Transplant Fertilizer Solution and Early Season Plastic Mulch Increase Tomato Yield in Adequate Fertility Clay Loam Soil

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SUMMARY. It is commonly recommended to apply phosphorus- or nitrogen- and phosphorus-containing water-soluble fertilizers to annual vegetables at transplant to improve establishment and enhance yield. Plastic mulches are also recommended to increase soil temperature and enhance yield through similar root growth-promoting mechanisms early in the season. Our aim was to determine if the recommendations for transplant fertilizer solutions and plastic mulch are justified, and if the effects are interactive in a clay loam soil with moderate or high levels of existing phosphorus fertility and organic matter. We transplanted ‘Plum Dandy’ tomato (*Solanum lycopersicum*) in 2014 and 2015 into a field with high fertility using black polyethylene mulch or no mulch, and transplant solution containing water, 320 mg/plant nitrogen, or 320 mg/plant nitrogen + 475 mg/plant phosphorus. Mulch was removed 26 to 28 days after transplanting to eliminate midseason and late season mulch effects. We found yield-promoting and maturity-hastening effects in both years from transplant solutions containing both nitrogen and phosphorus (18% greater total ripe fruit weight than water control), and similar benefits of early season black plastic mulch (24% greater total ripe fruit weight than no mulch), indicating usefulness of either treatment in tomato production. We found no interactive effects of mulch and transplant solution.

Nonreflective plastic mulches are regularly shown to increase early and total yield in tomato, and most of this effect has been attributed to increased soil temperature (Díaz-Pérez and Dean Batal, 2002; Grubinger et al., 1993; Schonbeck and Evanylo, 1998a). The assumption is that elevated early season soil temperature under plastic mulch enhances the ability of roots to assimilate nutrients, especially phosphorus (P), which plays a large role in increasing yield (Grubinger et al., 1993; Wien et al., 1993). Transplant solutions containing P are recommended to commercial tomato growers (Rosen and Eliason, 2005; University of Minnesota, 2016) and gardeners (Rosen et al., 2008) for similar purposes: to provide ready access to early season P, which ultimately enhances and accelerates yield (Jones and Warren, 1954). Nitrogen (N) content of transplant

solutions is not considered in recommendations, except when adjusting for total N applied before planting.

We are aware of no published research on tomato grown in plastic mulch in lower-temperature heavy, fertile soils widespread in the upper midwestern United States. Soil texture and drainage properties have a large impact on soil temperature (Jin et al., 2008), perhaps influencing response to plastic mulch and its interaction with transplant solution. In addition, the little published information on transplant solution P provides no consensus on whether transplant solution P is universally beneficial under all circumstances. Reported impacts of transplant solution P on yield are minimal or variable in high-P-fertility

soils or P-fertilized soils (Arnold, 1953; Grubinger et al., 1993). The objective of this study was to evaluate the ability of black plastic mulch, P- and N-containing transplant fertilizer solutions, and combinations of mulch and transplant solutions to increase and hasten tomato yield in a fine-texture clay loam soil with little pre-existing need for P fertilizers. We are specifically interested in determining if the increased soil temperatures under plastic mulch replace the utility of P-containing transplant solutions in these soils, and if mulch and transplant solution effects are independent. We also sought to distinguish the effects of N compared with combined N + P in the transplant solution.

Materials and methods

The experiment was conducted in a Nicollet-Webster soil (fine-loamy mixed mesic Aquic Hapludoll and Typic Endoaquoll) in Waseca, MN (lat. 44.076°N, long. 93.523°W). In both 2014 and 2015, the previous crop was cabbage (*Brassica oleracea* var. *capitata*) and brussels sprouts (*B. oleracea* var. *gemmifera*). In 2014, 40 lb/acre nitrogen (urea, 46N-0P-0K) was incorporated into the soil before establishing two 30-inch-wide raised beds in an east-west orientation, 6 ft apart on center and 4 inches high. No additional P- or potassium (K)-containing fertilizers were broadcast in 2014 despite recommendations, because little yield response was expected from broadcast P and K. In 2015, a single raised bed was made first, then granular fertilizers (0N-0P-49.8K potassium chloride, 18N-20.1P-0K diammonium phosphate, and 0N-20.1P-0K triple superphosphate) were broadcast over a 5-ft-wide area including the raised bed, giving 15 lb/acre N, 32.8 lb/acre P, and 41.5 lb/acre K, to ensure P and K

