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Nitrogen, phosphorus, calcium, and magnesium applied individually or as a slow release or controlled release fertilizer increase growth and yield and affect macronutrient and micronutrient concentration and content of field-grown tomato plants

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ABSTRACT

The U.S. Environmental Protection Agency (USEPA) has restricted concentrated animal feeding operation (CAFO) release of waste products into U.S. waters. These waste products must be disposed of using best management practices. Most of the waste is spread on cropland, but some operations have found other creative uses for waste products. Use of a phosphorus (P) reduction system to remove P from wastewater results in magnesium ammonium phosphate (MAP), a slowly soluble fertilizer. Using a P reduction system will not eliminate the need for land application of manure and wastewater, but it reduces the nutrient load in the waste that is applied thereby making compliance with regulations easier. In the first year of this study, MAP was compared to a controlled release fertilizer (CRF) with a similar nutrient element ratio on plant growth, fruit yield, nitrogen (N), P, potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn) concentration in tomato (*Solanum lycopersicum* L. 'Mountain Fresh Plus') plant parts. Plant growth and fruit production were similar with the two fertilizers, but the number of tomato culls was greater with either fertilizer than on control plants. Foliar N, P, Ca, and Mg concentration did not differ regardless of fertilizer treatment. Plants fertilized with CRF had a greater leaf K concentration than those fertilized with MAP, but foliar K concentration did not differ between fertilized and nonfertilized plants. Iron and Mn concentration in above-ground vegetative plant parts (stems and leaves) did not differ regardless of fertilizer treatment, but Zn concentration increased linearly as CRF increased. In the second year, MAP, each of the essential elements contained in MAP separately, and a hand mixture of each of these elements was tested for their effect on tomato plant growth, fruit yield, and tissue N, P, K, Ca, Mg, Fe, Mn, and Zn concentration and content. Magnesium ammonium phosphate and the hand mixture of fertilizer resulted in greater above-ground biomass excluding fruit stem weight and fruit yield than any of the individual nutrient treatments. Calcium sulfate resulted in a greater number and weight of tomatoes harvested than MAP. Nitrogen concentration did not differ among the fertilizer treatments for roots, stems, or leaves, but N content was greater in red fruit with the hand mix of fertilizer than with no fertilizer or with ammonium sulfate or Mg oxide. In immature green fruit at termination of the study, N content was greater with no fertilizer or Ca sulfate than with MAP or triple superphosphate (TSP). Phosphorus, K, and Ca concentrations did not differ among fertilizer treatments for any tissue tested. Magnesium concentration in green tomatoes differed among fertilizer treatments such that Mg concentration of green tomatoes from plants fertilized with TSP was greater than Mg concentration of green tomatoes fertilized with ammonium sulfate or Mg oxide. Phosphorus and K content of green fruit differed among fertilizer treatments with P and K concentration highest in green fruit from plants fertilized with Ca sulfate and lowest in green fruit from plants fertilized with MAP or TSP.

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Iron and Mn concentrations did not differ among fertilizer treatments for any tissue tested. Zinc concentration in leaves was greater when plants were fertilized with MAP, TSP, Ca sulfate, or Mg oxide than with ammonium sulfate. Zinc concentration of green fruit was greater when fertilized with MAP than with the hand mix, Ca sulfate or Mg oxide. Iron content was highest in green fruit from plants fertilized with TSP and lowest in plants fertilized with ammonium sulfate or control plants. Manganese content of leaves from control plants was greater than that of plants receiving ammonium sulfate while red fruit from plants fertilized with the hand mix had a greater Mn content than red fruit from any other treatment. Foliar Zn content was greater in plants fertilized with Ca sulfate than in those fertilized with the hand mix, ammonium sulfate, or TSP. In contrast, Zn content of red fruit fertilized with the hand mix was greater than for red fruit in any other treatment. Green fruit from control plants and those receiving MAP had a greater Zn content than plants fertilized with the hand mix, TSP, or Mg oxide. Fertilizer application increased Fe, Mn, and Zn content of several plant tissues. None of the labels of fertilizers applied stated that they contained micronutrients; however, small amounts of contamination were possible. Differing micronutrient contents of various plant tissues among fertilizer treatments were probably associated with other elements affecting plant growth or nutrient uptake. The nutrient elements present in the various fertilizers were not always the nutrient elements affected in the plants likely due to another element that may have limited plant growth or nutrient uptake.

1. Introduction

In 2003, the USEPA revised regulations for CAFOs. With this revision, the number of CAFOs regulated increased, and new regulations addressed land application of manure from CAFOs (USEPA, 2003). To comply with USEPA regulations, CAFOs must have a National Pollutant Discharge Elimination System Permit. One of the permit requirements is development of a nutrient management plan. The purpose of this plan is to reduce the amount of nutrients leaving CAFO sites that might pollute waterways. No discharge of manure, poultry litter, or wastewater from a CAFO production area may enter U.S. waters. Producers must use best management practices to either apply the manure, which may require large land areas, or producers may use innovative technologies to achieve pollutant reductions.

One way to reduce the amount of manure, and therefore the land area on which it must be spread, is to precipitate MAP (also called struvite). A recently developed P reduction system involves wastewater flowing through a fluidized-bed reactor causing P to precipitate as MAP (Rutherford, 2010). Plant producers can use MAP as a slowly soluble fertilizer in production of crops. One advantage of using slowly soluble fertilizer compared to traditional highly soluble fertilizers is that plant nutrients are released over a longer time period that may or may not correspond better with plant needs. Because of slower nutrient release, nutrients are less likely to leach through the soil profile below plant roots or be carried to waterways resulting in potential for pollution of those waterways.

Many horticultural crop producers use CRFs. Similar to slowly soluble fertilizers, CRFs release nutrients over a longer time period than highly soluble fertilizers, but the mechanism for this slower release is different than for slowly soluble fertilizers. Controlled release fertilizers discharge nutrients slowly because they are encapsulated in a semipermeable polymer covering. Abraham and Pillai (1996) noted that about 40 to 70% of applied urea was lost to the environment, but losses were reduced by coating urea with copolymer of acrylamide. Environmental conditions affect nutrient release of slowly soluble and CRFs. Slowly soluble fertilizers require moisture and soil microorganism activity for nutrient release (Morgan et al., 2009). Controlled release fertilizers depend on diffusion through coatings which is moisture and temperature dependent (Morgan et al., 2009). Thus cool or dry periods may result in inadequate nutrient release to support plant growth and hot or wet conditions may result in nutrient discharge faster than plant uptake.

Nitrogen, P, K, Ca, and Mg are essential plant macronutrients. Nitrate and ammonium are the major forms of N taken up by plants (Barker and Bryson, 2007). Under normal, aerated conditions in soils, nitrate is the predominant form of N taken up by plants. Nitrate is readily mobile in plants, but it must be reduced to ammonium for synthesis of proteins and other organic compounds. Plants recycle N from the cycling of proteins and other nitrogenous compounds as ammonium (Barker and Bryson, 2007). Scholberg et al. (2000) noted that N concentrations in various tissues of tomato plants vary throughout the growing season.

The total amount of soil P is often much greater than the amount of plant available P (Tisdale and Nelson, 1975). The maintenance of a suitable concentration of P in the soil solution for plant uptake depends on the relative rate of organic matter decomposition, and on the ability of the soil's inorganic fractions to fix soluble orthophosphates in insoluble or slightly soluble forms. Addition of soluble phosphate fertilizers can increase the amount of soluble orthophosphates in the soil solution for a short time, but depending on soil pH, P quickly reacts with iron, aluminum, or silicate clays and becomes unavailable for plant uptake.

Rehm and Schmitt (2002) noted that K can occur in unavailable, slowly available, or readily available forms in soils. Only a small amount of slowly available K is available for plant uptake during a single growing season. Readily available K is dissolved in the soil solution and readily taken up by plants. Potassium uptake is affected by soil moisture content, soil aeration and oxygen level, soil temperature, and competing ions

Like K, Ca and Mg in soils originate from decomposition of bedrock and minerals that contain these elements (Tisdale and Nelson, 1975). Compared to other minerals, Ca weathers relatively quickly and can become unavailable to plants via leaching in highly weathered (mature) soils (Pilbeam and Morley, 2007).

