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Root-growth Characteristics Contributing to Nitrogen Efficiency of Reciprocally Grafted Potatoes (*Solanum tuberosum* L.) Under Hyroponic Conditions

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Abstract
To assess whether grafting could improve the nitrogen (N) efficiency of potato cultivars and to determine which physiological and morphological characteristics are predominantly contributing to N efficiency, a hydroponic experiment was conducted. Two contrasting potato cultivars (Agria: N-efficient and Van Gogh: N-inefficient) were grafted reciprocally onto each other. Grafted and non-grafted control plants were grown in a growth chamber for 42 days in 8 L pots filled with continuously aerated nutrient solution under two N rates (Low-N : 0.5 mM N and High-N : 3.0 mM N) by using a deep water culture (DWC) technique. The shoot and root fresh (FW) and dry (DW) weights, main stem length, number of leaves, total leaf area, photosynthetic activity of leaves, shoot and root N concentration, total N uptake, total root length and root volume of potato plants were significantly increased with increased N rate. The grafted plants produced significantly higher above ground biomass than non-grafted ones, indicating that N efficiency was significantly improved by the reciprocally grafting under low and high N rates. Non-grafted cv. Agria showed higher numbers of shoot and root FW and DW, total leaf area, intensity of photosynthesis net measurements, compared to non-grafted cv. Van Gogh under both N rates. In reciprocal grafting, the growth performance of cv. Agria slightly increased when it was grafted onto cv. Van Gogh, whereas a significant increase in crop growth performance was recorded when cv. Van Gogh was grafted onto cv. Agria. The N efficiency of non-grafted cv. Agria was closely associated with its vigorous root growth and active root system under both N conditions. Same root morphological characteristic could not be exhibited by the N-inefficient cv. Van Gogh. Our study suggested that root morphological characteristics are contributing more than shoot characteristics to N efficiency of potatoes. These traits could be useful characters to breed/select N-efficient potato rootstocks for sustainable agriculture in the future.

Keywords Grafting · N efficiency · Potato · Root morphology · Solanum tuberosum

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Wurzelwachstumseigenschaften, die zur Stickstoffeffizienz von wechselseitig gepfropften Kartoffeln (*Solanum tuberosum* L.) unter hyroponischen Bedingungen beitragen

Zusammenfassung

Um zu beurteilen, ob das Pfropfen die Stickstoff(N)-Effizienz von Kartoffelsorten verbessern könnte und um zu bestimmen, welche physiologischen und morphologischen Merkmale vorwiegend zur N-Effizienz beitragen, wurde ein hydroponisches Experiment durchgeführt. Zwei unterschiedliche Kartoffelsorten (Agria: N-effizient und Van Gogh: N-ineffizient) wurden wechselseitig aufeinander gepfropft. Gepfropfte und nicht gepfropfte Kontrollpflanzen wurden 42 Tage lang in einer Wachstumskammer in 8-Liter-Töpfen, die mit kontinuierlich belüfteter Nährlösung gefüllt waren, unter zwei N-Raten (niedrig: 0,5 mM N; hoch: 3,0 mM N) mithilfe einer Tiefwasserkultur angebaut. Die Frischgewichte (FW) und Trockengewichte (DW) von Spross und Wurzel, die Länge des Hauptstamms, die Anzahl der Blätter, die gesamte Blattfläche, die photosynthetische Aktivität der Blätter, die N-Konzentration von Spross und Wurzel, die gesamte N-Aufnahme, die gesamte Wurzellänge und das Wurzelvolumen der Kartoffelpflanzen nahmen mit steigender N-Rate signifikant zu. Die gepfropften Pflanzen produzierten signifikant mehr oberirdische Biomasse als die nicht gepfropften, was darauf hindeutet, dass die N-Effizienz durch die gegenseitige Pfropfung bei niedrigen und hohen N-Raten signifikant verbessert wurde. Die nicht gepfropfte Agria zeigte höhere Werte bzgl. Spross- und Wurzel-FW und -DW, Gesamtblattfläche, Intensität der Photosynthese-Nettomessungen, verglichen mit der nicht gepfropften Van Gogh unter beiden N-Raten. Bei gegenseitiger Pfropfung stieg die Wachstumsleistung von Agria leicht, wenn sie auf Van Gogh gepfropft wurde, während ein signifikanter Anstieg der Wachstumsleistung zu verzeichnen war, wenn Van Gogh auf Agria gepfropft wurde. Die N-Effizienz der nicht gepfropften Agria war unter beiden N-Bedingungen eng mit ihrem kräftigen Wurzelwachstum und ihrem aktiven Wurzelsystem verbunden. Die gleiche wurzelmorphologische Charakteristik konnte bei der N-ineffizienten Van Gogh nicht gezeigt werden. Unsere Studie deutet darauf hin, dass wurzelmorphologische Merkmale mehr zur N-Effizienz von Kartoffeln beitragen als Sprossmerkmale. Diese Eigenschaften könnten nützlich für die Züchtung/Selektion von N-effizienten Kartoffelwurzelstöcken für eine nachhaltige Landwirtschaft in der Zukunft sein.