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.2366	cup(s)	L	4.2268
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
28,350	oz	mg	3.5274 × 10 ⁻⁵
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Table 1. Fertilizer recommendations [nitrogen (N), phosphorus (P), or potassium (K)] directed at three different types of tomato growers: local (Minnesota) or regional (midwestern United States) commercial growers, or local gardeners. Recommendations are based on preplant soil test results in 2014 and 2015. Amount of each nutrient applied preplant or sidedress (“granular”) and in one of three transplant solutions applied to each plant at transplant [1 cup (0.24 L) containing either water, urea ammonium nitrate [UAN (28N–0P–0K)], or ammonium polyphosphate [APP (10N–14.9P–0K)]] is also shown. Half the granular N was applied before planting, and half was applied 26–28 d after transplant.

Nutrient	Nutrient amount (lb/acre) ^z								Nutrient supplied by transplant solution (2014 and 2015)		
	2014				2015						
	Recommendations			Granular nutrient applied	Recommendations			Granular nutrient applied			
	Local grower ^y	Local gardener ^x	Regional grower ^w		Local grower ^y	Local gardener ^x	Regional grower ^w				
N	90	130.7	80–100	80	110	130.7	80–100	80	0	3.5	3.5
P	21.9	0	21.9	0	32.8	0	32.8	32.8	0	0	5.2
K	83	43.6	83	0	41.5	36.6	41.5	41.5	0	0	0

^z1 lb/acre = 1.1209 kg·ha⁻¹.

^yRosen and Eliason (2005).

^xRosen et al. (2008).

^wUniversity of Minnesota (2016).

Fig. 1. Average minimum and maximum (—) and overall average (■) air temperature for 11-d periods, beginning at transplanting, in 2014 and 2015. 30-year (1984–2013) average minima, maxima (—), and overall average (□) are also shown, as well as harvest period (shaded area). Daily precipitation is indicated by vertical bars; $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$, 1 inch = 2.54 cm.

sufficiency despite high soil test levels. Then, 25 lb/acre N (28N–0P–0K urea) was applied, but the urea was only applied to the top of the bed itself. These fertilizers were

incorporated into the raised bed with a single-wheel cultivator before applying plastic mulch in 2015. In both years, 1.0-mil embossed black plastic mulch (Climagro™; Leco Industries,

Saint-Laurent, QC, Canada) was applied to the full length of each raised bed mechanically. The mulch remained intact for 5 d until just before transplanting, when the plastic was manually removed from the “no mulch” treatments so that each mulch-treated plant had a minimum of 18 inches of plastic mulch within the length of the row, and each nonmulched plant had a minimum of 18 inches bare soil within the length of the row. The cut edges of the mulch were secured by covering with soil.

‘Plum Dandy’ tomato seeds (Territorial Seed, Cottage Grove, OR) were sown on 16 Apr. 2014 or 21 Apr. 2015 in 3204 trays with peat-based potting mix (Sunshine® LC8; SunGro Horticulture, Anderson, SC), and germinated under mist. They were transplanted to 1801 trays after emergence. Transplants were fertilized once in 2014 and twice in 2015 with 125 mg·L⁻¹ N using 15N–2.2P–12.5K fertilizer (Peter’s Excel Cal-Mag; Everris International, Geldermalsen, Netherlands) before transplanting. After hardening off outdoors (8 d), transplants were hand-planted to the lowest true leaf, and the lowest two leaves were removed at that time. Then 1 cup of transplant solution was applied to the planting hole. The transplant solution was either reverse osmosis water, urea ammonium nitrate (UAN) in water [28N–0P–0K (320 mg/plant N, 1354 mg·L⁻¹ N)], or ammonium polyphosphate (APP) in water [10N–14.9P–0K (320 mg/plant N + 475 mg/plant P, 1354 mg·L⁻¹ N + 2012 mg·L⁻¹ P)]. Adjacent soil was used to cover the planting hole in the plastic mulch, and the equivalent was performed

for unmulched plants. Total fertilizer application for each year is summarized in Table 1.

