Project Title: **Optimizing application of phosphorus and potassium to processing tomatoes under drip-irrigation to maximize quality and yield while minimizing adverse impacts on water quality**

(Annual report for year 2008)

Researchers: **T.Q. Zhang (Soil Fertility & Water Quality)**
C.S. Tan (Water Management)

Post-doctoral Fellow: **K. Liu (Nutrient Management)**

Technical Support: **M. Reeb, D. Pohlman, K. Rinas, and T. Oloya**

Funding Sources: **International Plant Nutrition Institute**
Ontario Tomato Research Institute
Ontario Agri-Business Association
A & L Canada Laboratories East, Inc.
Agriculture and Agri-Food Canada

Greenhouse and Processing Crops Research Centre
Agriculture and Agri-Food Canada, Harrow, Ontario N0R 1G0
zhangt@agr.gc.ca

Jan. 2009

Interpretative Summary

Processing tomatoes, a major high-value crop in Ontario, are high in nutrient demands. The nutrient needs can further increase with drip-irrigation/fertigation due to the largely enhanced yield potential. Our studies in the past five years showed that fertilizer nitrogen (N) rate required for processing tomato production with drip fertigation can be as high as 300 kg N ha^{-1}, which is about 3 times of the previous recommendation, and has been approved as an official guideline in Ontario. With increased needs for fertilizer N, other nutrients, such as phosphorus (P) and potassium (K), must be supplied accordingly in sufficient amounts to provide balanced nutrients that are essential to the development of the maximum yield potential. Over application of nutrients can cause build-up in soil, such as P, and consequently contaminate water resource at the cost of reduced fertilizer investment profits. In addition, more and more demands on quality (soluble solids, lycopene, and vitamin C) of processing tomatoes have become an emerging issue for both processors and consumers. Application rates of fertilizer P and K to processing tomatoes must be optimized in a way that minimizes adverse effects on water quality, while maximizing marketable yield and improving product quality.

The long-term objectives of this study are 1) to develop the optimum rates of P and K with drip-irrigation under Ontario conditions, which meet the needs for maximum economic yield and quality, while minimizing the potential for P losses; 2) to determine P and K removals; and 3) to determine changes in soil P and K for programming soil fertility management. The short-term objectives for 2008 were 1) to determine the relationships between fertilizer P and K and yield and quality of processing tomatoes with drip-irrigation in accordance with the newly developed N rate in Ontario; 2) to determine crop nutrient (N, P, K) uptake and removal; 3) to evaluate changes in soil test P and K and the potential leaching losses of soil P and N; and 4) to determine the differences between drip-irrigation and non-irrigation as to both agronomic and environmental performances of processing tomato production.

The experiment was conducted in a sandy loam soil at GPCRC, Harrow, ON. The treatments included four fertilizer P rates ranging from 0 to 90 kg P ha^{-1}, four fertilizer K rates ranging from 0 to 600 kg K ha^{-1}, and two water management regimes including natural rainfall (non-irrigation) and natural rainfall enhanced with drip-irrigation to best satisfy crop physiological needs in an optimum manner. The experiment was arranged as a split-plot design, with four blocks and a total of 128 plots. The two water management regimes were assigned to the main plots, with P and K treatment combinations assigned to the subplots.

The major results drawn from the 2008 growing season are as follows.

Yields: Drip-irrigation increased the marketable fruit yield by 42% through the increases of total fruit yield (by 26%) and fruit size (by 25%), and the decreases of BER (by 92%) and culled fruit yields (by 61%), relative to non-irrigation. Drip-irrigation also decreased stover biomass yield, an implication of enhanced translocation of carbohydrates towards

fruit formation, and thus the increased yield formation efficiency of photosynthesis products.

Total and marketable fruit yields responded quadratically to fertilizer P rate applied, and reached their maximum at P rates of 54.5 and 53.5 kg P ha^{-1}, respectively.

Increased fertilizer P from 30 to 90 kg P ha^{-1} decreased BER (blossom end rot) yield by up to 3.3%.

Fruit quality: Drip-irrigation caused a decrease in soluble solids content of fruits, but it would be compensated with the substantially increased fruit yield.

The best fitted curves between soluble solids contents and fertilizer K rate were quadratic, because of the high level of background soil test K. Fertilizer K rates of 346 and 286 kg K ha^{-1} were required to produce the maximum soluble solids for the drip-irrigation and non-irrigated treatments, respectively. Production of processing tomatoes with drip-irrigation required higher rate of fertilizer K to obtain increased content of soluble solids in fruits.

Addition of fertilizer P increased the contents of vitamin C by 12%.

