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The effect of drip irrigation for potatoes on soil nitrogen dynamics

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Abstract: The effects of potato drip irrigation on soil nitrogen dynamics and potato yield was studied in small-plot field trials. The trials were evaluated during three experimental times (2016–2018). Four variants of irrigation were determined, i.e. non-irrigated, 60, 65 and 70 ASWC (available soil water capacity). At the same time, two pre-planting fertilisation dates were set at a maximum of 120 kg N/ha a in divided, i.e. 60 kg N/ha before planting and 60 kg N/ha by fertigation during vegetation. Pre-planting crop fertilisation or in-season fertigation did not have any significant effect on the potato yields of most variants. In all studied parameters, the positive, beneficial effect of irrigation was recorded and compared to the non-irrigated control. The mitigation of drought stress in plants during the growing season is the most important advantage of irrigation. In the trials, on average, across all years and cultivars, the yield of the irrigated variant increased by 41% compared to the non-irrigated variant. Maintaining optimal soil moisture has a favourable effect use of applied fertilisers. The highest mineral nitrogen content in the soil was recorded for the variant without irrigation. Considering the increased use of nitrogen fertilisers, the subsurface drip line appeared optimal for creating suitable conditions for nitrogen availability to plants in the root zone.

Keywords: *Solanum tuberosum* L.; irrigation frequency; split application; C/N ratio

Water and nitrogen (N) are key factors in potato production management (Li et al. 2016). Potato is a shallow-rooted crop that responds negatively to variations in water supply (Shock et al. 2007). In recent years, the traditional potato production region in the Czech Republic has also suffered from a lack of soil moisture. Determining the optimal water and/or fertiliser rate affects the benefit of artificial irrigation. Drip irrigation is used for maximum water savings. Water is directly supplied to every plant in the amount the plant needs. Under the conditions of the potato production region, the water rate at the level of 65 ASWC (available soil water capacity) seems to be optimal. The importance and quality of qualified irrigation management have become an important condition for potato growth in the Czech Republic (Slavík 2010). Sanford (2006) stated that with an irrigation regime, energy consumption could be reduced per yield unit, depending on the crop. To date, with small exceptions, potatoes have been grown without the use of irrigation in the potato production region. Zavadil et al. (2006) state that potatoes suffer from water stress in periods with soil moisture deficits and are highly sensitive to stress. Due to high demands for water, potatoes are ranked among crops with a positive response to irrigation. Li et al.

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(2016) referred to water and nitrogen as key factors in potato production management. Supplemental irrigation during the growing season can increase nutrient (especially nitrogen) utilisation by potato plants, reducing nitrate leaching into lower soil layers. Optimal management of nitrogen and irrigation is important to improve N uptake efficiency and minimise N losses while maintaining high yields and quality (Alva 2004). The synchronisation of N fertiliser applications, N soil availability and N uptake by potatoes is highly challenging considering the short cycle of potato growing and irregular precipitation (Stanley and Toor 2010). Water management has an impact on the transformation of nitrogen sources applied to the soil and nitrate transport to the soil. Nitrogen leached below the root zone is probably less available to plants, and therefore, improved irrigation procedures and controlled fertiliser rates have substantial benefits for maximal N use (Scholberg et al. 2013). Nitrate leaching below the root zone causes economic loss and contributes to groundwater pollution without a point source. Based on Alva et al. (2006), nitrogen optimisation at irrigation and managing the irrigation water rate is an important step in supporting net yields with simultaneous minimisation of groundwater pollution. Fertigation could be used as part of irrigation regimes, whereas fertiliser could be applied to the irrigation water rate. Papadopoulos (1988) states that a fertigation is a prospective tool for soil nitrogen concentration maintenance at the required level for the whole growing period without excessive loss due to leaching. Based on Rolbecki et al. (2015), fertigation through drip irrigation increases potato yield by up to 5.9 t/ha (25%). The irrigation efficiency increased from 171 kg/ha/mm to 284 kg/ha/mm compared to the irrigation + broadcast nitrogen application and drip irrigation + fertigation. Badr et al. (2011) analysed soil samples at the end of fertigation. A substantial effect of the fertigation frequency was indicated on the NO_3-N distribution in the potato root zone. NO_3-N in the lower soil profiles (40–60 cm) with a high nitrogen rate was marginally affected by everyday, alternative day and weekly fertigation, while NO_3-N in the corresponding soil depth was significantly higher in the two-week fertigation. Frequent fertigation is necessary for reaching maximum potato yield in sandy soil with reduced nitrate leaching from the root zone. The combined analysis results showed a significant effect of nitrogen and the nitrogen × irrigation frequency interaction on yield ability and water use efficiency.