Table 2. Preplant soil test results in 2014 and 2015. Relative nutrient levels are indicated based on Rosen and Eliason (2005). Olsen-phosphorus was not measured in 2014 because pH was 7.4 (Rosen and Eliason, 2005).

Property	2014 ^a	2015
pH	7.4	7.5
Organic matter (%)	5.0 (H)	4.4 (M)
Phosphorus (mg·kg ⁻¹) ^y		
Bray	35 (MH)	30 (MH)
Olsen	—	19 (MH)
Potassium (mg·kg ⁻¹)	155 (H)	162 (VH)

^aVH = very high; H = high; MH = medium-high; M = medium.

^y1 mg·kg⁻¹ = 1 ppm.

The experiment was planted in a randomized complete block design each year, with 10 complete blocks in 2014 (planted on 29 May) and six complete blocks in 2015 (planted on 27 May). The two mulch treatments and three transplant solution treatments were arranged randomly within each complete block. A single tomato plant was grown per treatment in each block (six tomato plants per block; 60 total plants in 2014, 36 in 2015). Tomato plants were spaced 42 inches apart within the row. At transplant, short-stature freely branching 'Little Becka'-sunflower (*Helianthus annuus*) was seeded between each tomato (21 inches from tomato plants, and offset 6 inches across the bed) to act as a border between fertility and mulch treatments. The sunflowers also helped to clearly delineate single tomato plants, making harvest easier. Three sunflowers were

sown and thinned to a single plant between each tomato after emergence.

Soil temperature was recorded on each plot in six blocks in each year. Temperatures were recorded manually at 4-inch depth using a digital stem thermometer (Traceable® Lollipop™ 4731; Control Co., Friendswood, TX). Measurements were made at different times between 0830 and 1500 HR, 12 times total in 2014 and 8 times in 2015, all occurring between planting and removal of mulch. All plastic was removed from mulched plots 26 or 28 d after transplanting (24 June each year). An additional 40 lb/acre N (Agrotain®-treated urea; Genesis Growing Solutions, Le Sueur, MN) was surface-applied to each raised bed the day after mulch was removed each year, assuming 5 ft between raised beds for area calculations.

Plants were irrigated with drip irrigation as needed and sprayed with

Table 3. Effects black plastic mulch transplant solution on cumulative yield and number of marketable pink, light red, or red 'Plum Dandy' tomatoes in 2014 and 2015. Transplant solutions were 1 cup (0.24 L) of either water, urea ammonium nitrate in water [UAN (1354 mg·L⁻¹ nitrogen)], or ammonium polyphosphate in water [APP (1354 mg·L⁻¹ nitrogen + 2012 mg·L⁻¹ phosphorus)]. Plants were grown for 26–28 d with (+) or without (–) black plastic mulch at the beginning of the season. Fruit count data were square root transformed before analyses [$\sqrt{(\text{number of fruit})}$], and untransformed means are reported.^z