Schlüsselwörter Pfropfung · N-Effizienz · Kartoffeln · Wurzelmorphologie · Solanum tuberosum

Introduction

Potato (*Solanum tuberosum* L.) is a crop of great economic importance and number one non-grain food commodity (Rykaczewska 2013). It is the third most important consumed food crop in the world after rice and wheat (Hielke et al. 2011; Birch et al. 2012), with a global cultivation exceeding 19.34 million hectare of land in more than 158 countries with an estimated annual production of 376 million tons (FAOSTAT 2018).

Potato is one of human kind's most valuable food crops and it is a major part of the diets of more than a billion consumers worldwide (Mondal 2003). It is regarded as high potential food security crop because of its ability to provide a high yield of high-quality product per unit input with a shorter crop cycle (mostly <120 days) than major cereal crops such as, maize (Adane et al. 2010).

Nitrogen (N) is the most limiting nutrient in crop production and is higher in concentration than all other mineral nutrients in most plants (Foth and Ellis 1996). It makes up 1 to 4% of dry matter of the plant. Nitrogen is taken up from the soil in the form of nitrate (NO_3^-) or ammonium (NH_4^+). In the plant N combines with compounds produced by carbohydrate metabolism to form amino acids and proteins. Being the essential constituent of proteins, it is involved in all the major processes of plant development and yield formation. A good supply of nitrogen stimulates root growth and development as well as the uptake of other nutrients (Brady and Weil 2002). Plants obtain readily available N forms from different sources.

N availability can affect both of physiological processes and morphological traits of potato crop including the rate of canopy development, the rate of leaf appearance, the rate of individual leaf growth, final leaf size, the life span of individual leaf, the integral of light interception by the crop over time, the rate of photosynthesis, the number of lower and sympodial branches, the onset of tuberization, final tuber yield-quality and final harvest index (Tiemens-Hulscher et al. 2007). Potato is sensitive both to N deficiencies and excesses. Under excessive N, growth causes increased development of stem and leaves rather than in tuber production, delayed crop maturity, declined tuber yield and quality and can result in the need for higher rates of defoliant chemicals before harvest. Conversely, N deficiency may occur stunted growth due to inhibition of cell division and cell enlargement, decrease in respiration rate (photosynthesis), postponed tasselling, premature growth and significant decrease in yield and quality of the crop and reduction in tuber growth (Harris 1992). Therefore, current study was conducted with the objective of determine shoot

and root characters that play important role in N efficiency by reciprocal grafting of two potato cultivars. In previous screening experiment, two potato cultivars were characterized differently as N-efficient (Agria) and N-inefficient (Van Gogh) based on various growth and development parameters. However, N efficiency characters of these cultivars were not clearly known whether these characters are controlling and relating directly with shoot or root traits. Therefore, the aim of the study was to assess whether grafting could improve the nitrogen (N) efficiency of potato cultivars and to determine which physiological and morphological characteristics are predominantly contributing to N efficiency.

Materials and Methods

Experimental Set-up

Two different potato cultivars (Agria (N-efficient) and Van Gogh (N-inefficient)) were used as plant materials in this study. Potato plants were grown as non-grafted plants, and reciprocally-grafted plants. All of the plants were planted in a peat-perlite growth medium, in a climate chamber conditions at the Faculty of Agriculture, Erciyes University, Kayseri, Turkey. For the vegetation period, the average day/night temperatures were 25/22 °C, the relative humidity was 60–80%. The supplied photon flux in the growth chamber was almost 350 µmol m^{-2} S^{-1} with an intensity of 16/8 h (light/dark) photoperiod. To produce homogenous plantlets for grafting process, tubers of potato cultivars were precultured in a peat-perlite growth medium. Thereafter, homogenously produced potato plantlets were carefully cut and freed from the tubers with no root damage and then grafted with each other as a reciprocal. The non-grafted plantlets were used as control plants. Grafted plants were transplanted to plastic pots for six weeks, after roots were washed. Each pot was filled with 8 L Hoagland solution that was aerated by an air pump. Due to transplanting small seedlings, the solutions were changed completely in the first two weeks and subsequently every 7th day.