Magnesium deficiency symptoms may occur when Mg is limited, but they may also be associated with an antagonistic relationship between Mg ions (Mg^{2+}) and other cations. The competition of Mg with other cations for uptake ranges from highest to lowest as follows: $K > NH_4^+ > Ca > Na$ (Mills and Jones, 1996; Peñalosa et al., 1995).

Numerous fertilizer formulations provide plant macronutrients individually or in combinations to the soil. Application of macronutrient fertilizers usually affects nutrient availability to plants. Micronutrients are generally present in sufficient amounts in most soils, but their availability may be limited due to a variety of conditions. Most micronutrients are more available when the soil pH is below 7. Soil pH affects nutrient solubility and consequently availability. Interactions with other elements, colloidal organic matter, soil moisture and temperature can have major impacts on availability or uptake of certain micronutrients. In addition, non-target organisms immobilize micronutrients and small amounts are lost by erosion and leaching.

Total Fe content of soil is of little value in diagnosing Fe deficiencies in plants (Tisdale and Nelson, 1975). Soil conditions that lead to Fe deficiency include pH above 7, low soil moisture and low organic matter content (Foth and Ellis, 1997). Iron uptake can be reduced by high concentrations of P, Mn, copper, nickel or Zn (Tisdale and Nelson, 1975).

Manganese availability for plant uptake decreases as soil pH increases. Divalent Mn is the form absorbed at the root surface cell membrane. As soil pH decreases, the proportion of exchangeable Mn^{2+} increases dramatically (Bromfield et al., 1983). Manganese deficiency is largely due to high soil pH, but it can to a lesser extent be induced by an imbalance of other elements such as Ca, Mg, and ferrous iron (Tisdale and Nelson, 1975).

Similar to Fe and Mn, plant availability of Zn depends on soil pH, P concentration, organic matter content and adsorption by clays (Tisdale and Nelson, 1975). The amount of Zn present in the soil is not a reliable indicator of plant availability. Zinc deficiency is common in plants growing in highly weathered acid or calcareous soils (Trehan and Sekhon, 1977). Zinc ions can be immobilized in organic matter so that they become unavailable for root uptake (Ballinger et al., 1966; Storey, 1957). However, in most situations the Zn complex with colloidal organic matter increases availability (Foth and Ellis, 1997). High concentrations of soil P intensify Zn deficiency.

Addition of N, P, K, Ca, and Mg must occur frequently enough to supply plant needs by maintaining each of these nutrients in the soil solution. Because slowly soluble and CRF fertilizers release nutrients over time, they replenish nutrients in the soil solution as those nutrients are released from the fertilizer. Presence and availability of adequate plant nutrients are vital for plant growth and fruit production. The objectives of this study were to determine (1) if the slow release fertilizer, MAP (precipitated from animal wastewater through a fluidized-bed reactor) and a CRF with a similar nutrient ratio, affects plant growth, yield and N, P, K, Ca, Mg, Fe, Mn, or Zn concentration in field-grown tomato plant foliage, and (2) the effect of N, P, Ca, and Mg alone or in combination as a hand mixture of the individual elements or the slow release fertilizer MAP on plant growth, yield, and tissue N, P, K, Ca, Mg, Fe, Mn, or Zn concentration and content of field-grown tomato plants. Applying elements individually allowed evaluation of a critical nutrient shortage of a single element versus supplying all elements as in the case of MAP or the mixture.

2. Materials and methods

2.1. Experiment 1, magnesium ammonium phosphate versus controlled release fertilizer

2.1.1. Cultural practices

'Mountain Fresh Plus' tomato seedlings (Gardner, 1999, 2002) were planted into a Renfrow loam (fine, mixed, superactive, thermic Udertic Paleustolls) soil at Stillwater, OK (N 36° 09.412′, W 97° 01.788′) on 4 May 2011. Plant spacing within row was 1.8 m and 1.8 m between rows. This spacing was used to assure that fertilizer treatments were unique to each plant and no treatment influenced adjacent fertilizer treatments. The spacing also allowed for easy harvest of fruit. Planting holes were dug with a 15-cm-diameter auger to a depth of about 15 cm. Plants were hand-watered with a hose immediately after planting and then as needed until drip irrigation was installed on 8 May 2011. Then plants were watered daily at 0700 HR for 1 h and at 1300 HR for 1 h with drip irrigation (62 ml m^{-1} min^{-1}) until the study was terminated. Air temperature was measured at 30 min intervals using dataloggers (WatchDog 1225, Spectrum Technologies, Aurora, IL). High and low temperatures were determined for each day during the experiment then average daily maximum/minimum temperatures of 35.4/21.4 °C were calculated.

Baskets constructed from woven field fence (Red Brand; Peoria, IL) with 10 cm by 10 cm spaces between the wires were placed around each plant 48 h after planting. Baskets were 53.3 cm in diameter and 122 cm tall. Glyphosate ((*N*-phosphonomethyl)glycine, Eraser; Surrender brand, Control Solutions, Pasadena, TX) was applied 5 June, 2011 at 7.5 g L^{-1} a.i. outside of the baskets for weed control. Weeds were controlled inside of the baskets by hand weeding.

2.1.2. Treatments

A soil test conducted prior to the study showed that the site was low in N and P, and recommended a single application of 4.9 g m^{-2} N and applying 12 g m^{-2} P annually. No fertilizer was applied prior to the experimental fertilizer treatments. For plants receiving fertilizer treatments, fertilizer was spread uniformly in the bottom of the planting hole prior to planting the plants. The MAP fertilizer (TerraPhos; Kansas Environmental Management Associates, Salina, KS) consisted of 4N-11.2P-0.4 K (4N-26P_2O_5-0.5 K_2O) with 8% Ca and 9% Mg and Floricote CRF (Floricote; Florikan, Sarasota, FL) was 10N-21P-0 K (10N-49P_2O_5-0 K_2O). Both MAP and CRF were applied at 0, 2.45, 4.9, or 9.8 g m^{-2} N. These application rates provided 0, 2.7, 5.5, or 11.0 g m^{-2} P, respectively with MAP and 0, 5.1, 10.3, or 20.6 g m^{-2}, respectively with CRF. The manufacturer estimated complete release of nutrients in the CRF within 90 d at 26.6 °C.

2.1.3. Data collection

Plant height and width (two perpendicular measurements) were measured 2, 4, and 8 weeks after planting. Fruit were harvested daily as red color appeared (breaker red stage). Fruit were graded as edible fruit or considered culls if they were damaged such that they were unacceptable for the fresh market. Generally damage was due to feeding by birds and other wildlife. Fruits were counted and weighed daily, including weekends.

Above-ground plant parts were harvested beginning 29 Aug. 2011 and separated into immature tomatoes and stems with leaves. Leaves and stems were dried in an oven at 55 °C to a constant weight and then weighed.

Prior to plant harvest, the uppermost three to five fully expanded leaves of plants from all treatments in the first four blocks were removed and dried in a drying oven at 55 °C to a constant weight then weighed. Dried leaves were ground with a Wiley mill to pass through a 0.84 mm mesh screen and stored in glass jars for later analysis. Leaf elemental concentrations of N were determined with a Leco N analyzer (Tru Spec N, St. Joseph, MI). Samples were dry ashed in a muffle furnace at 500 °C, dissolved in 20% HCl, filtered through Whatman 41 filter paper, and brought to the appropriate dilution with 2% lanthanum solution. Phosphorus was determined colorimetrically (Genesys 10 Spectrophotometer, ThermoSpectronic, Rochester, NY) and K, Ca, Mg, Fe, Mn, and Zn were analyzed using atomic absorption spectroscopy (PerkinElmer model 2380, Waltham, MA).

2.1.4. Experimental design and data analysis

The experiment consisted of a randomized complete block design with 10 single-plant replications. Because of financial limitations only the first 4 blocks were used for foliage N analysis. Eight treatments (two fertilizers applied at four rates each) were applied. Data were analyzed using the GLM procedure in SAS (version 9.1;

SAS Institute, Cary, NC), and application rate trends were calculated using orthogonal contrasts within each fertilizer type.