Source of variation	First 99 d after transplanting		End of season	
	Yield (kg fresh weight) ^z	Yield (no. fruit)	Yield (kg fresh weight)	Yield (no. fruit)
Year (Y)				
2014	3.7	39	5.5	59
2015	3.4	45	8.4	128
<i>P</i> > <i>F</i>	0.459	0.259	<0.001	<0.001
Mulch (M)				
–mulch	3.0	34	5.9	76
+mulch	4.1	47	7.3	93
<i>P</i> > <i>F</i>	<0.001	<0.001	<0.001	<0.001
Transplant solution (TS)				
Water	3.3 a ^y	37 a	6.1 a	79 a
UAN (28N–0P–0K)	3.6 ab	40 ab	6.4 a	79 a
APP (10N–14.9P–0K)	3.9 b	46 b	7.2 b	96 b
<i>P</i> > <i>F</i>	0.013	0.026	0.003	<0.001
Interaction (Y × M) ^x				
2014 –mulch	3.0	31	4.7	49
2014 +mulch	4.4	46	6.3	69 ^w
2015 –mulch	3.0	39	7.9	122
2015 +mulch	4.8	50	8.9	132
<i>P</i> > <i>F</i>	0.066	0.147	0.197	0.007
Interaction (M × TS) ^{NS}				
–mulch Water	2.7	32	5.3	72
–mulch UAN	3.1	34	5.7	69
–mulch APP	3.2	36	6.7	88
+mulch Water	3.8	42	7.0	86
+mulch UAN	4.0	45	7.2	88
+mulch APP	4.6	55	7.7	104

^z1 mg·L⁻¹ = 1 ppm, 1 kg = 2.2046 lb.

^yMeans in a column followed by the same letter are not significantly different based on Tukey's honestly significant difference ($\alpha = 0.05$).

^{NS}All other interactions were nonsignificant for all responses ($NS, P > 0.2$) and were removed from the model.

^wMulched plants produced significantly more ripe fruit by the end of 2014 but not by the end of 2015 based on Holm-adjusted *t* tests ($\alpha = 0.05$).

copper hydroxide (Kocide® 3000; DuPont, Wilmington, DE), chlorothalonil (Bravo Weather Stik®; Syngenta, Greensboro, NC), azoxystrobin (Quadris®; Syngenta), and/or acibenzolar-S-methyl (Actigard™; Syngenta) to control diseases throughout the season. The plants were staked and supported with a Florida weave system to ≈15 inches, beyond which no support was provided. No pruning was performed, and all plots were hand-weeded.

Tomato harvest began on 25 Aug. 2014 and 11 Aug. 2015. Pink, light red, or red fruit {ripeness stage 4, 5, or 6 [U.S. Department of Agriculture (USDA), 1975]} were harvested four times in 2014 (until 9 Sept.) and 11 times in 2015 (until 5 Oct.). Fruit without cracking, sunscald, disease, or insect damage were counted and weighed at each harvest. The 2014 season was shortened by an unusually early frost (13 Sept.), so all fruit remaining on the plants (ripeness stage 1, 2, or 3) were removed and weighed on 9 Sept. that year. Seasonal temperature, precipitation, and harvest dates are shown in Fig. 1.

Soil temperature was analyzed by averaging measurements from all time points within each plot, then using linear mixed-effect modeling (Pinheiro et al., 2015) to study the interactive effects of year, mulch, and fertilizer. Separate blocks within each year were random effects. The same analysis was used to study cumulative marketable yield from the first 99 d after transplant and at the end of the season. R software was used for all analyses (R Core Team, 2015), and the “multcomp” package was used for multiple comparison testing of transplant solution main effects (Hothorn et al., 2008). Holm-adjusted *t* tests were carried out for additional a priori hypothesis testing of significant interactions or effects, and 95% confidence intervals (CI) were calculated for *t* test results. Fruit count data were square root transformed before analysis ($\sqrt{\text{count}}$) to increase residual normality.