Between complete renewals of the nutrient solution (7 days' intervals) all nutrients were replaced when the N concentration of the nutrient solution in the 3.0 mM N rate pots fell below 0.5 mM, as measured daily with nitrate test strips (Merck, Darmstadt, Germany) by using a NitracheckTM reflectometer. Two different nitrogen concentrations (Low *N*: 0.5 mM N, High *N*: 3.0 mM N) was supplied and $Ca(NO_3)_2$ was used as N source. The nutrient solution had the following composition (µM): K_2SO_4 (500); KH_2PO_4 (250); $CaSO_4$ (1000); $MgSO_4$ (325); NaCl (50); H_3BO_3 (8); $MnSO_4$ (0.4); $ZnSO_4$ (0.4); $CuSO_4$ (0.4); $MoNa_2O_4$ (0.4); Fe-EDDHA (80). A randomized complete block design was used with three replicates for four grafting combinations (non-grafted: Agria and Van Gogh; Agria/Van Gogh or Van Gogh/Agria), each of them consisting of 6 plants.

Shoot and Root Fresh and Dry Weight and Main Stem Length Measurements

Shoot and root were fractioned into the leaf, stem and roots for the fresh weight determination. And then, samples were stored separately in paper bags and dried in a ventilated oven at 74 °C for 72 h. Root to shoot ratio was calculated by dividing the root dry weight by sum of leaf and stem dry weights. Main stem length (cm) was measured by using a ruler.

Total Leaf Number and Leaf Physiological Measurements

Each fully developed leaf was counted and recorded as LN/plant. The total leaf area (cm^2) of the plants was measured with a leaf area measuring device LI-COR (LI-COR Model 3100, LI-COR. Inc., Lincoln, NE, USA). The measurements were carried out at the temperature of 25/22 °C (average day/night temperatures), the relative humidity of 60–80%. The supplied photon flux in the growth chamber was almost 350 µmol m^{-2} S^{-1} with an intensity of 16/8 h (light/dark) photoperiod. Prior to harvest, non-destructive measurements of the leaf-level CO_2 gas exchange (µmol CO2 m^{-2} s^{-1}) were done in controlled growth chamber by using a portable photosynthesis system (LI-6400XT; LI-COR Inc., Lincoln, NE, USA) on the youngest fully expanded leaves. Gas exchange in the leaves was performed on the youngest fully expanded leaves, using four replicate leaves per treatment in the third and fifth weeks of the growth period.

Root Morphological Measurements

The plant root morphological parameters such as total root length (m), total root volume (cm^3) and average root diameter (mm) were measured by using a special image analysis software program WinRHIZO (Win/Mac RHIZO Pro V. 2002c Regent Instruments Inc., Québec, QC G1V 1V4, Canada) in combination with recording device of Epson Expression 11000XL scanner (Long Beach, CA, USA).

Shoot and Root Nitrogen Analysis

After grinding shoot (leaf) and root dry materials, almost 200 mg from each dry plant samples were taken to analyze the shoot and root N concentration by using Kjeldahl Nitrogen Determination Method, introduced by Johan Kjeldahl

in 1883 (Labconco 1998). After determination of shoot and root N concentration, the value was multiplied by total shoot and root dry matter in order to calculate the total shoot and root N content (N uptake) of a whole plant (mg N/plant).

Statistical Analysis

All measured biomasses and other morphological plant parameters were analyzed based on the correlations between the reciprocal graft combinations at different N treatments. Analysis of variance (ANOVA) was performed using the SAS program (SAS Institute, Cary NC, USA). If ANOVA determined that the effects of the treatments were significant ($P < 0.05$ for F-test), then the treatment means were separated by Duncan's Multiple Range Test.