2.2. Experiment 2, elemental combinations

2.2.1. Cultural practices

'Mountain Fresh Plus' tomato seedlings were transplanted as described above on 25 April., 2012. The site and irrigation system were the same as those used in experiment 1 described above. Cultural practices were performed as described above. Average daily maximum/minimum air temperatures were 32.3/19.1 °C.

2.2.2. Treatments

The following fertilizer treatments were applied: (1) MAP at 4.9 g m^{-2} N, (2) calcium sulfate ($CaSO_4$, 23% Ca) at 9.8 g m^{-2} Ca, (3) magnesium oxide (MgO, 58% Mg, Crop Mag 58; Martin Marietta, Baltimore, MD) at 11.0 g m^{-2} Mg, (4) ammonium sulfate ($(NH_4)_2SO_4$) Sulf-N; Honeywell, Morristown, NJ) at 4.9 g m^{-2} N, (5), TSP (Bonide, Oriskany, NY); 0N-19.4P-0 K (0N-45P_2O_5-0 K_2O,) at 7.1 g m^{-2} P, (6) hand mix of Ca sulfate, Mg oxide, ammonium sulfate, and TSP at the rates listed in treatments 2 through 5 above, and (7) no fertilizer treatment (control). All N, P, Ca, and Mg treatments were applied at rates equal to that applied with MAP. Fertilizers were placed in the bottom of the planting hole as described above for plants in respective fertilizer treatments.

2.2.3. Data collection

Fruit were harvested between 21 June, 2012 and 24 July, 2012 as red color appeared. Grading was as described above with fruit counted and weighed.

Plants were harvested 24 July, 2012 and separated into mature fruit, immature fruit, leaves, stems, and roots. Mature and immature fruit were air dried in a greenhouse with a daily high temperature of about 50 °C until dry and then weighed. Leaves, stems, and roots were dried in ovens at 55 °C to a constant weight and weights recorded.

Nitrogen, P, K, Ca, Mg, Fe, Mn, and Zn concentration were determined as described above. Weight of N, P, K, Ca, Mg, Fe, Mn, or Zn for each component of the plant was determined by multiplying the component weight by the respective nutrient concentration.

2.2.4. Experimental design and data analysis

Treatments were arranged in a randomized complete block design with seven treatments (described above) and ten single-plant replications. Data were analyzed using a mixed model (PROC MIXED in SAS 9.4 software; SAS Institute, Cary, NC). Weighted means were calculated using LSMEANS with mean comparisons using the protected LSD (DIFF option).

2.3. Experiment 3, fertilizer solubility kinetics

The kinetics of nutrient release from each fertilizer material listed above for treatments 1–6 (Section 2.2.2), plus CRF, was monitored under laboratory conditions. Fertilizers were weighed and placed in 250 mL bottles with a pH 6 buffer solution (0.1 M Na acetate) to achieve a solid:solution ratio of 1:2500. A pH 6 was chosen since this was representative of the pH of the soil used in the field experiments. For each of the seven treatments, six samples represented nutrient concentrations measured at 0.5, 1, 3, 6, 24, and 48 h after initiation of the experiment. Each treatment-time was replicated three times. Bottles were placed on a reciprocating shaker and removed at the appropriate times for analysis. Solutions were allowed to settle for five minutes before decanting, and then analyzed for P, Ca, and Mg by atomic emission spectroscopy, and NH_4-N and NO_3-N by flow injection autoanalyzer (LACHAT, 1994).

Solubility was quantified and normalized by expressing the mass of the nutrient dissolved per mass of nutrient contained in the material. Thus, a value of one indicates 100% solubility with respect to a given nutrient.

3. Results

3.1. Experiment 1, magnesium ammonium phosphate versus controlled release fertilizer

Plant height and width 2 weeks after planting and plant width 4 weeks after planting were greater for plants fertilized with MAP (12.4 cm, 20.0 cm, and 34.4 cm, respectively) than for those fertilized with CRF (11.5 cm, 18.5 cm, and 32.2 cm, respectively) (Table 1). Plants receiving fertilizer, regardless of source were taller (26.2 cm) and wider (34.5 cm) 4 weeks after planting and wider (68.0 cm) 8 weeks after planting than control plants (22.5 cm, 29.8 cm, and 61.0 cm, respectively). Plant height and width of plants receiving MAP increased linearly as rate increased at 2, 4, and 8 weeks after planting. Plant height and width at 4 weeks after planting and plant width 8 weeks after transplanting increased linearly as CRF rate increased. Above-ground plant biomass (stems and leaves) was greater with fertilizer than without, but did not differ between the fertilizers. Above-ground biomass increased linearly with MAP rate, but no relationship existed between above-ground biomass and CRF rate.

The number, weight and per fruit weight of edible fruit did not differ among fertilizers or between untreated control plants and those receiving fertilizer (Table 2). In contrast, total weight and per fruit weight of culls was greater with MAP (278.2 g and 22.7 g, respectively) than with CRF (193.9 g and 19.4 g, respectively). The number of culls and total weight of culls was greater with either fertilizer (8 culls and 284 g, respectively) than for non-fertilized control plants (3 culls and 93 g, respectively). The number of edible fruit, number of culls, and total weight of culls increased linearly with increased MAP rate. Number of culls increased linearly while total cull weight increased curvilinearly as CRF rate increased.

Foliar N concentration did not differ between the two fertilizer treatments or between plants receiving fertilizer and untreated control plants (Table 3). A curvilinear relationship between MAP concentration and foliar N concentration occurred such that plants receiving 2.45 or 4.9 g m^{-2} N had lower foliar concentrations than plants receiving no MAP or MAP at 9.8 g m^{-2} N.

Phosphorus concentration in leaves did not differ regardless of fertilizer treatment, and P concentration in leaves from plants receiving either fertilizer did not differ from that of nonfertilized control plants (Table 3). A curvilinear relationship between leaf P concentration and MAP application rate indicated fertilization with 9.8 g m^{-2} N derived from MAP resulted in the highest leaf P concentration. Thus it appears that MAP added more P than CRF resulting in a significant trend between application rate and plant P concentration. Controlled release fertilizer did not affect leaf P concentration.

Plants receiving fertilizer (regardless of source) had a greater leaf K concentration than nonfertilized plants (Table 3). No trends between K concentration and fertilizer application rate occurred for either fertilizer. Note that both fertilizers contained only trace amounts of K. Leaf Ca and Mg concentrations were not affected by presence or absence of fertilizer or by fertilizer type (data not shown).

No differences in foliar Fe, Mn, or Zn concentration occurred between plants fertilized with MAP or CRF or between the non-fertilized and fertilized plants (data not presented). Likewise, no trends in foliar Fe or Mn concentration occurred when plants were fertilized with MAP or CRF occurred (data not presented). Foliar Zn

Table 1

Tomato plant height and width (average of two perpendicular measurements) 2, 4, and 8 weeks after planting (WAP) and above-ground plant biomass (stems and leaves) at harvest with selected rates of magnesium ammonium phosphate (MAP) or controlled release fertilizer (CRF) in 2011. $n = 10$.

Fertilizer	Concentration (g/m^2)	2 WAP		4 WAP		8 WAP		Above-ground biomass (g)
		Height (cm)	Width (cm)	Height (cm)	Width (cm)	Height (cm)	Width (cm)	
None	0	11.4	19.4	22.5	29.8	65.4	61.0	1596
MAP	2.45	11.7	18.2	24.2	33.8	67.4	64.0	1730
	4.90	12.3	19.9	25.8	35.6	68.0	68.5	1833
	9.80	13.9	22.4	29.8	38.6	71.6	70.2	2182
CRF	2.45	11.3	17.5	24.5	30.8	66.0	69.1	2009
	4.90	11.9	19.1	26.6	34.3	67.9	67.2	1835
	9.80	11.4	18.0	26.3	34.1	70.6	69.3	1811
Contrasts:								
MAP vs. CRF		*	**	NS	**	NS	NS	NS
Control vs. fertilizer		NS	NS	***	***	NS	**	*
MAP	Linear[a]	**	**	***	***	*	**	**
CRF	Linear	NS	NS	**	**	NS	*	NS

NS,*,**,*** Contrasts not significant (NS) or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

[a] Quadratic and Residual trends were not significant for height or width at any number of days after treatment for either fertilizer ($P \leq 0.05$). Likewise quadratic and residual trends were not significant for above-ground biomass.

