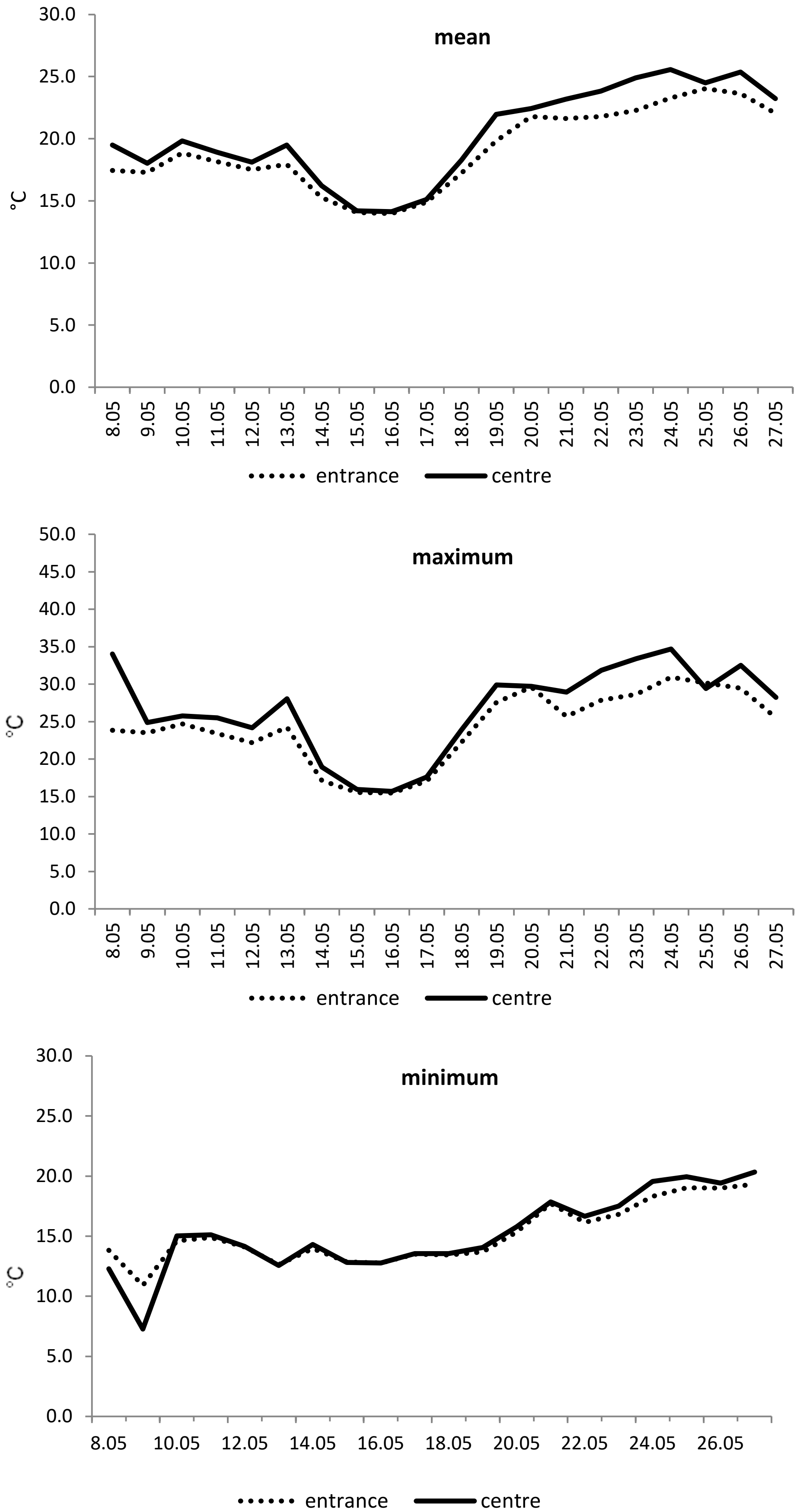

Fig. 2b. Soil temperature at the depth 10 cm in the high tunnel during cucumber vegetation, 2014