Results and Discussion

Biomass Production and Partitioning

The grafted and non-grafted plants under high N supply produced higher shoot and root fresh and dry weights, main stem length and root:shoot ratio than plants under low N supply (Tables 1 and 2). The shoot and root fresh and dry matter, main stem length and root:shoot ratio were significantly ($P < 0.001$) affected by N rate. Regardless of graft combinations, plants under high N supply displayed generally an improved performance in shoot and root growth, main stem length and root:shoot ratio than plants grown under low N supply. Increasing N supply increased the shoot fresh matter by almost 117.9%, root fresh matter 27%, main stem length 46.4%, shoot dry matter by almost 68.5%, root dry matter by almost 22.5% at high N condition. The significantly highest shoot dry matter was shown by Agria while the lowest was shown by Van Gogh at low N supply. These results clearly indicate that Agria can be characterized as 'N-efficient' due to realizing an above-average yield (shoot dry biomass) under suboptimal (low) N supply (Graham 1984). Based on this reference, the lowest shoot dry biomass yielding Van Gogh can be characterized as 'N-inefficient'. The highest root dry matter, total root length and total root volume was shown by the 'N efficient' characterized Agria, while the lowest was shown by the 'N-inefficient' characterized Van Gogh at low N supply. Furthermore, Van Gogh showed significantly lowest root dry biomass yield, root:shoot ratio, total root length and total root volume as compared to Agria at low and high N rates. Similar results also observed by Ulas et al. (2019) at watermelon plants. He observed that plants grown under high N supply (3.0 mM N) produced significantly highest shoot dry matter than plants grown under low N supply (0.3 mM N). In spite of Ulas et al. (2019) results, a significant increase of root fresh matter of grafted and non-grafted plants was found under high N supply. This might be due to capability of the rootstock, since the gourd rootstocks has a strong and vigorous root system as compare to the potato plants used as a rootstock in this study. Comparable and corroborative results have been also reported by Adam (2018) on different tomato genotypes regarding root fresh and dry matters under high N rates (3.0 mM) than low N rates (0.3 mM).

The shoot and root fresh and dry matter, main stem length and root:shoot ratio were significantly ($P < 0.001$) affected by scion, rootstock, scion × rootstock, scion × N rate, rootstock × N rate interactions; however the shoot and root

Table 1 Shoot and root fresh weight and main stem length of non-grafted and reciprocal grafted potato cultivars (Agria and Van Gogh) grown under low (0.5 mM) and high (3.0 mM) N supply

Graft combination	Shoot fresh weight (g/plant)		Root fresh weight (g/plant)		Main stem length (cm/plant)	
(Scion/Rootstock)	Low N	High N	Low N	High N	Low N	High N
Agria	62.35 f	142.85 c	29.39 c	38.13 b	11.48 d	17.60 a
Van Gogh	51.29 g	135.00 c	20.65 e	24.67 d	9.63 e	15.55 b
Agria/Van Gogh	75.27 e	160.57 b	24.89 d	31.87 c	12.53 cd	18.18 a
Van Gogh/Agria	92.38 d	174.60 a	32.34 c	41.50 a	13.27 c	17.35 a
F-Test						
Scion	***		**		***	
R. stock	***		***		***	
N rate	***		***		***	
Scion × R. stock	***		***		***	
Scion × N rate	n. s.		n. s.		*	
R. stock × N rate	*		***		n. s.	

Values denoted by different letters are significantly different between graft combination within both columns at $P < 0.05$
ns non-significant
* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$

Table 2 Shoot and root dry weight and root:shoot ratio of non-grafted and reciprocal grafted potato cultivars (Agria and Van Gogh) grown under low (0.5 mM) and high (3.0 mM) N supply

Graft combination	Shoot dry weight (g/plant)		Root dry weight (g/plant)		Root:shoot ratio (g/g)	
(Scion/Rootstock)	Low N	High N	Low N	High N	Low N	High N
Agria	6.05 e	9.21 c	0.95 c	1.20 b	0.16 a	0.13 b
Van Gogh	4.76 f	8.56 cd	0.48 d	0.64 d	0.10 c	0.07 d
Agria/Van Gogh	6.79 e	11.13 b	1.02 c	1.08 bc	0.15 a	0.10 c
Van Gogh/Agria	8.11 d	14.43 a	1.05 c	1.38 a	0.13 b	0.10 c
F-Test						
Scion	*		***		***	
R. stock	***		***		***	
N rate	***		***		***	
Scion × R. stock	***		***		n. s.	
Scion × N rate	*		***		*	
R. stock × N rate	n. s.		***		n. s.	