Nutrient removals and uptake: Drip-irrigation enhanced remarkably both uptake and removal of nutrients NPK of processing tomatoes. Fruit nutrient removal and plant nutrient uptake with drip-irrigation increased respectively by 25 and 7% for N, by 34 and 21% for P, and by 29 and14% for K, compared with the non-irrigation.

Crop P uptake responded quadratically to the fertilizer P rate applied. The maximum plant P uptake of 20.3 kg P ha^{-1} was obtained with P fertilizer applied at 61.3 kg P ha^{-1}.

Nutrient use efficiency: Use efficiency of fertilizer P, measured by either partial factor productivity (PFP) or agronomic efficiency (AE), decreased linearly with increases in fertilizer P rate. Values of fertilizer P use efficiency were 796 and 1192 kg kg^{-1}, determined by PFP, and 86.3 and 180.8 kg kg^{-1}, determined by AE, for non-irrigation and drip-irrigation, respectively, when the maximum marketable fruit yield was produced.

Drip-irrigation improved fertilizer P use efficiency by 33%, determined using PFP, and by 51%, determined using AE, compared with the non-irrigation.

Soil test NPK: Post-harvest soil test P and K increased linearly with increased fertilizer rates, regardless of irrigation, except for soil test K which responded quadratically to fertilizer K rate when drip-irrigation was applied. Addition of each kg fertilizer P resulted in soil test P increment of 0.1077 mg P kg^{-1}. Addition of each kg fertilizer K increased soil test K by 0.7875 mg K_2O kg^{-1} when drip-irrigation was not applied. With drip-irrigation, the maximum soil K was obtained with K fertilizer applied at 492 kg K ha^{-1}.

Drip-irrigation decreased post-harvest soil test NPK. Soil mineral N, Olsen P, and ammonia acetate extractable K was 37%, 8%, and 75% lower with drip-irrigation than without irrigation.

Soil profile (0-100 cm) water extractable P decreased by 17% under drip-irrigation due to the increased crop P utilization relative to non-irrigation.

Drip-irrigation increased N and P use efficiency and thus reduced the potentials for adverse impacts of soil residual nutrients on water and air quality.

This study is to be continued in 2009

Introduction

Processing tomatoes, a major high-value crop in Ontario, are high in nutrient demand. The nutrient needs can further increase with drip-irrigation/fertigation, due to the largely enhanced yield potential. Our studies in the past 5 years showed that fertilizer nitrogen (N) rate required for processing tomato production with drip-irrigation/fertigation should be as much as 300 kg N ha^{-1}, approximately 3 times of previous provincial recommendation. The result has been approved as an official guideline for processing tomato production by the Ontario Soil Management Research and Service Committee in 2007. As implicated by the “Law of the Minimum”, with increased needs for fertilizer N, other nutrients, such as phosphorus (P) and potassium (K), must be supplied accordingly in sufficient amounts to develop the maximum yield potential.

On the other hand, over application of fertilizer P can cause P build-up in soil, and consequent contamination of water resource, as P is the key element controlling eutrophication of water bodies. Over-applied K may result in crop luxury uptake without profitable economic return. Investment profitability of fertilizers has increasingly become a concern, especially when fertilizer prices have been roaming since the last few years and the circumstance may continue in the near future. For instance, fertilizer prices are predicted to increase by 32% for N, 79% for P, and 83% for K, in 2009 (Corn E-Digest, Sept. 2008). Optimized fertilization for processing tomatoes with drip-irrigation can maximize farmers’ profitability, while reducing environmental contamination by decreasing nutrient losses to water body, especially in the great lakes area where there is an increasing concern on water quality.

The provincial government of Ontario has placed the protection of water source as one of its top priorities, and passed the Nutrient Management Act (ON. REG. 267/03) in 2002. The regulation restricts land application of nutrients and encourages adoption of BMPs to mitigate the potential impacts on water quality. The OMAFRA-NMN series of nutrient management computer programs have been developed to assist producers with nutrient management planning. Optimum fertilizer rates along with crop nutrient removal are the key variables for OMAFRA-NMN. However, data on fertilizer P and K effects on yield and nutrient removals are not available for processing tomatoes grown with drip-irrigation, and related studies are needed for the specific Ontario conditions.

More and more demands on quality of processing tomatoes have become an emerging issue to processors and consumers. The major food quality variables related to processing tomatoes include soluble solids, lycopene, and vitamin C. Potassium is a well-known element highly related to crop quality and has been linked with tomato yield and quality. However, information on the roles of P and K in the formation of these food quality variables are limited and often in controversy, depending on the soil and weather conditions. There are no data available with this regard in Ontario, especially under drip-irrigation/fertigation.