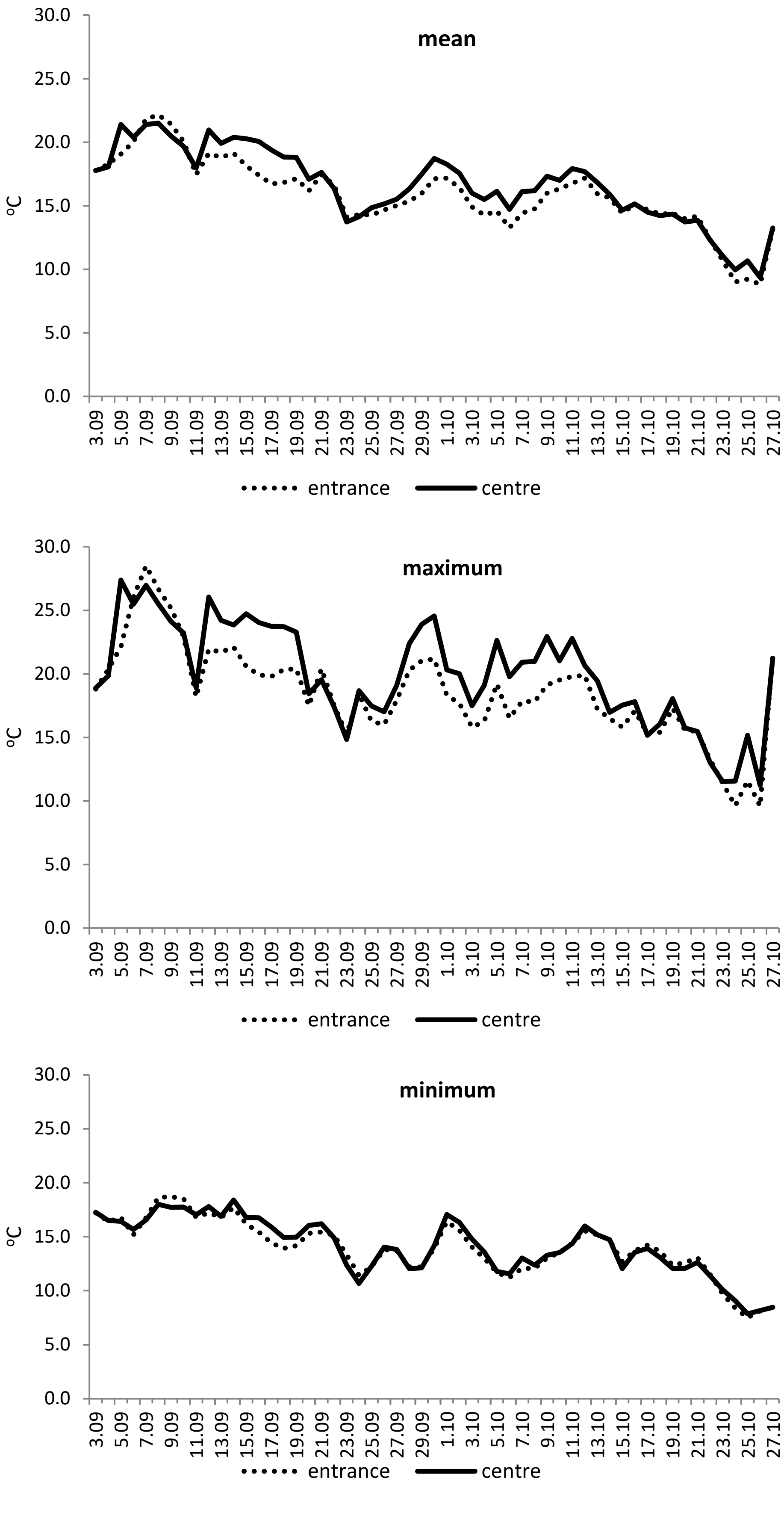

Fig. 2c. Soil temperature at the depth 10 cm in the high tunnel during autumn lettuce vegetation, 2014

Table 10. Yield of butterhead lettuce in two zones in the high tunnel, spring 2014–2015

Zone	Head mass (kg)			Marketable yield (kg m^{-2})		
	2014	2015	2014–2015	2014	2015	2014–2015
0–10 m from east entrance	0.187 a	0.156 a	0.171 a	1.55 a	1.29 a	1.42 a
10–20m from east entrance	0.208 a	0.205 b	0.206 b	1.73 a	1.70 b	1.71 b

Means followed by the same letter are not significantly different

Table 11. Marketable yield (kg m^{-2}) of cucumber depending on the zone in the high tunnel, 2014–2015

Zone	Pickling	Brining	Salad	Marketable yield	Pickling	Brining	Salad	Marketable yield
	2014				2015			
0–10 m from east entrance	7.07 a	1.67 a	0.06 a	8.75 a	9.28 a	2.68 a	0.44 a	11.96 a
10–20 m from east entrance	7.24 a	1.81 a	0.06 a	9.05 a	10.32 a	2.80 a	0.54 a	13.12 a