Values denoted by different letters are significantly different between graft combinations within both columns at $P < 0.05$
ns non-significant
* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$

fresh matter was not significantly affected by scion × N rate interactions and main stem length also was not significantly affected by rootstock × N rate interactions. Furthermore, shoot dry matter was not significantly affected by rootstock × N rate interactions. Root:shoot ratio was not significantly affected by scion × N rate interactions. Grafting also had significantly positive effects and therefore the grafted plants showed significantly higher performance in shoot and root growth, main stem length than non-grafted plants grown at both low and high N rates (Tables 1 and 2). As compared to non-grafted plants, the grafting increased shoot fresh matter by almost 47.5% and 20.6%, shoot dry matter by almost 37.8% and 43.8%, root fresh matter by almost 14.4% and 16.8%, the root dry matter by 22.5% and 33.9%, main stem length by 22.2% and 7% at low and high N rate, respectively. These results highly verify several grafting experiments (Nawaz et al. 2017; Adam 2018; Ulas et al. 2019), examined to enhance the growth, development and the tolerance of various scions (tomato and watermelon) to low N stress conditions. Compared to non-grafted plants, Van Gogh/Agria showed the highest shoot and root fresh and dry matter production and main stem length at both low and high N rates. Conversely, Agria/Van Gogh produced highest main stem length at high N rates. This is in agreements with the finding of Ofori (2015) where he also observed that shoot biomass production was higher in grafted plants than non-grafted plants. Also, grafted plants produced large root biomass than non-grafted plants. Similar results have been also reported by Adam (2018). He observed that grafted tomato plants produced significantly higher shoot fresh and dry matter, root fresh and dry matter and main stem length than non-grafted plants under high N rates as compare to low N rates.

Total Leaf Number, Total Leaf Area and Intensity of Photosynthesis Net Measurements

The grafted and non-grafted plants under high N supply produced higher total leaf number, total leaf area and the intensity of photosynthesis net measurements than plants under low N supply (Fig. 1). Total leaf number, total leaf area and the intensity of photosynthesis net measurements were significantly ($P < 0.001$) affected by N rate. Irrespective of graft combinations, plants under high N supply displayed generally an improved performance in total leaf number, total leaf area and the intensity of photosynthesis net measurements than plants grown under low N condition. Increasing N supply increased the total leaf number by almost 24.3%, the total leaf area 98.8% and the intensity of photosynthesis net measurements 34.4% at high N condition. Ulas et al. (2019) stated that in watermelon, increasing N supply increased the total leaf area 183% and the intensity of photosynthesis net measurements 67% at high N condition. In agreement with several studies, our results obviously showed that nitrogen has a significant positive effect on shoot growth that might have subsidized to a higher leaf area formation and therefore a higher photosynthetic and enzymatic (NRA) activity of leaves (Ulas et al. 2012; 2019; Adam 2018). This is in line with research carried by Cardarelli et al. (2015) where they found that effect of nitrogen to plant have positive correspondent to leaf area development.

Total leaf number, total leaf area and the intensity of photosynthesis net measurements were significantly ($P < 0.001$) affected by scion, rootstock, scion × rootstock, scion × N rate, rootstock × N rate interactions; however total leaf number and the intensity of photosynthesis net mea-