Results and discussion

Recommended fertilizer rates for commercial tomato growers and gardeners vary (Table 1), but the soil in this experiment is generally medium- to high-fertility [adequate to high levels of organic matter, P, and K

(Table 2)]. We found that the combination of N and P in the transplant solution resulted in greater early season yield compared with water alone, but a solution containing only N (UAN) was equivalent to both water and N+P [APP (Table 3)]. However, by the end of the season, APP-fertilized plants had more cumulative fruit and fruit weight than UAN-fertilized plants or water (Table 3). The amount of N was the same in the UAN and APP treatments, so the yield benefits of the APP treatment, both early and full season, can be attributed to either the added P or P in the presence of additional N. Transplant solution P (424 mg/plant) has been shown to increase total P uptake from the soil (Jones and Warren, 1954), perhaps explaining the benefit we found.

A study similar to ours using 26% more transplant solution P than we did found increased total yield only in one of two years when no broadcast P was added on a low-P soil (2 to 3 mg·kg⁻¹ P), and found no yield effect

of transplant solution P on a low- (2 mg·kg⁻¹ P) or higher- (15 mg·kg⁻¹ P) testing soil fertilized with broadcast P (Grubinger et al., 1993). The soil in those studies (Howard gravelly loam, organic matter not reported) was substantially different from the soil in the current study [Nicollet Webster silty clay loam, >4% organic matter (Table 2)].

We used a relatively low rate of nitrogen fertilizer (Table 1) because ‘Plum Dandy’ is a short-statured cultivar with Roma-type fruit (Gardner, 2000) and our soil has >3% organic matter (University of Minnesota, 2016). It is possible that increased yield in the APP treatment was due to a low overall rate of N fertilization, and the transplant solution N helped to alleviate N deficiency. However, N alone was unable to significantly increase early or full season yield (Table 3), and N in the transplant solutions was equivalent to just 3.5 lb/acre N. It seems that the proximity of the additional N to the transplant roots may have been useful for enhanced

Fig. 2. Soil temperature at 4-inch (10.2 cm) depth measured next to tomato plants in bare soil (“no mulch”) or under black plastic mulch in 2014 and 2015. Data were recorded adjacent to 18 individual mulched or nonmulched plants, 12 times in 2014 and 8 times in 2015. Data are not separated by transplant solution treatments (not significant). Mulch increased soil temperature by an average of 1.4 °C ($P < 0.001$). Boxplots indicate percentiles as illustrated; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Fig. 3. Weight of unripe tomato fruit remaining on plants at the end of the growing season in 2014. Tomato plants were grown for 26 d at the beginning of the season on bare soil (“no mulch”) or black plastic mulch (“mulched”). Average (± 2 SE) of green fruit weight is shown, and average weight of ripe (pink, light red, or red) fruit harvested before frost is also indicated. Transplant solutions were 1 cup (0.24 L) of either water, urea ammonium nitrate in water [UAN (1354 mg·L⁻¹ nitrogen)], or ammonium polyphosphate in water [APP (1354 mg·L⁻¹ nitrogen + 2012 mg·L⁻¹ phosphorus)]. The mulch $\times$ transplant solution interaction was significant ($P = 0.005$); 1 mg·L⁻¹ = 1 ppm, 1 kg = 2.2046 lb.

early season growth, but only in the presence of added P (Table 3). Additional information on the role of transplant solution N would be possible by comparing effects of soluble P without N, or by studying a different range of N rates in the starter solution. Other studies have found that pretransplant P and N fertility can impact fruit yield (Garton and Widders, 1990). It may be that less than optimum management of seedlings in the current study (one or two fertigations, in addition to starter charge in the media) impacted the response to transplant solution, but further work would be necessary to test this hypothesis.

In this experiment, plants mulched for less than a month showed more marketable fruit and more fruit harvested within 99 d of transplanting and at the end of the season compared with unmulched plants (Table 3). Total harvested weight was 0.57 to 2.2 kg greater from mulched plants (t test, 95% CI of the difference). Soil temperature under black plastic mulch was greater in both 2014 and 2015 [1.1 to 1.7 °C greater with mulch, 95% CI across both years (Fig. 2)], indicating

