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ORIGINAL PAPER

RESPONSE OF 'RED DELICIOUS' APPLE TREES TO DIFFERENT LIMING STRATEGIES AFTER DRIP FERTIGATION WITH AMMONIUM NITRATE*

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Abstract

Under temperate climate, soil liming in apple orchards is necessary to avoid excessive soil acidification. A critical factor inducing soil acidification is the use of nitrogen (N) as ammonium. The aim of this study was to examine the impact of different liming strategies on tree responses in an ammonium nitrate-fertigated apple orchard. The study was conducted from 2010 to 2015, in a commercial apple orchard. 'Red Delicious' trees/M.9 rootstocks were planted in the spring of 2010 on coarse-textured soil. The trees were annually drip-fertigated with N in the form of ammonium nitrate at a dose of 10-15 g N plant^{-1} applied weekly over a 12-week period, commencing at the full bloom stage. Ground calcitic limestone was applied annually at doses of 200, 300 or 400 kg CaO ha^{-1} (referred to as AL1, AL2 and AL3 treatments, respectively) or periodically, once every 3 years at a standard dose or doses increased by 50% and 100% (referred to as PL1, PL2 and PL3 treatments, respectively). After 6 years of the growth of apple trees, the soil pH values beneath the emitters down to the 40-cm in depth were lower (4.6-6.0) than those found 30 cm from the drippers (5.3-6.3). The lowest pH values at the 0-20 cm layer were beneath the emitters in AL1, AL2, PL1 and PL2 treatments (4.6-4.9) and at the 21-40 cm depth in AL1 and PL1 treatments (5.0-5.1). In most of the years, tree leaves in AL3 treatment contained the most N, magnesium and calcium and the least manganese. The leaf concentrations of these nutrients in each year were above the critical values. Over the 6-year period, the leaf concentrations of phosphorus, boron, iron, zinc and copper did not differ among the liming combinations. The trees in AL3 treatment were the only ones that did not exhibit symptoms of internal bark necrosis (IBN). The trees in AL1, AL2, PL1 and PL3 treatments had moderate IBN symptoms. The strongest growth and highest aggregated yield of the trees were observed in AL3 combination. However, the yield efficiency of the trees from this combination was comparable to that in the other liming treatments. No liming treatment affected the mean fruit weight. The results indicated that in the 'Delicious' group apple orchards fertigated with ammonium-N and planted on coarse-textured soil, liming should be applied annually at a dose enabling the neutralization of fertigation-induced soil acidification.

Keywords: apple tree, nitrogen, fertigation, vegetative and reproductive responses.

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INTRODUCTION

Irrigation is practiced in many regions where apples (*Malus domestica* Borkh.) are grown, as the amount or distribution of rainfall within a growing season is insufficient or inadequate (Chenafi et al. 2016). It is particularly recommended in high-density orchards where trees are planted in soils with low water-holding capacity (Gispert et al. 2017). In these orchards, many growers inject water-soluble fertilizers into irrigation systems (fertigation).

Despite the many advantages of orchard fertigation, it may lead to soil acidification (Neilsen et al. 1994). This occurs mainly in drip-fertigated orchards on soils with low pH buffering capacities (Regina de Souza et al. 2012). A critical factors acidifying the soil in fertigated orchards are fertilizers containing ammonium ions (NH_4^+) and urea (Zhou et al. 2014). The acidifying impact of these forms of nitrogen (N) results from the biological conversion of NH_4^+ into nitrate (NO_3^-) ions (nitrification process), thus generating hydrogen cations (Sahrawat 2008). The elimination of fertilizers containing N-NH_4 and N-amide is debatable, at least in apple orchards, because (i) prices of NO_3-based fertilizers are much higher than those of NH_4- and urea-based fertilizers (approximately 2.5 USD per 1 kg N from calcium nitrate *vs* approximately 0.70 USD per 1 kg N from urea or ammonium nitrate), (ii) NH_4^+ ions positively affect the initiation and development of flower buds (Buban et al. 1978), and (iii) in contrast to NO_3^- ions, NH_4^+ leaching below the tree rooting zone is limited (Toselli et al. 2011). For these reasons, the fertilizers used in fertigated apple orchards should contain both NO_3^-, and NH_4^+, at least under conditions of coarse-textured soils.