Table 2

Cumulative edible and cull fruit number, fresh weight, and weight per fruit from tomato plants fertilized with selected rates of magnesium ammonium phosphate (MAP) or controlled release fertilizer (CRF) in 2011. $n = 10$.

Fertilizer	Rate (g/m^2)	Edible fruit			Culls		
		Fruit (no.)	Total wt. (g)	Per fruit wt. (g)	Fruit (no.)	Total wt. (g)	Per fruit wt. (g)
None	0	18	887	50.8	3	93	22.2
MAP	2.45	19	904	51.0	8	334	29.7
	4.90	16	996	69.1	7	278	18.3
	9.80	25	1213	46.7	11	408	20.7
CRF	2.45	23	1053	48.2	7	220	14.4
	4.90	22	1129	51.6	7	259	27.2
	9.80	22	1030	41.8	7	203	13.6
Contrasts:							
MAP vs. CRF		NS	NS	NS	NS	*	*
Control vs. fertilizer		NS	NS	NS	***	***	NS
MAP	Linear	*	NS	NS	***	***	NS
	Quadratic	NS	NS	*	NS	NS	NS
	Residual	NS	NS	NS	*	*	NS
CRF	Linear	NS	NS	NS	*	NS	NS
	Quadratic	NS	NS	NS	NS	*	NS
	Residual	NS	NS	NS	NS	NS	NS

NS,*,**,*** Contrasts not significant (NS) or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 3

Nitrogen (N), phosphorus (P) and potassium (K) percentage in leaves of tomato plants fertilized with selected rates of magnesium ammonium phosphate (MAP), controlled release fertilizer (CRF), or no fertilizer (control) in 2011. $n = 4$. Orthogonal contrasts indicate if there were significant differences between fertilizer treatments or significant trends (linear or quadratic) between applied N rate and leaf N, P, or K concentration within each fertilizer.

Fertilizer	Rate (g/m^2)	Leaf N concn (%)	Leaf P concn (%)	Leaf K concn (%)
None	0	3.94	0.186	3.37
MAP	2.45	3.69	0.168	3.06
	4.90	3.69	0.162	3.24
	9.80	4.02	0.201	3.44
CRF	2.45	3.98	0.215	3.52
	4.90	3.88	0.180	3.46
	9.80	3.98	0.184	3.47
Contrasts:				
Control vs. fertilizer		NS	NS	*
MAP vs. CRF		NS	NS	NS
MAP	Linear	NS	NS	NS
	Quadratic	**	*	NS
	Residual	NS	NS	NS
CRF	Linear	NS	NS	NS
	Quadratic	NS	NS	NS
	Residual	NS	*	NS

NS,** Contrasts not significant or significant at $P \leq 0.01$, respectively.

Table 4
Foliar zinc (Zn) concentrations from tomato plants fertilized with selected rates of magnesium ammonium phosphate (MAP) or a controlled release fertilizer (CRF). $n = 4$.

Fertilizer	Rate (g/m^2)	Zn concn(μg/g DW)
None	0	34.8
MAP	2.45	28.2
	4.90	30.5
	9.80	31.8
CRF	2.45	39.2
	4.90	34.2
	9.80	28.2
Contrasts:		
MAP vs. CRF		NS
Control vs. fertilizer		NS
MAP	Linear[a]	NS
CRF	Linear	*

[NS,*] Contrasts not significant or significant at $P \leq 0.05$, respectively.

[a] Quadratic and Residual trends were not significant for Zn concentrations with either fertilizer ($P \leq 0.05$).

Table 5
Stem dry weight of tomato plants receiving selected fertilizer treatments in 2012. $n = 10$.

Fertilizer added	Stem dry weight (g)
None	141ab^{z}
MAP^{y}	171b
Hand mix^{y}	136ab
Ammonium sulfate	116a
Triple superphosphate^{y}	120a
Calcium sulfate	119a
Magnesium oxide	110a

[z] Means followed by the same letter are not significantly different by the protected LSD, $P \leq 0.05$.

[y] MAP = magnesium ammonium phosphate; hand mix refers to a mixture of ammonium sulfate ($(NH_4)_2SO_4$), triple superphosphate, calcium sulfate ($CaSO_4$), and Mg oxide (MgO) at the same concentration as each of these fertilizers applied in individual fertilizer treatments.

concentration was negatively related to CRF rate but no trend was apparent with MAP (Table 4).

3.2. Experiment 2, elemental combinations

Stem dry weight of plants receiving MAP was greater than that of plants fertilized with ammonium sulfate, TSP, Ca sulfate, or Mg oxide (Table 5). Root, leaf, and total dry weight did not differ among fertilizer treatments (data not presented).

The total fresh weight of edible fruit was greater with MAP or the hand mixture of fertilizer than with no fertilizer or with ammonium sulfate, Ca sulfate, or Mg oxide (Table 6). The weight of green fruit harvested was greater with Ca sulfate than with MAP, but the weight of green fruit from plants in other fertilizer treatments or the control treatment did not differ from either the MAP treatment or the Ca sulfate treatment. Likewise, the number of green fruit per plant was greater with Ca sulfate than with MAP, but other treatments did not differ in number of green fruit per plant from those treated with Ca sulfate or MAP. Cull and total fruit fresh weight and edible fruit, cull and total fruit number per plant did not differ among treatments (data not presented).

The weight of edible fruit harvested did not differ among the nonfertilized, MAP, and hand mix treatments during the first three 4-day harvest intervals (Fig. 1). During harvest interval 4 through 6, plants receiving MAP or the hand mixture yielded a greater weight of edible fruit than plants that received no fertilizer. Near the end of the growing season (harvest intervals 7 and 8), presence or absence of fertilizer did not affect edible fruit yield. The lack of response to fertilizer treatment at the end of the growing season may be related to excessive temperatures reducing fruit set in all treatments. Sato et al. (2000) showed that the release of pollen grains and pollen grain germination is decreased in elevated temperatures resulting in lower fruit set. Greater flower abortion also results in lower fruit set under elevated temperatures (Sato et al., 2004).

Table 6
Cumulative fresh weight and number of edible or green fruit from tomato plants receiving selected fertilizer treatments in 2012. $n = 10$.

Fertilizer added	Edible fruit	Green fruit
Fresh fruit weight/plant (g)		
None	3861a^{z}	2996bc
MAP^{y}	5478b	1961a
Hand mix^{y}	5770b	2636abc
Ammonium sulfate	4263a	2834abc
Triple superphosphate	4838ab	2107ab
Calcium sulfate	4030a	3368c
Magnesium oxide	3534a	2523abc
Fruit number/plant		
None	19	25ab
MAP^{y}	28	19a
Hand mix^{y}	30	25ab
Ammonium sulfate	21	26ab
Triple superphosphate	24	23ab
Calcium sulfate	20	33b
Magnesium oxide	19	25ab

[z] Means within columns and fruit weight or fruit number followed by the same letter are not significantly different by the protected LSD, $P \leq 0.05$.

[y] MAP = magnesium ammonium phosphate; hand mix refers to a mixture of ammonium sulfate ($(NH_4)_2SO_4$), triple superphosphate, calcium sulfate ($CaSO_4$), and magnesium oxide (MgO) at the same concentration as each of these fertilizers applied in individual fertilizer treatments.