MATERIAL AND METHODS

Experimental site. The field trials were established at the experimental area of the Potato Research Institute at Valečov, Czech Republic (GPS 49.6371179; 15.4857121) during the 2016 through 2018 rowing seasons. The experimental field is situated at the amplitude of 460 m a.s.l. The experimental plots were established in the form of random blocks of size 9.3 × 2.25 m (three lines). The soil on the experimental plot was loamy with fractions of 45.6% sand, 37.3% silt and 17.1% clay; the soil type is cambisol. The application of nitrogen in mineral fertiliser (urea 46% N) was carried out manually according to the trial variants. Based on the results of the agrochemical analysis of the soil, K was further applied at a dose of 99.6 kg K/ha and Mg at a dose of 24 kg Mg/ha. These nutrients were supplied in the mineral fertiliser Patentkali (24.5% K, 6.0% Mg). The fertiliser was applied uniformly to the test area with a mineral fertiliser spreader. The experiments were based on conventional technology. Each year, weed protection was carried out by applying herbicide with the active substances metribuzin and flufenacet 15–20 days after planting. Protection against fungal diseases was carried out every year on the basis of a negative forecast for the occurrence of potato late blight, the course of the weather and the infectious pressure of fungal diseases. Fungicides based on the active substances metalaxyl, mandipropamide, difenoconazole, cyazofamide, fluopicolide, and propamocarb hydrochloride were used. In 2016, 7 applications were made, and in 2017 and 2018, 5 applications of fungicides. One insecticide intervention was carried out each year against the Colorado potato beetle. The application time ranged from the second to the third decade of June, based on reaching the pest's harmfulness threshold. An insecticide with the active substance thiacloprid was used. The monthly precipitation and average temperature progress during the growing

Table 1. Mean monthly air temperatures (°C) during the growing season at the locality Valečov

Month	Normal	2016	2017	2018
April	7.7	7.6	6.8	12.9
May	11.9	13.6	14.3	16.6
June	15.5	17.4	18.3	17.4
July	16.8	18.8	18.7	19.7
August	16.7	17.1	19.1	21.1
September	12.5	15.8	11.5	14.3

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Table 2. Monthly sums of precipitation during the growing season at the locality Valečov

Month	Normal	Precipitation (mm)	Number of rainy days			
			below 2	2–5	above 5	total number of rainy days
2016						
April	41.5	31.9	6	3	2	11
May	77.9	49.8	6	2	4	12
June	89.6	71.4	3	4	5	12
July	85.3	105.0	3	1	8	12
August	88.8	27.3	3	4	1	8
September	49.7	12.0	2	1	1	4
2017						
April	41.5	116.1	5	6	7	18
May	77.9	81.4	1	4	6	11
June	89.6	104.5	3	6	3	12
July	85.3	104.1	7	2	6	15
August	88.8	35.4	4	3	1	8
September	49.7	77.7	3	5	4	12
2018						
April	41.5	28.2	1	3	2	6
May	77.9	56.7	2	4	3	9
June	89.6	95.8	2	3	6	11
July	85.3	29.3	3	1	2	6
August	88.8	24.5	2	4	2	8
September	49.7	75.9	2	5	3	10

period in individual years are listed in Tables 1 and 2. Two potato cultivars differing in their growing season durations (very early cv. Monika and medium-early cv. Jolana) were used for experiments. For irrigation, a single-use irrigation hose Streamline 16060 (Netafim, Hatzerim, Tel Aviv, Israel) with a spacing between drippers 0.5 m and a flow rate of 1.05 L/ha was used. After planting potatoes, the pipe was buried at a 30–50 mm depth under the ridge surface. Four variants were established for both cultivars with varying irrigation regimes (Table 3). The irrigation would be started at specified levels of available soil water capacity, i.e. non-irrigated, 60 ASWC, 65 ASWC and 70 ASWC. Under given soil conditions, these values represent 15, 20, and 25% of the volume of soil moisture. The specific moisture at which the irrigation would automatically start was calculated from the available values for water capacity and wilting point based on