To avoid a negative response of orchard trees to excessive soil acidification, periodic liming (every 3-4 years) is the strategy most frequently recommended (Fidalski, Auler 2008). However, considering the fact that drip fertigation of N-NH_4 induces soil acidification beneath emitters (Neilsen et al. 1994), periodic liming may not guarantee optimal nutrition and subsequent high yields for dwarf apple trees that develop roots in a small soil volume. Therefore, the main aim of this study was to examine the impacts of differential doses of annually and periodically applied lime on the nutrition and vegetative and reproductive responses of NH_4-fertigated 'Red Delicious' apple trees. An additional purpose was to examine the ability of liming treatments to neutralize fertigation-induced soil acidification.

MATERIAL AND METHODS

Study location, plant material and growth conditions

The study was conducted from 2010 to 2015 at a commercial apple orchard in Central Poland. 'Red Delicious' nursery trees of the knip-boom type, budded on M.9 rootstock, were planted in the spring of 2010, in Luvisol soil

containing 12 g carbon (C) kg^{-1} and 66% of sand (0.05-2 mm), 25% of silt (0.002-0.05 mm) and 9% of clay fraction (< 0.002 mm) at the 0-20 cm deep layer. The bulk density of this layer was 1.3 g cm^{-3}; the reaction (pH) was 6.7, and the phytoavailability of nutrients was as follows: 12 mg $N\text{-}NH_4^+ + NO_3^-$, 35 mg phosphorus (P), 75 mg potassium (K), 48 mg magnesium (Mg), 388 mg calcium (Ca), 80 mg iron (Fe), 35 mg manganese (Mn), 5.8 mg zinc (Zn), 3.9 mg copper (Cu) and 1.1 mg boron (B) per kg of soil. The soil analyses were conducted on a composite sample, consisting of ten subsamples, taken from randomly the entire field area in the autumn of 2009. Subsamples were mixed thoroughly, and then 2 dm^3 of soil material was placed in an open-top box. The moist soil material was ground manually, sieved through a 2-mm plastic mesh screen and stored in a plastic bag within 24 h at 4°C. The fractions of sand, silt and clay were determined by the aerometric method, the bulk density according to the core method, the organic matter by the dry combustion method at a temperature of 950°C in the presence of pure oxygen using a Leco TruSpec CNS analyzer (Leco Corp., St. Joseph, MI, USA), and pH was measured potentiometrically at a ratio of one part air-dried soil to 2.5 parts 1 M KCl, after shaking for 1 h. The availability of macro- and micronutrients was determined by extracting the soil with a solution of 0.03 N acetic acid containing ethylenediaminetetraacetic acid (EDTA). Extracted NO_3^- and NH_4^+ ions were determined with the colorimetric method in a continuous flow analyzer (Skalar Sanplus; Skular Analytical B.V.; AA Breda, Netherlands), and other nutrients were measured by inductively coupled plasma spectroscopy (Thermo Jarrell Ash, Franklin, MA, USA). Soil nutrient concentrations were expressed on a dry weight basis. The details of the soil analysis methods were presented by Wójcik, Filipczak (2015).

The experimental trees were planted at a spacing of 3.5 x 1 m (2,857 trees ha^{-1}). Immediately after planting, all of the lateral shoots were lightly pruned. During the next two years, branches mechanically damaged and those with sharp crotch angles and a diameter > 50% of the leader diameter were removed. After the fourth year, renewal pruning was conducted.

In the first year after planting, all of the flowers at the pink bud stage were removed. In the following years, flowers were chemically thinned using ammonium thiosulphate fertilizer (ATS). Sprays of this preparation were applied 2-3 days before petal fall, at a dose of 12 kg ha^{-1}, using 500 l water. Additionally, summer hand thinning was conducted to remove small, scarred, blemished and/or deformed fruitlets. The control of pathogens and pests was performed according to current recommendations for integrated apple production.