Nitrogen concentration did not differ among fertilizer treatments for any plant part tested (data not presented). Nitrogen content did not differ among fertilizer treatments for roots, stems, or leaves, but red and green fruit N content differed among treatments. Plants receiving the hand mix of fertilizer had greater N content in red fruit than red fruit receiving no fertilizer, ammonium sulfate, or Mg oxide (Table 7). Nitrogen content of red fruit in MAP, TSP or Ca sulfate treatments did not differ from that of fruit from plants receiving the hand mixture or plants receiving no fertilizer, ammonium sulfate, or Mg oxide. Nitrogen content of green fruit at termination of the study was greater with no fertilizer or Ca sulfate than with MAP or TSP. Green fruit N concentration in plants treated with the hand mix, ammonium sulfate, or Mg oxide did not differ from those of plants receiving no fertilizer or Ca sulfate or from plants receiving MAP or TSP.

Phosphorus and K concentration did not differ among fertilizer type for any of the tissues tested (data not presented). Phosphorus and K content were greatest in green fruit from nonfertilized plants or those receiving Ca sulfate while green fruit from plants fertilized with MAP or TSP had the lowest P and K concentrations (Table 7). Phosphorus and K concentration in green fruit from plants receiving the hand mixture, ammonium sulfate, or Mg oxide did not differ from that of any other fertilizer treatment. Phosphorus and K content did not differ among fertilizer treatments for any other plant part.

Calcium concentration did not differ among fertilizer treatments for any plant part (data not presented). Leaves of nonfertilized plants or those receiving MAP had greater Ca contents than those fertilized with ammonium sulfate or Mg oxide (Table 7). Leaves of plants fertilized with the hand mix, TSP, or Ca sulfate did not differ in Ca content from leaves of plants fertilized with any other fertilizer. Red fruit of plants fertilized with MAP had a greater Ca content than red fruit from any other fertilizer treatment (including the nonfertilized control) except for the hand mix. Red fruit from plants fertilized with the hand mix did not differ in Ca content from red fruit of plants receiving any other fertilizer treatment or nonfer-

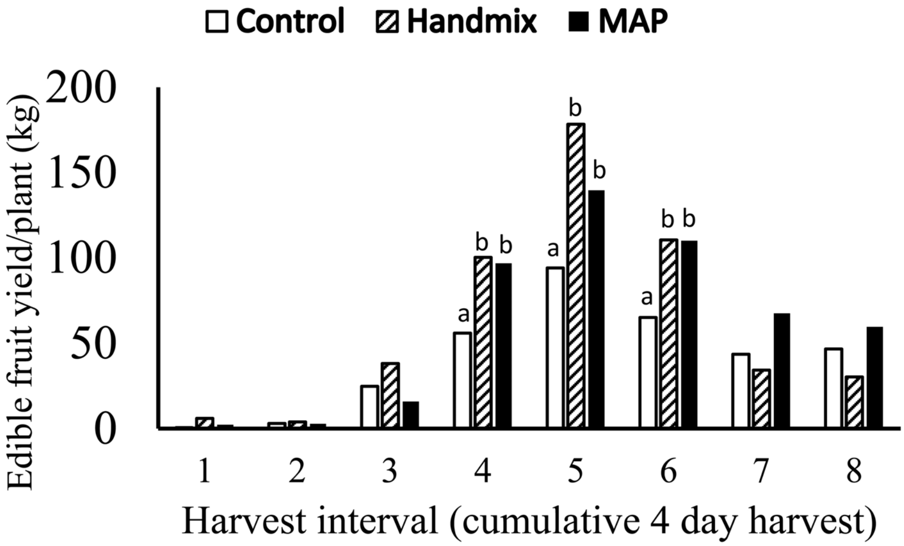

Fig. 1. Tomato harvest at 4-day intervals from plants fertilized with 4.9 g m^{-2} magnesium ammonium phosphate (MAP), a hand mixture of calcium sulfate, magnesium oxide, ammonium sulfate, and triple superphosphate to provide the same amount of Ca, Mg, N, and P as the MAP, or not fertilized. Bars with the same letter within harvest interval are not significantly different by the protected LSD, $P \leq 0.05$.

tilized plants. Calcium content of green fruit from plants fertilized with MAP or TSP was lower than that of green fruit from nonfertilized plants or those fertilized with Ca sulfate. Calcium content of green fruit from plants fertilized with the hand mix, ammonium sulfate, or Mg oxide did not differ from that of green fruit from any other fertilizer treatment. Total plant Ca content was greatest in nonfertilized plants or those fertilized with MAP, and lowest in those fertilized with Mg oxide, TSP or ammonium sulfate. Total plant Ca of plants receiving Ca sulfate was greater than total plant Ca of plants receiving Mg oxide, but did not differ from that of nonfertilized plants or those fertilized with MAP. Plants fertilized with the hand mix did not differ in plant Ca content from plants in any fertilizer treatment or nonfertilized control plants.

Magnesium concentration and content did not differ among fertilizer treatments for roots, stems, or leaves (data not presented). Magnesium concentration also did not differ among fertilizer treatments for red fruit, but green fruit from plants fertilized with triple superphosphate had a greater Mg concentration than green fruit from plants fertilized with the hand mix or Mg oxide (Table 8). Green fruit of plants fertilized with MAP or Ca sulfate did not differ in Mg concentration from green fruit of plants fertilized with any other fertilizer or nonfertilized plants. Magnesium content in red fruit from plants fertilized with MAP or the hand mix was greater than for red fruit from plants fertilized with Mg oxide. Red fruit from nonfertilized plants or plants fertilized with ammonium sulfate had a lower Mg content than red fruit from plants fertilized with the hand mix. Red fruit from plants fertilized with triple superphosphate or Ca sulfate did not differ in Mg content from red fruit of nonfertilized plants or plants fertilized with any other fertilizer. In contrast, green fruit from plants fertilized with Ca sulfate had a greater Mg content than green fruit from plants fertilized with MAP or TSP. Green fruit from nonfertilized control plants had a greater Mg content than green fruit from plants fertilized with MAP. Green fruit from plants fertilized with the hand mix, ammonium sulfate, or Mg oxide did not differ in Mg content from green fruit of nonfertilized plants or plants receiving any other fertilizer.

Iron and Mn concentrations were similar among fertilizer treatments for all plant parts tested (data not presented). Likewise, Fe and Mn content of roots and stems and total plant Fe and Mn content did not differ among fertilizer treatments (data not presented). Iron content in leaves and red fruit was similar among fertilizer

Table 7
Nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) content (g/plant part) in tomato leaves, red fruit, and green fruit at harvest of plants receiving selected fertilizer treatments in 2012. *n* = 10.

Fertilizer applied	Leaf	Red fruit	Green fruit	Total
N content (g/plant part)				
None	8.99	12.0a[z]	4.12b	31.2
MAP[y]	8.68	16.0ab	2.77a	34.0
Hand mix[y]	7.30	17.9b	3.51ab	32.4
Ammonium sulfate	6.81	12.0a	3.71ab	26.6
Triple superphosphate	7.00	14.3ab	2.75a	27.7
Calcium sulfate	9.18	13.4ab	4.52b	32.9
Magnesium oxide	6.46	11.4a	3.20ab	21.2
P content (g/plant part)				
None	0.454	1.15	0.439b	2.52
MAP[y]	0.415	1.37	0.280a	2.52
Hand mix[y]	0.330	1.55	0.361ab	2.48
Ammonium sulfate	0.325	1.18	0.381ab	2.19
Triple superphosphate	0.362	1.35	0.289a	2.28
Calcium sulfate	0.461	1.23	0.476b	2.62
Magnesium oxide	0.300	1.00	0.344ab	1.60
K content (g/plant part)				
None	6.28	20.98	7.05b	43.27
MAP[y]	5.26	27.07	4.48a	46.59
Hand mix[y]	4.37	30.02	5.89ab	45.49
Ammonium sulfate	4.28	22.06	6.29ab	38.930
Triple superphosphate	4.79	25.85	4.84a	41.11
Calcium sulfate	5.99	23.48	7.70b	45.52
Magnesium oxide	5.20	19.25	5.59ab	29.50
Ca content (g/plant part)				
None	9.83b	0.457a	0.18b	13.52c
MAP[y]	10.16b	0.621b	0.10a	13.88c
Hand mix[y]	7.90ab	0.603ab	0.13ab	10.85ac
Ammonium sulfate	6.49a	0.502a	0.15ab	9.78ab
Triple superphosphate	7.28ab	0.520a	0.12a	9.89ab
Calcium sulfate	9.17ab	0.444a	0.19b	13.00bc
Magnesium oxide	5.67a	0.427a	0.13ab	7.87a

[z] Means within columns and N, P, K, or Ca content followed by the same letter do not significantly differ by LSD, $P \leq 0.05$.