Table 3. Trial variants

Variant	Irrigation regime	N rate (kg/ha)	Date of nitrogen application
1	no irrigation	120	pre-planting
2	irrigation from 15% soil moisture	120	
3	irrigation from 20% soil moisture	120	
4	irrigation from 25% soil moisture	120	
5	no irrigation	60 + 60	split application*
6	irrigation from 15% soil moisture	60 + 60	
7	irrigation from 20% soil moisture	60 + 60	
8	irrigation from 25% soil moisture	60 + 60	

*split application prior to planting and through fertigation during the growing season

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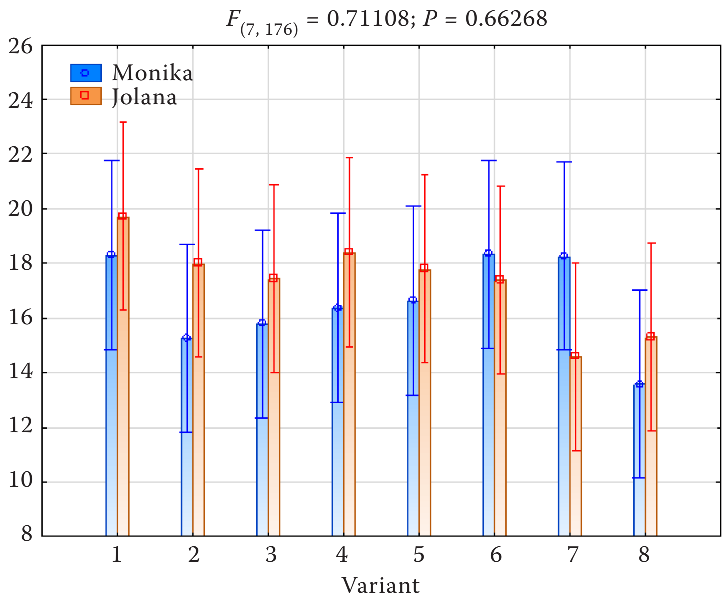

Figure 1. The effect of a trial variant on marketable potato yield (t/ha)

the soil adsorption water capacity determination. The irrigation rate corresponded to 10 mm water/day.

Soil samples were taken in the first decade of July (after the start of irrigation), in the first decade of August (during the period of full irrigation) and after the harvest of the experiment. Mineral nitrogen was determined by the sum of nitrate nitrogen (determined by an ion-selective electrode) and ammonia nitrogen (spectrophotometrically determined by ISO 14 256).

The terminal leaflet from the last fully developed leaf was collected at the potato flowering stage (BBCH 60–61). Plant material was immediately dried and ground into a fine powder with a vibratory micro mill (Pulverisette 0, Fritsch, Weimar, Germany). The content of carbon (C) and nitrogen (N) elements in potato leaf was determined with elemental analyser Vario PYRO Cube (Elementar, Langenselbold, Germany) coupled to isotope mass spectrometer Isoprime precisION (Elementar, Stockport, UK).

The data were processed in the statistical software Statistika.cz (Prague, Czech Republic) using variance analysis (ANOVA) and Tukey's test.

RESULTS AND DISCUSSION

Potato yield. Statistically significant differences were recorded for potato yields within cultivars

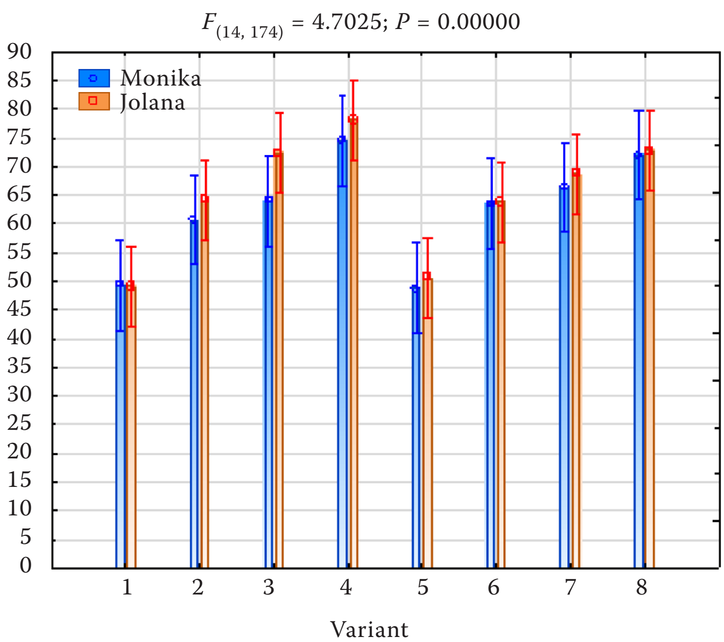

Figure 2. The effect of a trial variant on potato yield (t/ha)