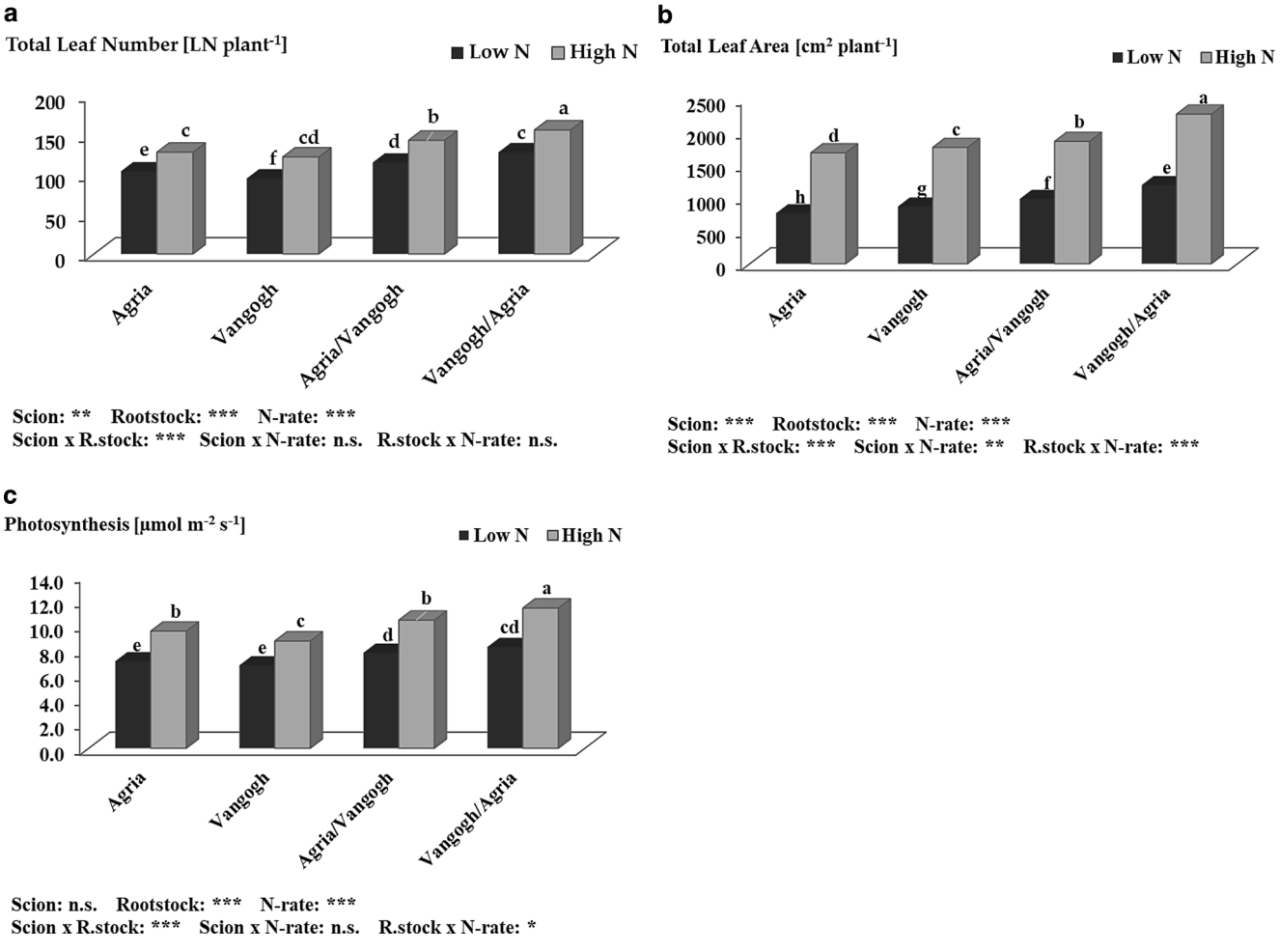


Fig. 1 Total leaf number (**a**), total leaf area (**b**) and the intensity of photosynthesis net measurements (**c**) of non-grafted and reciprocal grafted potato cultivars (Agria and Van Gogh) grown under low (0.5 mM) and high (3.0 mM) N supply. Values denoted by different letters are significantly different between graft combinations within both columns at $P < 0.05$. ns, non-significant. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$

surements were not significantly affected by scion × N rate and rootstock × N rate interactions (Fig. 1). Grafting also had significantly positive effects and therefore the grafted plants showed significantly higher performance in total leaf number, total leaf area and the intensity of photosynthesis net measurements than non-grafted plants grown at both low and high N rates. As compared to non-grafted plants, the grafting increased (maximum) the total leaf number by almost 22% and 19.5%, the total leaf area by 33.2% and 19.6%, and the intensity of photosynthesis net measurements by 15.8% and 19.5% at low and high N rate, respectively. Compared to non-grafted plants, Van Gogh/Agria showed significantly highest total leaf number, total leaf area and the intensity of photosynthesis net measurements at both low and high N rates. Ulas et al. (2019) reported that in watermelon, grafting increased the total leaf area by 78% and 336%, and the intensity of photosynthesis net measurements by 33% and 23% at low and high N rates, respectively. Similar results have been also reported at different grafting studies who examined to enhance the growth, development and the tolerance of various scions (melon, watermelon and tomato) to low N stress conditions (Colla et al. 2010; Nawaz et al. 2017; Adam 2018).