[y] MAP = magnesium ammonium phosphate, hand mix refers to a mixture of ammonium sulfate ($(NH_4)_2SO_4$), triple superphosphate, calcium sulfate ($CaSO_4$), and magnesium oxide (MgO) at the same concentration as each of these fertilizers applied in individual fertilizer treatments.

Table 8
Magnesium (Mg) concentration (%) and content (g/plant part) in red and green tomato fruit at harvest of plants receiving selected fertilizer treatments in 2012. $n = 10$ for all other plant parts.

Fertilizer applied	Plant part	
	Red fruit	Green fruit
	Mg concn (% DW)	
None	0.167	0.242bc[z]
MAP[y]	0.158	0.238abc
Hand mix[y]	0.165	0.232ab
Ammonium sulfate	0.153	0.229a
Triple superphosphate	0.166	0.251c
Calcium sulfate	0.182	0.238abc
Magnesium oxide	0.153	0.235ab
	Mg content (g/plant part)	
None	0.750ab	0.312bc
MAP[y]	1.003bc	0.204a
Hand mix[y]	1.105c	0.261abc
Ammonium sulfate	0.745ab	0.276abc
Triple superphosphate	0.913abc	0.225ab
Calcium sulfate	0.876abc	0.341c
Magnesium oxide	0.664a	0.252abc

[z] Means within columns and Mg concentration or content followed by the same letter did not significantly differ by LSD, $P \leq 0.05$. Means within columns and elemental concentration or content without letters did not significantly differ ($P \leq 0.05$) among treatments.

[y] MAP = magnesium ammonium phosphate, hand mix refers to a mixture of ammonium sulfate ($(NH_4)_2SO_4$), triple superphosphate, calcium sulfate ($CaSO_4$), and magnesium oxide (MgO) at the same concentration as each of these fertilizers applied in individual fertilizer treatments.

Table 9
Iron (Fe) and manganese (Mn) content and zinc (Zn) concentration and content in leaves, red fruit and green fruit of tomato plants receiving selected fertilizer treatments in 2012. $n = 10$ for all plant parts.

Fertilizer applied	Plant part		
	Leaf	Red fruit	Green fruit
	Iron content (mg/plant part)		
None	22.9	21.5	11.2 cd[z]
MAP[y]	23.0	27.0	10.3bcd
Hand mix[y]	18.6	32.1	7.4ab
Ammonium sulfate	16.3	27.1	11.4 cd
Triple superphosphate	17.1	26.7	5.7a
Calcium sulfate	22.1	25.3	12.8d
Magnesium oxide	14.9	22.3	7.9abc
	Manganese content (mg/plant part)		
None	30.2b	7.7a	3.1
MAP[y]	26.6ab	10.5b	2.2
Hand mix[y]	20.3ab	12.7c	2.8
Ammonium sulfate	17.4a	8.1ab	2.9
Triple superphosphate	18.6ab	9.3ab	2.2
Calcium sulfate	25.0ab	9.4ab	3.5
Magnesium oxide	19.9ab	6.9a	2.8
	Zinc concn. (µg/g DW)		
None	29ab	25	64ab
MAP[y]	34bc	22	103b
Hand mix[y]	31ab	29	49a
Ammonium sulfate	27a	26	66ab
Triple superphosphate	35bc	27	60ab
Calcium sulfate	39c	28	56a
Magnesium oxide	38c	26	32a
	Zinc content (mg/plant part)		
None	8.7abc	11.2a	8.3c
MAP[y]	9.8bc	13.9a	9.8c
Hand mix[y]	7.2ab	19.4b	5.5ab
Ammonium sulfate	6.0a	12.6a	7.9bc
Triple superphosphate	7.8ab	15.1a	5.4ab
Calcium sulfate	11.1c	13.1a	8.1bc
Magnesium oxide	7.9abc	11.0a	3.4a

[z] Means within columns and Fe or Mn content or Zn concentration or content followed by the same letter do not significantly differ by LSD, 5% level. Means within columns and Fe or Mn content without letters did not significantly differ (5% level) among treatments.

[y] MAP = magnesium ammonium phosphate, hand mix refers to a mixture of ammonium sulfate ($(NH_4)_2SO_4$), triple superphosphate, calcium sulfate ($CaSO_4$), and magnesium oxide (MgO) at the same concentration as each of these fertilizers applied in individual fertilizer treatments.

treatments, but Fe content of green fruit from plants fertilized with ammonium sulfate, Ca sulfate, or nonfertilized control plants was greater than when fertilized with the hand mix or TSP (Table 9). Green fruit from plants fertilized with Ca sulfate had a greater Fe content than when fertilized with Mg oxide, TSP, or the hand mix.

Leaf Mn content was greater in nonfertilized plants than in plants fertilized with ammonium sulfate (Table 9). Manganese content of leaves from nonfertilized plants or plants fertilized with ammonium sulfate did not differ from that of leaves from plants receiving any other fertilizer treatment. Manganese content of red fruit from plants fertilized with the hand mix was greater than that of red fruit from plants fertilized with MAP. Manganese content of red fruit fertilized with MAP was greater than for red fruit from plants fertilized with Mg oxide or nonfertilized plants. Red fruit from plants fertilized with ammonium sulfate, TSP, or Ca sulfate did not differ in Mn content from red fruit of plants fertilized with MAP, Mg oxide, or nonfertilized plants. Fertilizer treatments did not affect Mn content of green fruit.

Zinc concentration and content did not differ among fertilizer treatments for roots or stems, and total plant Zn content was similar among fertilizer treatments (data not presented). Zinc concentration was greater in leaves of plants fertilized with Ca sulfate or Mg oxide than in foliage from plants fertilized with ammonium sulfate, the hand mix, or nonfertilized plants (Table 9). Foliar Zn concentration of plants fertilized with MAP or TSP was greater than foliar Zn concentration of plants treated with ammonium sulfate, but did not differ from plants receiving any other fertilizer or nonfertilized plants. Zinc concentration of green fruit from plants fertilized with MAP was greater than Zn concentration of green fruit from plants fertilized with the hand mix, Ca sulfate, or Mg oxide, but green fruit from plants fertilized with ammonium sulfate, TSP, or nonfertilized plants did not differ in Zn concentration from green fruit of plants fertilized with MAP, the hand mix, Ca sulfate, or Mg sulfate.

Foliar Zn content from plants fertilized with Ca sulfate was greater than for plants fertilized with the hand mix, ammonium sulfate, or TSP. Zinc content of red fruit from plants fertilized with the hand mix was greater than for red fruit from any other fertilizer treatment (Table 9). Zinc content of green fruit from nonfertilized plants or those fertilized with MAP was greater than Zn content of green fruit from plants fertilized with the hand mix, TSP, or Mg oxide.

3.3. *Experiment 3, fertilizer solubility kinetics*

Based on the solubility index experiment, nutrient release was always faster for conventional sources such as Ca sulfate, ammonium sulfate, and TSP, compared to MAP and CRF (Fig. 2). In fact, the conventional fertilizers reached near 100% solubility very quickly for N and Ca. Although the release was slower, MAP was generally able to achieve nearly equal nutrient release to conventional nutrient sources by hour 48 of the solubility experiment. An exception to this general observation was for Mg; MAP released more Mg in a shorter time compared to Mg oxide. In general, MAP was much more soluble and had faster dissolution kinetics than CRP.