In 2010, from May to the end of August, the entire orchard floor was kept free of weeds by harrowing. The weeds were controlled mechanically when they were approximately 5 cm high. In the early spring of 2011, a mixture of perennial grass species consisting of ray-grass (*Lolium perenne* L.), red fescue (*Festuca rubra* L.) and Kentucky bluegrass (*Poa pratensis* L.) was

sown on 2.5-m wide strips. In the same year, strips free of weeds along the tree rows were made with a rotary weeder. In subsequent years, the strips along the tree rows were kept free of weeds by the application of post-emergence herbicides containing glyphosate, propaquizafop, and 2,4-dinitrophenylhydrazine.

Trees were surface drip irrigated using 16-mm lines stretched singly along each tree row and spaced approximately 20 cm from the trunks. Drip emitters were placed every 60 cm, and each delivered 3 dm^3 of water h^{-1}. Irrigation was conducted from May to the end of August when the soil water potential at the 15-cm depth dropped to -0.03 MPa. The soil moisture was measured with a tensiometer (model SR, Irrometer Co. Inc., CA, USA) inserted 15 cm from an emitter. Water from a deep well was used for irrigation. It had a pH of 7.5 and electrical conductivity (EC) of 0.37 mS cm^{-1} and contained 0.02 mg $N\text{-}NH_4^+$, 0.7 mg $N\text{-}NO_3^-$, < 0.01 mg $P\text{-}HPO_4^{2-}$, 2.3 mg K^+, 25 mg Mg^{2+}, 75 mg Ca^{2+}, 0.04 mg Fe, 0.01 mg Mn, 0.03 mg B, 0.06 mg Zn, and < 0.01 mg Cu dm^{-3}. These values are the means of water samples taken each year of the study.

The experimental apple trees were annually fertigated with N as NH_4NO_3 (34% N) at doses of 15 g, 12 g and 10 g N $plant^{-1}$ in 2010, 2011 and 2012-2015, respectively. Fertigation was performed weekly over a 12-week period beginning from mid-May, and using an equal dose of N in each fertigation term. The annual doses of N and the fertigation period were as described by Treder (2006). The injection of the NH_4NO_3 fertilizer into the irrigation system was controlled by a water-powered proportional dosing pump.

Starting in 2012, when the trees were fully mature, K in the form of K-sulfate (0N-0P-48K) was broadcast over the whole orchard surface at the swollen-breaking bud stage, at a dose of 80 kg K ha^{-1}.

Treatments and experiment layout

Different liming treatments were tested using ground calcitic limestone (50.4% CaO). The calcium carbonate ($CaCO_3$) equivalent of this lime was 92%, and the effective neutralizing value was 76%. The following liming treatments were studied: annual liming (AL) from 2010 at a dose of 200, 300 or 400 kg CaO ha^{-1} (referred to as AL1, AL2 and AL3 treatments, respectively) and periodic liming (PL), once in 3 years (in 2012) at the standard dose or increased by 50% and 100% (referred to as PL1, PL2 and PL3 treatments, respectively). The annual doses of lime corresponded to the range of Ca losses from the top layer of soil under Polish climate conditions (Wójcik 2004). In the case of periodic liming, the standard dose of lime used in 2012 was assessed based on the pH of the composite soil sample, consisting of subsamples taken during the summer, beneath the emitters at a 0-20 cm depth, from plots that were to be limed periodically. In all cases, lime was applied to the surface of the herbicide strips in the autumn.

The study was set up in a completely randomized block design with 4

replications, i.e. with a replicate of each treatment within one row. Each experimental plot consisted of 20 trees. Plots within a row were separated by 2 trees. There was a buffer row between the limed tree rows.