a strong positive effect of early season soil heating on tomato yield. Root-zone temperature has been shown to be associated with tomato yield (Díaz-Pérez and Dean Batal, 2002; Grubinger et al., 1993; Schonbeck and Evanylo, 1998a) and photosynthetic capacity (Hurewitz and Janes, 1983), though plastic mulch may also have impacted unmeasured parameters, such as soil moisture, soil nitrate, and earthworm abundance (Schonbeck and Evanylo, 1998a, 1998b). Reduced N leaching and greater N mineralization have been noted under black plastic mulch on a sandy loam soil, for example (Zhang et al., 2012). It is possible that, as a mobile nutrient, N leached more from the unmulched plots compared with the mulched plots because 6.7 (2015) and 11.4 (2014) inches of precipitation fell before mulch removal (Fig. 1). However, we found no significant mulch $\times$ transplant solution interaction (Table 3), so effects of leaching in nonmulched plots was minimal or equivalent to mulched plots. Earlier yield in mulched plots may have resulted from earlier flowering, which was noted in 2014 [2 d earlier (data not

shown)], but not measured in 2015. The fact that a positive yield response was obtained in both years with less than 1 month of plastic mulch supports potential for degradable plastic mulch, lasting less than 1 month, to increase or hasten tomato yield in our production system and location, assuming adequate soil heating is possible while the mulch is intact (Moreno and Moreno, 2008).

There was no difference between cumulative yield of plants mulched and receiving water at transplanting vs. nonmulched plants receiving APP at transplanting [$P = 0.74$, 95% CI of the difference = -1.4 to 1.9 (Table 3)]; the cumulative yield-promoting effects of early season plastic mulch and starter fertilizer containing N and P were equivalent. Once again, the lack of interactive effects of mulch and transplant solution contents (Table 3) means yield increases caused by transplant solutions were independent of mulch, and mulch enhanced yield independent of transplant solution. Another study reported similar combined benefits from using both transplant solution and mulch (Grubinger et al., 1993).

In 2015, average weight of unripe fruit remaining after the final harvest was small [0.07 ± 0.07 kg (mean $\pm$ SD)], so no analyses were performed to determine treatment effects on unripe fruit. However, an unusually early frost shortened the 2014 season (13 Sept.), so unripe fruit [ripeness stage 1, 2, or 3; green, breaker, or light pink (USDA, 1975)] were harvested and weighed 4 d before frost. The general trend was for transplant fertilizer solutions or mulch to reduce unripe fruit weight at the end of the season in 2014, though unlike ripe yield, the effects of mulch and transplant solution on unripe yield were interactive. For nonmulched plants, UAN and APP reduced the weight of unripe fruit compared with water (Fig. 3). Unripe fruit made up 71% of total fruit weight in nonmulched plots transplanted with only water, but unripe fruit weight was only 35% of total fruit weight in mulched plots transplanted with APP solution (Fig. 3). The percentage of unripe fruit was 51% to 59% of total fruit weight in the other four treatments. The abundance of unripe fruit remaining on the plant at the end of 2014 can explain the significant interaction of year $\times$ mulch affecting end-of-season ripe fruit count

(Table 3). If early season mulch hastens ripening without increasing the number of fruit produced in a full season, a frost-shortened season will result in more fruit harvested from mulched plants, and a full season (2015) will result in no greater number of fruit. It should be noted, however, that there was no year $\times$ mulch interaction affecting end-of-season total fruit weight (Table 3). The discrepancy can be explained by differences in fruit size. Averaged over the season, fruit from mulched plants were larger in 2015 compared with nonmulched plants (data not shown), so a similar number of fruit per plant still allowed for more total fruit weight.

Overall, the tomato yield-promoting and hastening effect of N alone in transplant solution (no P) was no different from water alone. Recommendations for gardeners and commercial growers in Minnesota to use P-containing transplant solutions seem justified, even in moderate- to high-fertility soils. Plastic mulch also enhanced early and total yield independent of transplant solution, presumably through increased root-zone temperature. Both measures could be implemented together, especially for reducing risk of yield loss in weather-shortened seasons.

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