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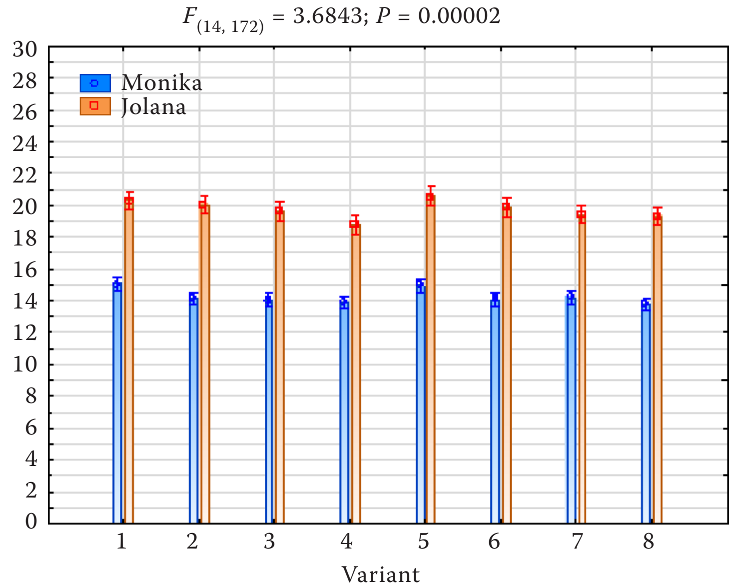

Figure 3. The effect of the trial variant on the starch content of the tubers (%)

in the variant with the highest irrigation rate. The yields from the variant with the highest irrigation rate (from 25% soil moisture) were increased by 41% on average across years and varieties compared to the non-irrigated control. Pre-planting crop fertilisation or in-season fertigation did not have any significant effect on the potato yields of most variants. Only variants with the same irrigation intensity were compared. A statistically significant difference was only found for the lowest irrigation rate in the cv. Jolana. In three years, irrigation also increased the yielding ability of marketable potatoes for both cultivars (Figure 1). Starch yield per hectare was also increased. Trends were similar to potato yield (Figure 2). The amount of irrigation water also affected the starch content (Figure 3) and the starch yield (Figure 4) in the tubers. Statistically, the highest starch content was recorded for non-irrigated variants, especially for the variant with a divided dose of nitrogen mineral fertiliser. Due to high tuber yields, the total starch yield was the highest on irrigated variants. Any substantial effect of irrigation was not recorded for other potato quality parameters. These effects were approximate twice those under furrow irrigation, indicating that the employment of a drip irrigation method can effectively address water shortage and sustainable potato production (Mubarak et al. 2018). The effect of the use of irrigation depends to a considerable extent on the course of the weather during the vegetation, especially the air temperature and the amount of precipitation. Of the three monitored years, the yield of tubers

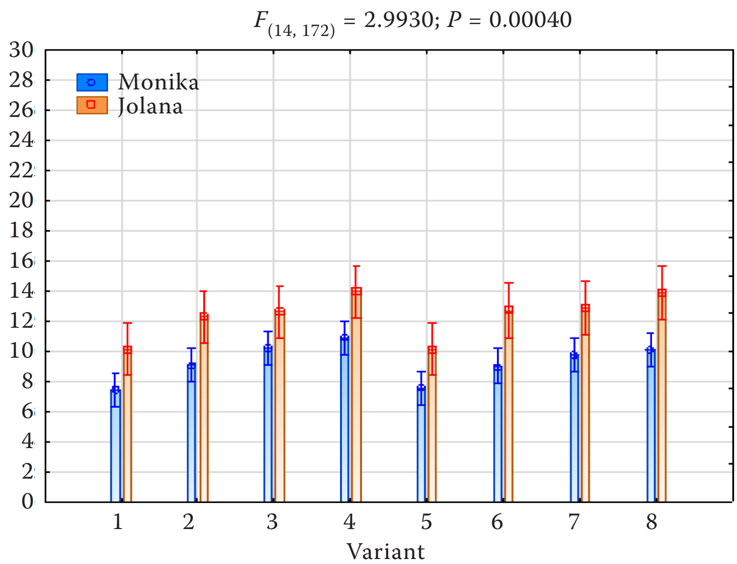

Figure 4. The effect of the trial variant on starch yield (t/ha)