Measurements, observations and statistical analysis

The following measurements and observations were performed: (i) the soil pH was determined both beneath the emitter and 30 cm from the dripper (outside the wetted soil zone) at 0-20, 21-40 and 41-60 cm depths. The soil samples were taken in mid-September 2015 using a auger with a diameter of 5 cm. Soil samples were air-dried at ambient temperature. The further preparation of soil samples and the analytical procedure to determine the pH were the same as those used prior to the tree planting; (ii) the plant nutrition was evaluated annually based on the leaf nutrient concentrations. One hundred leaf samples from each plot were collected in the first decade of August, from the mid-portion of the extension shoots of the current year's growth at the periphery of the crown. The leaves were rinsed with 0.01 M HCl and double-deionized water. Then, they were dried at 60°C in a forced -draft oven (model UT 6760, Heraeus, Hanau, Germany) and ground in a Wiley stainless steel mill to pass through a 40-mesh screen. Nitrogen was determined according to the Dumas method using a Leco TruSpec CNS analyzer. To determine other nutrients in the leaf material, microwave digestion in concentrated nitric acid was carried out in a microwave oven (model MLS 1200, Milistone, Inc., Monroe, CT, USA). Potassium, Mg, Ca, Fe, Mn, Zn, B and Cu were determined with an inductively coupled plasma spectrometer, and P was determined colorimetrically by the vanadomolybdate method, using a spectrophotometer (Cintra 916, GBC, Dandenong, Australia); (iii) plant vigor was determined immediately after tree planting and in the last year of the study, three weeks after harvest. It was assessed on all trees per plot based on the trunk cross-sectional area (TCSA) calculated from the measured trunk diameter (in 2010) or the circumference (in 2015) at 20 cm above the ground level (approximately 5 cm above the bud union); (iv) internal bark necrosis (IBN) was assessed on all experimental trees in the final year of the study based on typical symptoms such as the scaling and peeling of the outer layers of bark on trunks and/or branches. These signs were rated on a scale of 1 to-4, where 1 means no visual signs, 2 symptoms on one scaffold shoot per tree, 3 symptoms on more than one branch per tree, and 4 signs on all of the branches per tree and simultaneously on the trunk; and (v) the final set of variables examined was yield, tree productivity and mean fruit weight. The total fruit yield was weighed separately for each plot. Apples were picked at commercial maturity when the Streif index values were within the range of 0.05-0.10, as recommended by most Polish cooperatives for storage and fruit marketing. Tree productivity (yield efficiency) was calculated as the ratio of the cumulative fruit yield to the final TCSA. The mean fruit weight was calculated using a sample of 20 kg bulk fruit per plot.

The data of all the plant parameters were subjected to a one-way analysis of variance. In the case of the soil pH, a two-factorial analysis of variance was used, where one factor was the liming treatment and the second was the place of soil sampling (beneath the emitter or 30 cm from the dripper). The analyses were performed separately for each growing season using the Duncan's multiple range test at $P \leq 0.05$ by means of Statistica 10 software (StatSoft Polska, Krakow, Poland).

RESULTS AND DISCUSSION

Over the six-year period, the total amounts of lime used were 1,000 kg CaO ha^{-1} in AL1 and PL1 treatments, 1,500 kg CaO ha^{-1} in AL2 and PL2 treatments and 2,000 kg CaO ha^{-1} in AL3 and PL3 treatments. The same doses of lime were applied in these combinations because in 2012 the pH value in the periodically limed plots (beneath the emitters at a 0-20 cm depth) averaged 4.5, providing the basis to use 1,000 kg CaO ha^{-1} as the standard dose in PL1 treatment (Sadowski et al. 1990).

After six years of N fertigation, the soil pH values to a depth of 40 cm below the emitters were lower than those 30 cm from the drippers, averaged across all liming treatments: 4.9 and 5.7 at the 0-20 cm depth and 5.5 and 6.0 at the 21-40 cm depth, respectively (Table 1). Stronger soil acidification beneath the emitters down to the 40 cm depth can be attributed, at least partly, to an increased nitrification process rate induced by N-NH_4 fertigated at a dose of 5-7.5 g $tree^{-1}$ $year^{-1}$. The acidifying impact of NH_4-based fertilizers has been well documented in many culture systems of agricultural crops (Lesturgez et al. 2006, Russell et al. 2006, Vieira et al. 2008). In apple orchard, Neilsen et al. (1994) also reported a considerable decline in soil pH values beneath drip emitters down to a 30 cm depth as a result of NH_4-N fertigation at doses of 11.7 g and 23.5 g $tree^{-1}$ $year^{-1}$. It should be noted that in the present experiment, the soil pH values beneath the emitters at the 41-60 cm depth were comparable to those of 30 cm from the drippers, averaging 6.2 at both sampling places across all combinations (Table 1). This indicates that the acidifying processes induced by fertigated N-NH_4 in this soil layer did not occur or were insufficient in relation to the pH-buffering capacity.