Total Root Length, Total Root Volume and Average Root Diameter

Grafted and non-grafted plants under high N supply produced higher total root length and total root volume than plants under low N supply (Table 3). Total root length, root volume and average root diameter were significantly ($P < 0.001$) affected by N rate. Regardless of graft combinations, plants under high N supply exhibited usually an improved performance in root growth and root morphological development than plants grown under low N condition. Increasing N supply increased the total root length by almost 22.8% and the total root volume 11.6% at high N condition. Irrespective of graft combinations, watermelon plants under

Table 3 Total root length, root volume and average root diameter of non-grafted and reciprocal grafted potato cultivars (Agria and Van Gogh) grown under low (0.5 mM) and high (3.0 mM) N supply

Graft Combination	Total root length (m/plant)		Total root volume (cm^3/plant)		Av. root diameter (mm)	
(Scion/Rootstock)	Low N	High N	Low N	High N	Low N	High N
Agria	211.2 de	283.4 b	11.21 b	14.43 a	0.263 cd	0.253 e
Van Gogh	150.3 f	169.6 ef	9.25 d	9.63 cd	0.280 a	0.270 bc
Agria/Van Gogh	187.0 e	225.4 d	10.70 bc	11.87 b	0.273 ab	0.262 cd
Van Gogh/Agria	257.3 c	311.2 a	13.66 a	14.07 a	0.260 de	0.240 f
F-Test						
Scion	***		**		n. s.	
R. stock	***		***		***	
N rate	***		***		***	
Scion × R. stock	***		***		***	
Scion × N rate	***		***		**	
R. stock × N rate	***		**		n. s.	

Values denoted by different letters are significantly different between graft combinations within both columns at $P < 0.05$
ns non-significant
* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$

high N supply exhibited usually a lower root growth and root morphological development than plants grown under low N supply. Increasing N supply, reversely led to a decline in the total root length by almost 15.2% and the total root volume by almost 21.7% at high N condition (Ulas et al. 2019). This might be due to higher partitioning of dry matter to the root system under low N condition (Sattelmacher et al. 1994; Merrill et al. 2002) and an increased carbohydrate sink strength of the roots (Merrill et al. 2002). Like our study, increased root biomass and tuber yield in the potatoes were reported in response to increasing N level (Gray and Hughes 1978; Lynch and Rowberry 1997; Muleta and Aga 2019).

Total root length, root volume and average root diameter were significantly ($P < 0.001$) affected by scion, rootstock, scion × rootstock, scion × N rate, rootstock × N rate interactions; however average root diameter was not significantly affected by scion and rootstock × N rate interactions (Table 3). As compared to non-grafted plants, the grafting increased the total root length by almost 22.9% and 18.4% and the total root volume by 19.1% and 7.8% at low and high N rate, respectively. Compared to non-grafted plants, Van Gogh/Agria showed significantly highest total root length at both low and high N rates. On the other hand, non-grafted Agria produced significantly highest total root volume under high N rates. Moreover, non-grafted Van Gogh produced significantly highest average root diameter at both low and high N rates. Similar results have been also reported by Adam (2018). He observed that grafted tomato plants produced significantly higher total root length and total root volume than non-grafted tomato plants under high N rates as compare to low N rates. Djidonou (2012) also found similar results where total root length, average root diameter, root volume of grafted plants were higher than non-grafted plants and self-grafted plants. In spite of Ulas et al. (2019) results, total root length and total root volume of graft combinations were significantly ($P < 0.001$) but negatively affected by different rates of N supply. Opposite to nitrogen effects, grafting had significantly positive effects on root morphology and therefore increased (maximum) the total root length 65% and 58% and root volume 183% and 211% at low and high N rates, respectively, as compared to non-grafted watermelon plants. These findings can be explained that the influence of grafting to scion is related to the rootstocks root power. Based on these results, a low yielding 'N-inefficient' potato cultivar Van Gogh can be improved when it is grafted onto 'N-efficient' potato cultivar Agria. The grafted N-efficient potato cultivar Agria significantly subsidized to growth and biomass production of the N-inefficient potato cultivar Van Gogh plants as compared to non-grafted plants and thus showed a higher rootstock potential for potato.

Shoot and Root N Concentration and Total Plant N Uptake

The results indicate that shoot and root N concentration and total plant N uptake at the end of the growing cycle differed in the nutrient solution under different N levels (Table 4). The grafted and non-grafted plants under high N supply produced higher shoot and root N concentration and total plant N uptake than plants under low N supply. The shoot and root N concentration and total plant N uptake were significantly ($P < 0.001$) affected by N rate. Regardless of graft combinations, plants under high N supply showed generally an improved performance in shoot and root N concentra-

Table 4 Shoot and root N concentration and total plant N uptake of non-grafted and reciprocal grafted potato cultivars (Agria and Van Gogh) grown under low (0.5 mM) and high (3.0 mM) N supply