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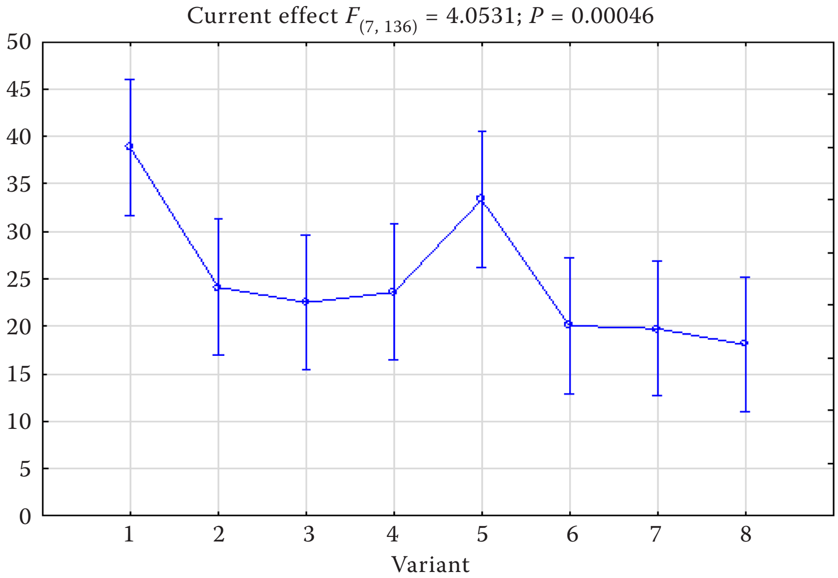

Figure 5. The effect of a trial variant on mineral nitrogen content in soil (mg/kg) – cultivar average

was most significantly affected by drip irrigation in the year with the driest growing season, 2018. In the experimental location, the long-term average total precipitation for the growing season (April–September) is 427 mm (Table 2). In 2018, a total of 335 mm of precipitation for vegetation was measured in this locality, of which 84 mm was in September, when these precipitations were no longer of essential importance for the development of potato stands and production of yield.

Nitrogen content in the soil. From the determination of the soil nitrogen content, we can conclude that the highest mineral nitrogen content was detected in the variants without irrigation (Figure 5). More significant differences were determined for the cv. Monika, especially in the non-irrigated variant, where the mineral N rate (120 kg N/ha urea) was applied before planting. The highest nitrogen content was recorded for cv. Monika (Figure 6) in the non-irrigated variant on the first sampling date (beginning of flowering, BBCH 60, Hack et al. 1993). On the second sampling date (end of flowering, BBCH 69, Hack et al. 1993), the highest content was again found in the non-irrigated variant. A similar situation was also identified for the cv. Jolana (Figure 7), however, higher nitrogen content was determined in non-irrigated variants. For cv. Jolana, particularly low residual N levels, were recorded at harvest. For cv. Monika, these low contents were only found in the variants with split nitrogen application, and doubled contents were determined in the other variants. The non-irrigated variant residual N content was 52 mg/kg

Comparing both potato cultivars, we can conclude that higher nitrogen uptake was found for cv. Jolana (medium-early cultivar) and that nitrogen use were supported by irrigation. Darwish et al. (2003) confirm that whereas N leaching occurs in micro-sprinkler irrigation, in the case of drip irrigation, nitrogen remains in the plant (potato) root zone. Janat (2007) confirms that furrow irrigation resulted in greater