The highest pH values in all layers of the soil profile were found for AL3 and PL3 treatments regardless of the place of sampling, although the soil acidity at the 0-20 cm depth in AL3 treatment was lower than that in PL3 treatment (Table 1).

Down to a 40-cm depth, the lowest pH values were found beneath the emitters in AL1, AL2, PL1 and PL2 treatments at the 0-20 cm layer and in AL1 and PL1 treatments at a depth of 21-40 cm (Table 1). In these treatments, the pH values were lower than the critical value of 5.5 proposed for

Table 1

Effects of different liming treatments on changes in soil pH values after 6 years of nitrogen-fertigation in 'Red Delicious' apple orchard

Soil layer depth (cm)	Sampling place	Liming treatment					
		AL1	AL2	AL3	PL1	PL2	PL3
0-20	beneath the emitter	4.7 a[z]	4.9 *ab*	5.7 *c*	4.6 *a*	4.6 *a*	5.2 *b*
	30 cm from the emitter	5.6 *c*	5.8 *c*	6.3 *d*	5.3 *b*	5.3 *b*	5.8 *c*
21-40	beneath the emitter	5.1 *a*	5.4 *b*	5.9 *c*	5.0 *a*	5.4 *b*	6.0 *cd*
	30 cm from the emitter	5.9 *c*	5.9 *c*	6.2 *d*	5.8 *c*	5.9 *c*	6.2 *d*
41-60	beneath the emitter	6.1 *a*	6.0 *a*	6.4 *b*	6.1 *a*	6.0 *a*	6.4 *b*
	30 cm from the emitter	6.0 *a*	6.0 *a*	6.4 *b*	6.0 *a*	6.1 *a*	6.4 *b*

Key:
for 0-20 cm depth: treatment (Trt) **, sampling place (SP) **, Trt x SP interaction **;
for 21-40 cm depth: Trt **, SP **, Trt x SP interaction **;
for 41-60 cm depth: Trt **.

[z] Means with the same letter within rows for each depth of soil profile are not significantly different according to the Duncan's multiple range test at $P \leq 0.05$.
** Probability level at $P \leq 0.01$.

apple trees by Oliveira et al. (2016). These results indicate that annual and periodic liming at doses of 1,000 kg and 1,500 kg CaO ha^{-1} were not able to successfully neutralize fertigation-induced soil acidification down to a depth of 40 cm.

At a depth of 41-60 cm, the lowest pH values were recorded in AL1, AL2, PL1 and PL2 treatments both beneath the emitters and 30 cm from the drippers. These values were higher than the critical pH value of 5.5 (Table 1).

The leaf N concentration was affected by the studied combinations, although in the first 2 years, effects of liming treatments on this trait were not observed (Table 2). From 2012 to 2015, only the leaves in AL3 treatment contained more N than leaves from the other liming treatments (Table 2). Except for the final growing season, the leaf N concentrations in all of the combinations were higher than the critical value of 21 g kg^{-1} recommended by Sadowski et al. (1990). In 2015, only the leaves in AL3 treatment had a higher N level than this critical value.

The leaf concentrations of P and K did not differ among the liming treatments studied, averaging 2.6 g kg^{-1} and 14.9 g kg^{-1} in 2010, 2.4 g kg^{-1} and 14.9 g kg^{-1} in 2011, 2.2 g kg^{-1} and 13.8 g kg^{-1} in 2012, 2.0 g kg^{-1} and 13.5 g kg^{-1} in 2013, 2.3 g kg^{-1} and 12.7 g kg^{-1} in 2014, and 2.1 g kg^{-1} and 12.4 g kg^{-1} in 2015, respectively. In each growing season, the leaf concentrations of P and K in all combinations were within the optimal ranges proposed by Sadowski et al. (1990).