Means followed by the same letter are not significantly different

Table 12. Yield of butterhead lettuce in the different zones in the high tunnel, autumn 2014–2015

Zone	Head mass (kg)			Marketable yield (kg m^{-2})		
	2014	2015	2014–2015	2014	2015	2014–2015
0–10 m from east entrance	0.280 a	0.250 a	0.260 a	3.07 a	2.40 a	2.74 a
10–20 m from east entrance	0.290 a	0.340 b	0.310 a	3.22 a	3.21 b	3.21 b
0–10 from west entrance	0.320 a	0.270 a	0.300 a	3.58 a	2.57 a	3.08 ab

Means followed by the same letter are not significantly different

Table 13. Dry matter and total sugars in butterhead lettuce and cucumber in the high tunnel, 2014

Zone	Dry matter (%)			Total sugars (%)		
	butterhead lettuce (spring)	cucumber	butterhead lettuce (autumn)	butterhead lettuce (spring)	cucumber	butterhead lettuce (autumn)
0–10 m from east entrance	5.52 b	4.16 a	4.40 a	1.41 b	2.48 ab	0.54 a
10–20 m from east entrance	5.07 a	4.05 a	4.09 a	1.26 a	2.42 a	0.65 ab
0–10 m from west entrance	–	–	4.50 a	–	–	0.80 b

Means followed by the same letter are not significantly different direct covers – mean 5.30 kg m^{-2} [Kalisz et al. 2018], and on the soil mulched with black nonwoven – mean 3.10 kg m^{-2} [Siwek et al. 2015] in the same climate. In the first days of cucumber vegetation, the mean, maximum and minimum temperatures in the centre of the tunnel were higher by 1.2, 4,3 and 0.1°C, respectively (Fig. 2b). Larger differences in soil temperature between the entrance and the centre had been obtained in a 1.5 m high tunnel, where its value greatly exceeded the maximum for the normal growth and development of sweet pepper [Mydlarz et al. 1994]. In the same climate, serious problems have been observed with the flowering and small fruits falling down in the centre of the tunnel.

In the case of the autumn aftercrop, heavier lettuce heads tended to be produced in the central and western zones of the high tunnel (Tab. 12). The yield obtained in the eastern zone was 15% lower than in the other ones. The most important meaning of this fact was connected with the shorter days and worse lighting in that zone. In addition, soil temperature in that zone was lower (mean by 0.7°C, maximum by 1.5°C, minimum by 0.1°C) than in the centre (Fig. 2c).

The quality of butterhead lettuce, as indicated by dry matter and total sugar content, was higher in the spring (Tab. 13). By contrast, the yield was higher in the autumn. This confirms that the crucial influence on the basic products of photosynthesis is exerted by solar radiation. The levels of dry matter and total sugars were similar to those in other experiments with spring cultivation under direct covers of butterhead lettuce [Siwek et al. 2012] and cucumber [Zawiska and Siwek 2014] in the same climatic conditions.

CONCLUSIONS

Microclimatic conditions in the STN 070 plastic tunnel depended significantly on the weather. In the hours before and after midday, the differences were greater on the cloudy day. No significant differences were observed between the zones of the tunnel for individual parameters, especially on the sunny day.

Higher temperature in the centre of the tunnel was conducive to obtaining greater yields of spring lettuce and cucumbers.

In the spring and summer periods, the amounts of dry matter and total sugars in the edible parts of the cultivated vegetables were higher in the eastern and central zones of the tunnel. In the autumn, with less solar radiation, the amount of sugars in lettuce leaves was greater in the western zone.

Physical parameters of the soil depended significantly on the crop rotation used in the tunnel (lettuce–cucumber–lettuce). Soil bulk density increased significantly after cucumber cultivation. During vegetative growth, soil water capacity decreased, while water stability of soil aggregates increased, as expressed by the overall index of soil structure resistance to water. During vegetative growth, the proportion of water-stable macroaggregates with diameters 5.0–2.5 mm also significantly increased, while the amount of microaggregates with a particle size of 1.0–0.50 mm decreased.

Sampling location in the tunnel was found to have an influence (zonal effect) on some soil physical parameters (bulk density, water capacity, and water-stability index of the soil structure).

The study demonstrated a systematic decrease in the amounts of available phosphorus, potassium and magnesium in the soil during the lettuce–cucumber–lettuce crop rotation in the plastic tunnel.

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