4. Discussion

In the first experiment, plants receiving the slowly soluble fertilizer MAP were taller and wider than those receiving CRF early in the study. Magnesium ammonium phosphate nutrient release

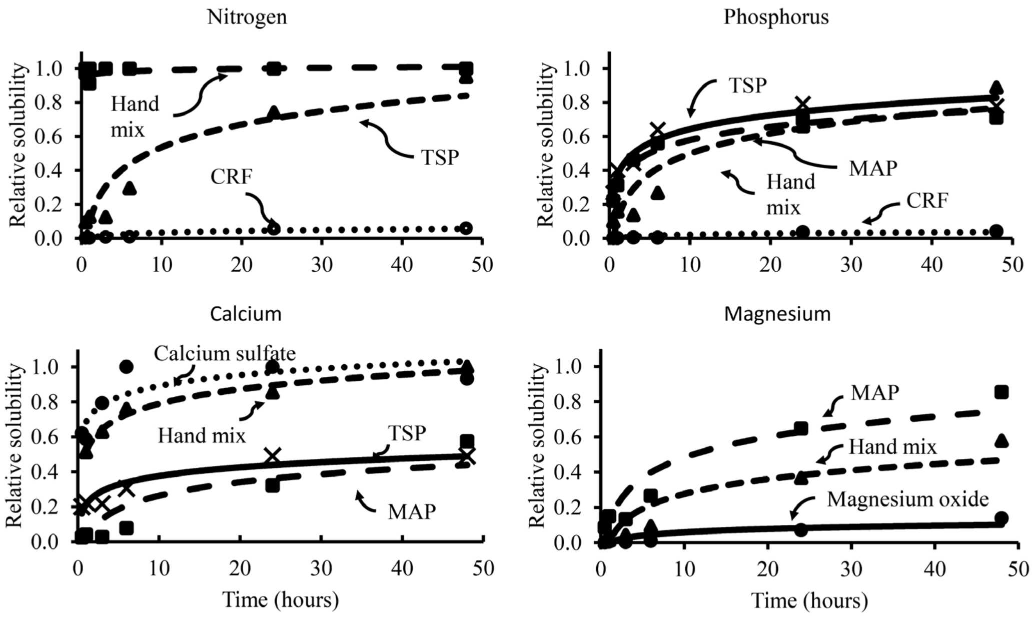

Fig. 2. Relative solubility (nutrient mass released/total nutrient content, a value of 0 indicates complete insolubility and 1 complete solubility) of nitrogen, controlled release fertilizer (CRF. circle) Y = 0.0144logX-0.0004, $R^2 = 0.84$, p = 0.01; hand mix (square), Y = 0.0126logX + 0.9612, $R^2 = 0.39$, p = not significant; triple superphosphate (TSP, triangle), Y = 0.1933logX + 0.091, $R^2 = 0.87$, p = 0.01; ammonium sulfate is not shown, all relative solubility values were 1. Phosphorus, CRF (circle) Y = 0.009logX-0.0006, $R^2 = 0.81$, p = 0.01; hand mix (triangle) Y = 0.11logX + 0.32, $R^2 = 0.98$, p = 0.001, magnesium ammonium phosphate (MAP, square) Y = 0.17logX + 0.10, $R^2 = 0.86$, p = 0.01, TSP (X) Y = 0.12logX + 0.37, $R^2 = 0.95$, p = 0.001. Calcium, hand mix (triangle) Y = 0.11logX + 0.62, $R^2 = 0.97$, p = 0.001; MAP (square) Y = 0.11logX + 0.006, $R^2 = 0.77$, p = 0.05, TSP (X) Y = 0.072logX + 0.21, $R^2 = 0.88$, p = 0.01; calcium sulfate (circle) Y = 0.09logX + 0.68, $R^2 = 0.73$, p = 0.05. Magnesium, hand mix (triangle) Y = 0.12logX-0.004, $R^2 = 0.81$, p = 0.01; MAP (square) Y = 0.17logX + 0.97, $R^2 = 0.87$, p = 0.01; magnesium oxide (circle) Y = 0.027logX-0.0035, $R^2 = 0.75$, p = 0.05.

was probably quicker than the CRF resulting in faster plant growth. Plant heights between fertilized plants were similar by four weeks after planting and plant widths were similar by eight weeks. The positive relationship between MAP concentration with height and width but lack of affect using CRF after two weeks growth supports this theory. By four weeks, positive trends between fertilizer with height and width were apparent for both fertilizers (Table 1).

Neither slowly soluble MAP nor CRF consistently affected edible fruit yield during the first year, but the number and weight of culls was greater with both fertilizers than with no fertilizer. This difference may be explained by the larger number and weight of fruit formed in the presence of fertilizer compared to without fertilizer. Culls were primarily due to mechanical damage from birds and other wildlife. The larger number of fruit or larger sized fruit in fertilized treatments may have been more visibly appealing and readily accessible to wildlife than in treatments without fertilizer. A study of American robins (*Turdis migratorius*) showed that berry choices made among *Crataegus monogyna* fruits were correlated with fruit abundance, fruit size, and fruit pulpiness (Sallabanks, 1993). While not tested in this study, it is also possible that fruit from fertilized plants contained compounds that made those fruit more attractive than fruit from nonfertilized plants. Fleming et al. (2008) found that in nectarivorous bird lineages hexose was the preferred sugar rather than sucrose in dilute diets, but sucrose was the preferred sugar source in more concentrated diets. We speculate that the greater fruit abundance, higher soluble solids or protein concentration in fruit from fertilized plants may have contributed to greater depredation losses.

In the second experiment stem dry weights of plants and total fresh weight of edible fruit receiving MAP or the hand mixture of individual elements generally were larger and produced more fruit than those plants that received individual nutrients or control plants. No nutrient deficiency symptoms were visible in any treatment, including the controls. Liebig's Law of the Minimum states that deficiency or absence of one nutrient with all others present limits plant growth (van der Ploeg et al., 1999). Magnesium ammonium phosphate and the hand mixture had several nutrients mixed together to meet plant demands; whereas, ammonium sulfate, Ca sulfate, or Mg oxide provided only one or two nutrient elements for plant use. Fertilization with a single element appeared to result in below optimal concentrations of certain essential elements on those treatments that affected plant growth and fruit development. Differences in plant performance did not consistently point to a single element being inadequate, but suggested that for certain aspects of plant development different elements were in short supply. Plants receiving Ca sulfate had greater numbers and weights of green fruit at termination of the experiment than plants receiving MAP (Table 6). Calcium is important in fruit cell wall and cell membrane stability, and Ca deficiencies often appear as fruit malformations including blossom end rot and catfacing in tomatoes (Mayfield and Kelley, 2012). While these symptoms were not present in any treatment, the highly soluble Ca sulfate may have provided more Ca for plant uptake resulting in greater green fruit numbers and weights at the conclusion of the study than with the slowly soluble MAP.

Davidson et al. (2000) noted that nutrient intensity and balance are reflected in the chemical composition of plant parts when plants are in the same stage of growth or development, all other factors being constant. In 2011 foliar N concentration in all fertilizer treatments was within the sufficiency range of 3.5% to 5.1% for broadleaved vegetable plants (Barker and Bryson, 2007). However, a significant trend of increasing foliar N concentration with MAP application rate existed (Table 3). The fact that this trend occurred for MAP and not CRF suggests that N supplied from CRF was not as soluble as MAP. The solubility index test confirmed that MAP released more N than CRF, and at a faster rate (Fig. 2). In 2012, foliar N concentration for untreated plants and those receiving MAP were below the sufficiency range, but they did not differ from those of plants in other treatments and were not low enough that N deficiency symptoms were apparent. Nitrogen concentration in both red and green fruit was similar to fruit N concentrations reported by Elia and Conversa (2012). Although the soil test prior to the study showed nitrate-N to be lacking, plants absorbed similar amounts of N regardless of fertilizer treatments. In the 1920′s and 1930′s cotton (*Gossypium hirsutum* L.) and was a common crop in this region, and it was often grown annually until soil nutrients were inadequate to produce an economical return. This study was conducted on such a site. When cotton was no longer deemed productive, the field was abandoned and allowed to revegetate naturally over the next 60 to 80 years. When it was tilled for this study, the predominant vegetation was native prairie grasses and forbs. Organic matter concentrations are relatively high in soils populated with prairie vegetation (Funderburg, 1997) and was about 2.3 percent in this soil. Organic matter is stable in untilled soil and usually only about 5 percent of it mineralizes yearly. The rate of decomposition is increased with tillage when temperature is favorable and tillage exposes soil organic matter to oxygen, and irrigation maintains adequate moisture to support rapid mineralization by microorganisms. We speculate that this source of N, not identified in the soil test, resulted in few differences in tissue N concentration among treatments, despite low soil nitrate prior to the study.