Except for the first year of the study, the leaf Mg concentrations in AL3 treatment were higher than those in the other treatments (Table 2). The leaf

Mg concentrations in this treatment were above the critical value of 2.1 g kg^{-1} recommended by SADOWSKI et al. (1990). Except for AL3 treatment, the leaf Mg concentrations during the last two years of the study were lower than the critical value (Table 2).

In 2010, the leaf Ca concentration was not affected by the treatments (Table 3). AL3 treatment leaves contained the greatest amount of Ca in the years following 2011 (Table 3). In 2012, the leaf Ca concentrations in AL1 and AL2 treatments were higher than those in PL1, PL2 and PL3 treatments (Table 3). In the next year, the leaves in PL3 combination contained more Ca than those in AL1, AL2, PL1 and PL2 treatments (Table 3). Despite these results, the leaf Ca exceeded the 7.0 g kg^{-1} deficiency concentration over the six growing seasons, indicating that the leaves contained an adequate amount of this nutrient (SHEAR, FAUST 1980).

The leaf Mn status depended on a treatment, although in 2010, the liming treatments had no observable effects (Table 3). The lowest leaf Mn concentrations were found in AL3 treatment from 2011 through the end of the study. These values were within the optimal range of 40-100 mg kg^{-1} proposed by SADOWSKI et al. (1990). The leaf Mn concentrations in the other treatments were comparable, although during the last three years, the leaves in PL3 treatment contained less Mn than those in AL1, AL2, PL1 and PL2 treatments (Table 3). It should be noted that since 2012, the leaf Mn concentrations in AL1, AL2, PL1, PL2 and PL3 treatments were on average greater than the excess value of 101 mg kg^{-1} proposed by SADOWSKI et. al. (1990). An exception was the concentration of Mn in the leaves from PL3 treatment in 2013, which did not exceed this threshold value (Table 3).

The leaf concentrations of B, Fe, Zn and Cu were not affected by the treatments and averaged 28.9 mg kg^{-1}, 54.4 mg kg^{-1}, 29.1 mg kg^{-1} and 6.4 mg kg^{-1} over the duration of the study, respectively. The leaf concentration ranges of these micronutrients were within the satisfactory ranges of 25-45 mg B kg^{-1} proposed by SADOWSKI et al. (1990) and 40-400 mg Fe kg^{-1}, 15-200 mg Zn kg^{-1} and 5-20 mg Cu kg^{-1} recommended by SHEAR, FAUST (1980).

After planting, the TCSA of trees did not differ among the treatments, indicating that the planting material was homogeneous (Table 4). After 6 years of growth, the highest value of TCSA was found in AL3 treatment (Table 4). This result was unsurprising because in each growing season only the apple trees in AL3 treatment contained sufficient concentrations of macro- and micronutrients in leaves. It appears that the optimal nutrition of apple trees in AL3 combination can be attributed, at least partly, to maintaining sufficient pH values (5.5-6.5) both directly beneath the drippers and away from the moist zone.

It should be noted that the TCSA in PL3 treatment was higher than that in AL1, AL2, PL1 and PL2 treatments (Table 4). Since the differences in tree nutrition among AL1, AL2, PL1, PL2 and PL3 treatments concerned mainly Mn during the final three years of the study, we hypothesize that

Table 2

Effects of different liming treatments on 'Red Delicious' apple leaf concentrations of nitrogen and magnesium

Combination	N (g kg^{-1} d.m.)						Mg (g kg^{-1} d.m.)					
	2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015
AL1	27.1 *a**	25.3 *a*	22.1 *a*	21.2 *a*	21.1 *a*	18.9 *a*	3.8 *a*	3.1 *a*	2.4 *a*	2.2 *a*	1.9 *a*	1.9 *a*
AL2	27.4 *a*	25.1 *a*	21.9 *a*	21.5 *a*	21.4 *a*	19.3 *a*	3.6 *a*	3.2 *a*	2.5 *a*	2.2 *a*	1.8 *a*	1.8 *a*
AL3	27.3 *a*	25.0 *a*	23.1 *b*	22.5 *b*	22.8 *b*	22.1 *b*	3.7 *a*	3.7 *b*	3.2 *b*	2.9 *b*	2.5 *b*	2.5 *b*
PL1	27.1 *a*	25.2 *a*	21.8 *a*	21.4 *a*	21.2 *a*	19.7 *a*	3.8 *a*	3.2 *a*	2.4 *a*	2.3 *a*	1.9 *a*	1.8 *a*
PL2	27.4 *a*	25.3 *a*	21.7 *a*	21.5 *a*	21.1 *a*	19.2 *a*	3.6 *a*	3.0 *a*	2.5 *a*	2.2 *a*	2.0 *a*	2.0 *a*
PL3	27.5 *a*	25.1 *a*	21.9 *a*	21.3 *a*	21.3 *a*	19.6 *a*	3.6 *a*	3.0 *a*	2.7 *a*	1.2 *a*	2.0 *a*	1.9 *a*