Graft combination	Shoot N conc. (mg g^{-1})		Root N conc. (mg g^{-1})		Total N uptake (mg N $plant^{-1}$)	
(Scion/Rootstock)	Low N	High N	Low N	High N	Low N	High N
Agria	32.28 f	45.39 c	14.37 ef	21.27 b	209.01 f	443.65 c
Van Gogh	30.30 f	40.83 d	13.22 f	18.56 c	150.61 g	361.17 d
Agria/Van Gogh	34.54 ef	47.73 b	15.30 e	21.78 b	250.08 ef	554.67 b
Van Gogh/Agria	36.34 e	51.50 a	16.91 d	23.87 a	312.33 e	776.12 a
F-Test						
Scion	n. s.		n. s.		n. s.	
R. Stock	***		***		***	
N rate	***		***		***	
Scion × R. Stock	***		***		***	
Scion × N rate	n. s.		n. s.		n. s.	
R. Stock × N rate	**		**		*	

Values denoted by different letters are significantly different between graft combinations within both columns at $P < 0.05$
ns non-significant
* $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$

tion and total plant N uptake than plants grown under low N condition. Increasing N supply increased the shoot N concentration by almost 39%, the root N concentration 42.9%, the shoot N uptake 135.1%, the root N uptake 75.5% and the total plant N uptake 131.6% at high N condition. Similar results also observed by Adam (2018) at tomato plants. He observed that plants grown under high N supply (3.0 mM N) produced significantly higher shoot and root N concentration and total plant N uptake compare to plants grown under low N supply (0.3 mM N). In another study, watermelon plants produced significantly higher shoot N uptake and shoot N concentration under high N supply (3.0 mM) as compare to low N (0.3 mM) supply (Ulas et al. 2019).

The shoot and root N concentration and total plant N uptake were significantly ($P < 0.001$) affected by rootstock, scion × rootstock, rootstock × N rate interactions; however there were no significant differences observed regarding the shoot and root N concentration and total plant N uptake between scion and scion × N rate interactions. Grafting also had significantly positive effects and therefore the grafted plants showed significantly higher performance in shoot and root N concentration and total plant N uptake than non-grafted plants grown at both low and high N rates (Table 4). As compared to non-grafted plants, the grafting increased the shoot N concentration by almost 13.3% and 15%, root N concentration by 16.7% and 14.6% and total plant N uptake by almost 56.4% and 65.3% at low and high N rate, respectively. Compared to non-grafted plants, Van Gogh/Agria showed significantly highest shoot and root N concentration and total plant N uptake at both low and high N rates. Similar results were observed on grafted tomato (Adam 2018) and watermelon (Ulas et al. 2019) under high (3.0 mM N) and low (0.3 mM N) N rates. The findings of Colla et al. (2010) indicate that grafted melon plants have higher N uptake and N utilization than non-grafted melon plants. Grafted plants which have a compatible rootstock show better absorption of nutrient and water and also utilize nutrients very effectively due to vigorous root system of the rootstock that transmits water and nutrients better to the scion (Gregory et al. 2013). Ruiz et al. (1997) stated that there was efficient absorption of nitrogen when melon cultivars 'Yuma' and 'Gallicum' were grafted on three hybrid rootstock of cucurbit which are 'Shintoza', 'RS-841' and 'Kamel'. Better absorption and effective use of nitrogen by grafted plant help to minimize low yield in crops mostly caused by insufficient soil fertility (Simonne et al. 2010). Ruiz and Romero (1999), studying N metabolism ingrafted melon plants, observed that the use of certain rootstocks in squash enhanced NO_3^- reduction and N use, defined as an increase in the content of organic N in leaf tissue, which ultimately boosted production. However, the response of grafted melon to N was investigated at one level of nitrate in the nutrient solution (6 mM of NO_3), whereas information was lacking concerning the influence of different levels of nitrate on grafted melon crop performance.

Conclusion

In this study, a climate chamber experiment was conducted in nutrient solution growth system under 2 N rates (0.5 mM and 3.0 mM N). Concerning the N efficiency characteristics, two potato cultivars (N-efficient: Agria, N-inefficient: Van Gogh) were selected and grafted by reciprocally under 2 N rates. The grafted N-efficient potato cultivars (Agria) significantly subsidized to growth and biomass production

of the N-inefficient potato plants (Van Gogh) as compared to non-grafted plants and thus showed a higher rootstock potential for potato. The graft combinations of Van Gogh/Agria showed best performance in N efficiency as compared to other combinations under both N rates. All these showed that root morphological traits are contributing more than shoot traits to N efficiency in potato cultivars.

Conflict of interest F. Ulas, H. Yetisir and A. Ulas declare that they have no competing interests.

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