Differences in N content among fertilizer treatments in red and green fruit were not due to differences in N concentration among treatments, but rather due to differences in the weight of red and green fruit produced among the treatments. Elia and Conversa (2012) noted that excess N results in greater vegetative growth and lower fruit set. In our study, ammonium nitrate likely provided N more quickly than MAP (Fig. 2), but red fruit N content did not differ between the ammonium sulfate-treated plants and MAP-treated plants (Table 7). The initial flush of soluble N from ammonium sulfate may not have corresponded with the timing of plant needs for N, while MAP served as a slow-release N source (Fig. 2). In contrast, ammonium sulfate was present in the hand mix, and N content of red fruit was greater with the hand mix than with ammonium sulfate alone (Table 7). This suggests that plants in the ammonium sulfate treatment lacked some other essential element that resulted in less fruit set than plants receiving the mixture of nutrient elements in MAP or the hand mix. Because N content of red fruit from the hand mix (contained N, P, S, Ca, and Mg) was greater than ammonium sulfate (contained N and S), and since the hand mix resulted in equal N contents to MAP (contained N, P, Ca, and Mg) and TSP (contained P and Ca), it is likely that increasing application of P alone or in combination with Ca improved overall N uptake.

In both years, P concentration in all vegetative plant parts (ranging from 0.109% to 0.150%) regardless of fertilizer treatment was at the low end of the sufficiency range (Sanchez, 2007), and no deficiency symptoms appeared supporting that P concentration was adequate. Phosphorus concentration of red and green fruit was greater than for vegetative plant parts and was well within the sufficiency range (Sanchez, 2007) for plants in all fertilizer treatments. Leaf K (3.36%), Ca (1.87%), and Mg (0.51%) regardless of presence or absence of fertilizer were within established sufficiency ranges for tomato (Mengal, 2007; Pilbeam and Morley, 2007; Merhaut, 2007). The unconventional MAP released P to the same degree as TSP, both alone and in a mix, although the P release was somewhat delayed compared to TSP. Compared to the un-conventional CRF, MAP released more P at a faster rate (Fig. 2).

In 2012, although P, K, and Ca concentration did not differ among fertilizer treatments in any plant tissue, the total P and K content of green fruit and Ca content of leaves, red fruit, green fruit, and total Ca content for plants differed among fertilizer treatments (Table 7). These variances were attributed to differences in growth and fruit yield among the fertilizer treatments in which bigger plants or plants with larger yield had more P and K in green fruit and greater Ca in leaves and fruit. For example, it is interesting to note that two of the most soluble P sources, as indicated by the solubility experiment (MAP and TSP; Fig. 2), contained significantly less P in the green fruit compared to the control and Ca sulfate, which received no P. For Ca contents in leaves, red and green fruit, and total Ca, notice that the MAP and control fertility treatments were always among the top two. Again, this suggests that the ability of the fertilizer to release the nutrient (Fig. 2) is not the only factor that has an impact on Ca content. It is possible that the timing of nutrient release could have affected the total Ca content; for example, MAP, which did not release as much Ca as Ca sulfate, provided a slow release of the nutrient that may have coincided with plant uptake demand. Even though Ca sulfate (either alone or in a mixture) released more Ca than MAP, the MAP treatment resulted in greater Ca content than Ca sulfate, although not always significant (Table 7).

Likewise, Mg concentration did not differ for any tissue tested except green fruit, but the Mg content of red fruit differed among fertilizer treatments due to more fruit mass in some treatments. Magnesium concentration of green fruit differed among fertilizer treatments, but it is interesting to note that the greatest Mg concentration occurred with TSP which contains no Mg. Applied P increases root growth (Anghinoni and Barber, 1980; Borkert and Barber, 1985) and may have contributed to enhanced Mg uptake and partitioning to the green fruit. Despite the greater Mg concentration with TSP, green fruit from plants fertilized with Ca sulfate contained more Mg than fruit from plants fertilized with TSP. Thus, fruit yield improved with Ca sulfate such that Mg content was greater in fruit from that treatment despite the Mg concentration advantage of fruit from plants fertilized with TSP. These results suggest that the ability of the fertilizer to supply Mg had less impact on the Mg content of red and green fruit than did the nutrient balance and added P since the top three treatments that contained the most Mg in red fruit were the only fertilizer treatments that added P (Table 8; mix, MAP, and TSP). From another perspective, three of the four treatments with the highest Mg content in green fruit (Table 8; mix, MAP, and Ca sulfate) all added sulfate, which increases Mg solubility. Regardless, Fig. 2 shows that the raw ability of the fertilizers to supply Mg to solution was the largest and most efficient (with regard to time) for MAP compared to the other fertilizer that contained Mg, either alone or in a mix (e.g. Mg oxide).

Foliar Fe, Mn, and Zn concentrations were within sufficiency ranges for field type tomato plants in all treatments (Mills and Jones, 1996). Iron and Mn concentrations in the various tissues tested did not differ by fertilizer treatment, but total Fe and Mn content in some tissues differed by fertilizer treatment. These differences were associated with treatments affecting dry weight of the various plant parts. Thus, uptake of Fe and Mn was greater when plants were larger although concentrations of these two elements suggested no treatment differences. In contrast, Zn concentration differed in leaves and green fruit among the fertilizer treatments. Although Zn was not added as a fertilizer other nutrients had a small, but noticeable impact on leaf Zn concentration. Both Ca sulfate and Mg oxide treatments enhanced leaf Zn concentration compared to the control, but other plant parts were unaffected (Table 9). The Zn content of leaves and green fruit did not follow the same pattern as Zn concentrations in these tissues, thus tissue concentration does not account for all of the differences in Zn content. The other variable affecting Zn content is dry weight of the various plant parts at harvest, which impacted Zn content of leaves, red fruit, and green fruit more than the concentration.

From this study, we conclude that the various fertilizers were effective in increasing N, P, K, Ca, and Mg and they maintained, increased, or decreased Fe, Mn, and Zn in various plant parts. The intensity of the effects differed depending on plant part tested and fertilizer source. Fertilizer differences were more apparent in total nutrient content of various plant parts than in nutrient concentration for all of the nutrients investigated. This reflects certain nutrients or combinations of nutrients enhancing growth or production resulting in a large amount of the nutrient absorbed and allocated to a demand center that was not detectable by measuring concentrations because of inherent variability. Mixtures of fertilizers (MAP, CRF, and hand mix) did not greatly affect concentration of N, P, K, Ca, or Mg compared to the individual fertilizers.

Micronutrient content was more sensitive to fertilizer treatment than concentration for Fe and Mn. This reflects certain nutrients or combinations of nutrients enhancing growth or production resulting in a large amount of the nutrient absorbed and allocated to a demand center that was not detectable by measuring concentrations. Likewise, although differences in Zn concentration existed in leaves and green fruit, the differences in total Zn content of leaves, red fruit and green fruit followed a different pattern. Mixtures of fertilizers (MAP, CRF, and hand mix) minimally affected the concentration of Fe and Mn compared to the individual fertilizers. Since none of the fertilizers contained micronutrients, unless unknowingly contaminated, the elements present in the fertilizers affected micronutrient uptake and allocation patterns indirectly. The absence of an element limited plant growth or nutrient uptake in some situations, and in other cases enhanced growth creating more demand for another element. In this study, no nutrients were clearly deficient, but plants responded in some instances with improved growth or yield. This suggests that either elemental sufficiency ranges may require minor adjustment or that the ratio of certain nutrients in index tissue may be useful in fine tuning fertility programs.

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