* Means within columns with the same letter are not significantly different according to the Duncan's multiple range test at $P \leq 0.05$.

Table 3

Effects of different liming treatments on 'Red Delicious' apple leaf concentrations of calcium and manganese

Combination	Ca (g kg^{-1} d.m.)						Mn (mg kg^{-1} d.m.)					
	2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015
AL1	7.1 *a**	12.4 *a*	14.2 *b*	15.6 *a*	15.9 *a*	15.4 *a*	56 *a*	90 *b*	201 *b*	207 *c*	237 *c*	242 *c*
AL2	7.3 *a*	12.7 *a*	14.3 *b*	15.8 *a*	16.1 *a*	15.3 *a*	58 *a*	89 *b*	209 *b*	215 *c*	238 *c*	237 *c*
AL3	7.3 *a*	13.6 *b*	15.8 *c*	18.3 *c*	18.9 *b*	18.6 *b*	60 *a*	65 *a*	68 *a*	68 *a*	72 *a*	87 *a*
PL1	7.0 *a*	12.3 *a*	13.2 *a*	15.2 *a*	15.5 *a*	15.1 *a*	54 *a*	96 *b*	207 *b*	217 *c*	232 *c*	239 *c*
PL2	7.3 *a*	12.2 *a*	13.1 *a*	15.5 *a*	15.6 *a*	15.4 *a*	55 *a*	91 *b*	215 *b*	209 *c*	241 *c*	229 *c*
PL3	7.3 *a*	12.2 *a*	13.1 *a*	17.0 *b*	16.0 *a*	15.9 *a*	58 *a*	95 *b*	198 *b*	91 *b*	125 *b*	129 *b*

* Means within columns with the same letter are not significantly different according to the Duncan's multiple range test at $P \leq 0.05$.

Table 4

Effects of different liming treatments on growth, the occurrence of internal bark necrosis, and fruit yields of 'Red Delicious' apple trees

Combination	TCSA (cm^2)		IBN (1-4)	Yield ($kg\ tree^{-1}$)					Cumulative yield ($kg\ tree^{-1}$)	Yield efficiency ($kg\ cm^{-2}$)
	2010	2015		2011	2012	2013	2014	2015		
AL1	1.14 *a**	7.81 *a*	3.6 *c*	6.5 *a*	12.8 *a*	12.1 *a*	12.1 *a*	12.1 *a*	55.6 *a*	7.12 *a*
AL2	1.19 *a*	7.92 *a*	3.8 *c*	6.9 *a*	13.1 *a*	12.4 *a*	12.5 *a*	11.9 *a*	56.8 *a*	7.17 *a*
AL3	1.20 *a*	11.03 *c*	1.0 *a*	7.9 *a*	15.3 *b*	16.4 *b*	19.9 *c*	18.9 *b*	78.4 *c*	7.11 *a*
PL1	1.25 *a*	7.97 *a*	3.5 *c*	6.9 *a*	13.0 *a*	12.1 *a*	12.2 *a*	12.2 *a*	56.4 *a*	7.08 *a*
PL2	1.23 *a*	7.89 *a*	3.2 *c*	7.2 *a*	12.9 *a*	12.6 *a*	12.3 *a*	11.5 *a*	56.5 *a*	7.16 *a*
PL3	1.21 *a*	9.34 *b*	2.4 *b*	7.0 *a*	12.7 *a*	13.9 *a*	15.3 *b*	17.8 *b*	66.7 *b*	7.14 *a*