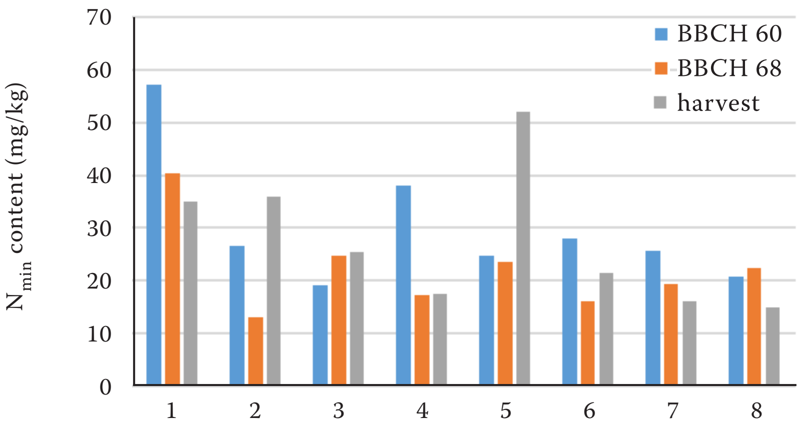

Figure 6. The effect of field trial variants with drip irrigation on soil mineral nitrogen (N_{min}) content (mg/kg) – the cv. Monika 2016–2018

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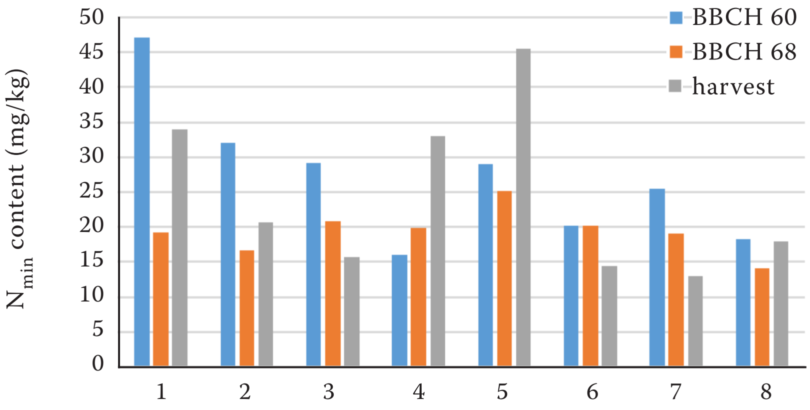

Figure 7. The effect of field trial variants with drip irrigation on soil mineral nitrogen (N_{min}) content (mg/kg) – the cv. Jolana 2016–2018

movements of NO_3-N below the root zone compared to drip irrigation. This is also confirmed by Zhou et al. (2018). Based on Köhling (2007), irrigation connected with fertilisation enables an optimal nutrient and water supply that ensures effective nitrogen use by plants. The effect of fertigation was also studied in the trials by Feng et al. (2017), Trifonov et al. (2018), and Jolaini and Karimi (2017). These authors concluded that the optimal application of a lower fertiliser amount into the active root zone combined with a controlled water regime resulted in a higher yield and improved tuber quality. Simultaneously, an interaction effect between these two parameters does not occur, and the efficacy of source utilisation is maximised Zotarelli et al. (2014). Observed characteristics considering the effect of irrigation on potato yields and quality agree with data from the literature. Irrigation combined with fertigation seems to be optimal for promoting nutrient use by plants.

Carbon and nitrogen in leaves. In all variants of N and C/N (Figure 8A, C), there was a significant difference between the two tested cultivars. The cv. Jolana had a higher N content and C/N ratio in all ASWC variants compared to the cv. Monika. The carbon content in the leaves of the cv. Jolana was not significantly different from cv. Monika in irrigated variants. The cv. Jolana had a difference in C content only for control plants versus irrigated variants; the carbon content decreased significantly with increasing ASWC.

Cv. Jolana sequestrated significantly more nitrogen than cv. Monika and the nitrogen content decreased with increasing available water capacity of the soil (Figure 7A). The cv. Monika had 3% nitrogen in the dry matter and the nitrogen content of the cv. Jolana was constant across different water contents in the soil. Both cultivars were fertilised with equal amounts of nitrogen.

The C/N ratio (Figure 8C) was significantly different for both cultivars in all irrigation treatments. The higher C/N ratios of 15–17 were found for cv. Monika and the C/N ratio were more or less constant during the ASWC increase. Cv. Jolana had a C/N ratio of 11.5 to 14, and the ratio increased significantly from the controls to the irrigated variants; the trend was the same for both cultivars.

Changes in carbon content between the control and irrigated treatments were 5% of the difference. This difference was approximately four times less than leaf nitrogen's (21% difference).