* Means within columns with the same letter are not significantly different according to the Duncan's multiple range test at $P \leq 0.05$.

the improved plant growth in PL3 treatment might have resulted from decreased concentrations of Mn in the leaves during these growing seasons (94-129 mg kg^{-1}). Further evidence for this hypothesis comes from the concentrations of Mn in the leaves of AL1, AL2, PL1 and PL2 treatments that varied from 201 to 242 mg kg^{-1}, which according to Brunetto et al. (2015), is believed to be high enough to be toxic, at least for the 'Delicious' group varieties.

No symptoms of IBN were observed in AL3 treatment (Table 4). Signs of IBN were slight in PL3 combination and moderate in the other treatments (Table 4). It should be noted that the occurrence of IBN corresponded negatively to the tree growth. It is not surprising since Ścibisz, Sadowski (1979) and Hoyt (1988) also observed reduced growth in apple trees affected by IBN. The cited authors attributed the reduced vigor of apple trees with IBN signs to plant Mn toxicity resulting from excessive acidification of soil (pH < 5.5). In our experiment, 'Red Delicious' apple trees with moderate IBN symptoms (in AL1, AL2, PL1 and PL2 treatments) grew in the soil in which the pH values up to a 0-40 cm depth beneath the emitters were below 5.5. Simultaneously, during the final four years of the study, the leaf Mn concentrations in these treatments varied from 201 to 242 mg kg^{-1}, which was comparable to a threshold value of 233 mg Mn kg^{-1} found by Hoyt (1988) in leaves of 'Delicious' apple trees with moderate IBN signs.

In 2011, the fruit yields did not differ among the treatments (Table 4). Over the next years, the highest yields were in AL3 treatment, varying from 15.3 kg $tree^{-1}$ (43.7 tons ha^{-1}) in 2012 to 19.9 kg $tree^{-1}$ (56.8 tons ha^{-1}) in 2014 (Table 4). In PL3 treatment, the yields in 2011-2013 and 2014-2015 were comparable to and higher than those in AL1, AL2, PL1 and PL2 treatments, respectively (Table 4). In 2015, the yield in PL3 treatment was as high as that in AL3 treatment (Table 4).

The highest aggregated fruit yield was found in AL3 treatment, being lower in PL3 treatment, and the lowest in AL1, AL2, PL1 and PL2 treatments (Table 4). Despite differences in aggregated yield among the treatments studied, yield efficiency values did not differ (Table 4).

The mean fruit weight was not influenced by the liming treatments and averaged 209 g in 2011, 187 g in 2012, 185 g in 2013, 178 g in 2014 and 182 g in 2015. Thus, despite the highest yields recorded in AL3 treatment in 2012-2015 and in PL3 treatment in 2015, the size of the fruit was not diminished. Ferree (1998) did not observe a decrease in fruit size for 'Starkspur Supreme Delicious' and 'Melrose' apple trees with moderate IBN symptoms. In this study, reduced fruit size was found only under conditions of dieback of shoots/limbs and severe bark cracking. Thus, it seems that for moderate IBN symptoms, changes in the fruit size are less pronounced than the effects on the growth and yield of apple trees.

CONCLUSIONS

The results of this study indicated that a six-year period of fertigation with NH_4NO_3 at annual doses of 10-15 g N tree^{-1} (29-43 kg N ha^{-1}) resulted in the acidification of coarse-textured soil down to a depth of 40 cm beneath the drip emitters, which consequently reduced growth and yield of 'Red Delicious' apple trees. Under these conditions, slight and moderate IBN symptoms were also found. Among the liming treatments studied, the annual use of ground calcitic limestone at a dose of 400 kg CaO ha^{-1} was the most successful in neutralizing the fertigation-induced soil acidification in the vegetative and reproductive responses of apple trees. Thus, we conclude that for NH_4-fertigated 'Delicious' group varieties planted at high density on soil with low pH buffering capacities, agricultural lime should be applied annually to mitigate the acidifying effect of fertigation.

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