The effect of low N availability with severe droughts on physiological and morphological characteristics through negative impacts on plant growth is important because of the potato crop's small and shallow root system. As a very early cultivar, Monika had less nitrogen in the leaves than the medium-early cv. Jolana (Figure 8A). Our findings are consistent with Iwama (2008). Early cultivars are associated with low N uptake and N use efficiency (NUE). Van Delden (2001) reported differences in sensitivity to N fertilisation between the early and late potato cvs. Junior (early) and Agria (late). The early cultivar had less nitrogen content in the plant, which agrees with our findings (Figure 8A).

Potato yield is more likely to be source-limited than sink-limited during the tuber bulking stage. Li et al. (2016) showed that water level, nitrogen level and the water and nitrogen interaction affected potato yield mainly by affecting source capacity. The water shortage influenced the opening of stomata through the net photosynthetic rate, total leaf area and life span. Sufficient nitrogen supply and well-watered conditions combined with sufficient nitrogen

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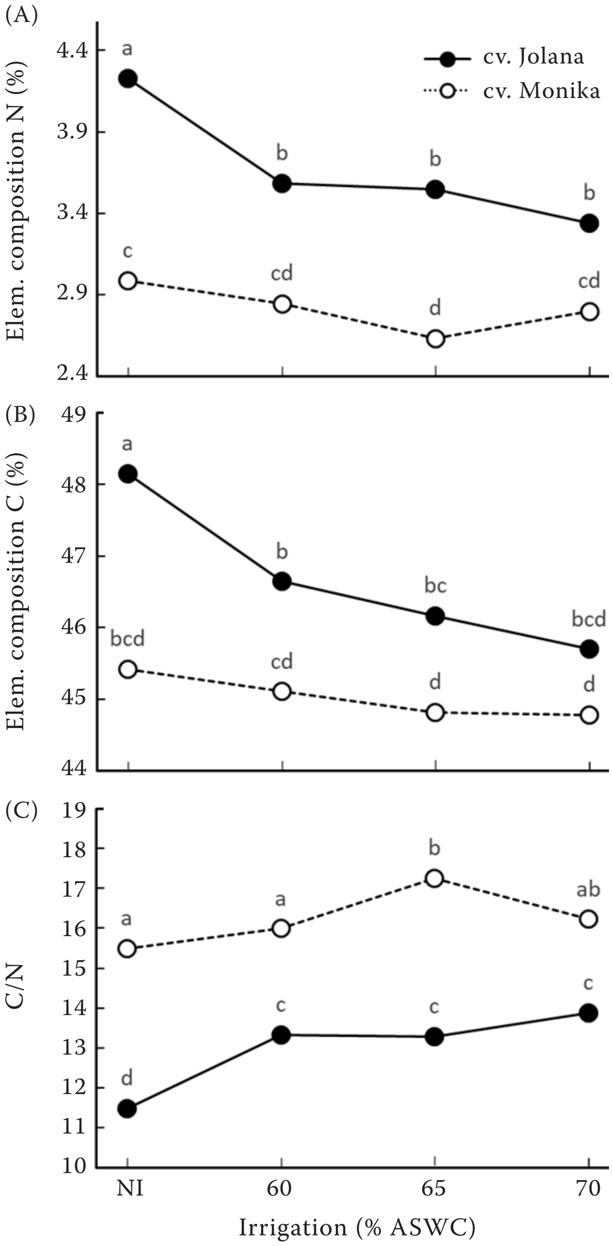

Figure 8. The relationship between elemental composition (A) nitrogen (N); (B) carbon (C); (C) C/N and soil moisture was maintained at a certain percentage of available soil water capacity (ASWC) by irrigation. The data represents the average of three years of four repetitions each year at Valečov Experimental Station. The same letters mean a homogenous group on α = 0.05 of the least significant difference (*LSD*) test by ANOVA analysis. NI – not irrigated

treatments increased yield mainly by enhancing the source capacity.

In comparison to a cv. Monika, the lowest C/N ratio of cv. Jolana was caused mainly by better uptake of nitrogen (Figure 8A) than by irrigation (Figure 8C). These findings are consistent with Sun et al. (2013) and Zheng et al. (2018), who found that the C/N ratio in the plants was not affected by irrigation regimes but was significantly influenced by N-fertilisation treatment.

From the results (Zheng et al. 2018) on the C/N ratio and tuber formation varying under different conditions of CO_2 or nitrogen supply, it can be concluded that the potato plant C/N ratio can be manipulated by adjusting the environmental CO_2 and the concentration of N or N supply. A higher C/N ratio in plants improves tuber formation.

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