Consequently, both industries and regional related authorities (OTRSC - Ontario Tomato Research and Service Sub-Committee; Ontario Soil Management Research and Service Committee, Sub-Committee for Horticultural Crops; IPNI – International Plant Nutrition

Institute) have identified that optimization of P and K application rates for processing tomatoes in an environmentally responsible manner to maximize yield and quality as a top research priority.

Objectives

1) To determine the relationships between fertilizer P and K and yield and quality of processing tomatoes with drip-irrigation in accordance with the newly developed N rate in Ontario;
2) To determine crop nutrient (N, P, K) uptake and removals;
3) To evaluate changes in soil test P and K and the potential leaching losses of soil P; and
4) To develop the optimum rates of P and K under Ontario conditions, which meet the needs for maximum quality and economic yield while minimizing the potential for P loss.

Activities Related to Field Year 2008

1) April - early May, 2008: transplant preparation; large field soil sampling using a grid approach and soil test P and K analysis for site selection; plot allocation;
2) Late May-September: plot layout; fertilization; transplanting; drip line installation and leakage checking; field management; soil moisture monitoring; drip-irrigation; field tours for visitors from industries, universities, and governments; in-season plant tissue sampling
3) Late August-October: harvesting; yield and quality measurements; final plant tissue sampling; soil sampling; plant sample preparation for analyses; report to OPVG and OTRI
4) November-January 09: plant and soil analyses for N, P, and K; report to IPNI

Materials and Methods

The experiment was conducted in a sandy loam soil at GPCRC, Harrow, ON. The treatments included four fertilizer P rates (0, 30, 60, 90 kg P ha^{-1}), four fertilizer K rates (0, 200, 400, and 600 kg K ha^{-1}), and two water management regimes (non-irrigation, drip-irrigation to best satisfy crop physiological needs in an optimum manner). The experiment was arranged in a split-plot design, with four blocks and a total of 128 plots. The water management regimes were assigned to the main plots, with the P and K treatment combinations assigned to the sub-plots. All fertilizer P and K was pre-transplant broadcasted and incorporated. Baseline soil fertility was 13 mg N kg^{-1}, 65 mg P kg^{-1}, and 216 mg K kg^{-1}. All plots received 270 kg N ha^{-1} fertilizer N. Other plot management followed the local practices.

Fruits from the central two rows of each plot were hand harvested at the 80% fruit ripening (or peak ripening) stage and graded into marketable, green, blossom end-rot and culled, and weights recorded. Total and assorted fruit yields were calculated. Fruit soluble solids and fruit size were measured. Fruit and stover samples were taken and analyzed for N, P, and K contents. Total N, P and K uptake of processing tomato were calculated according to the biomass yields and nutrient contents. Fruit lycopene analysis is to be completed.

Nutrient (i.e. P&K) use efficiency was expressed using partial factor productivity of applied nutrient (PFP) and agronomic efficiency of applied nutrient (AE). PFP was calculated as Y/F, and AE was calculated as $(Y-Y_0)/F$. Where Y is marketable fruit yield of tomatoes with applied nutrients, P or K. Y_0 is marketable fruit yield of processing tomatoes with no nutrient applied, and F was the amount of nutrient applied.

Soil profile samples (0-20, 20-40, 40-60, 60-80, and 80-100 cm depths) were taken shortly after harvesting and will be analysed for NO_3- and NH_4-N to evaluate the leaching potential of soil N as a function of fertiliser P and K rates and water regimes. Soil samples were analyzed for water extractable P to determine soil P loss potential.

Data were analyzed as a split-pot design using Proc Mixed in SAS. Data was fitted to a curve if relationship is apparent. When the treatment effects were significant, mean comparisons were completed by generating letter groupings at the 5% level of significance.

Results and Discussion

Fruit yields

Both total and sorted fruit yields, except for green fruit yield, were affected by drip-irrigation in 2008. Total, marketable, and BER yields were influenced by fertilizer P addition. However, neither interaction between fertilizer P addition and drip-irrigation nor the addition of fertilizer K and its interactions with fertilizer P or drip-irrigation were found affecting any of the yields determined.

Drip-irrigation effect: Total fruit yield with drip-irrigation increased by 12 Mg ha^{-1}, an equivalent of 26%, relative to the non-irrigation (Fig. 1). Similarly, in comparison with the non-irrigation, marketable fruit yield increased by 15 Mg ha^{-1}, an equivalent of 42%, with drip-irrigation (Fig. 2). As a result, drip-irrigation caused greater increase in marketable yield than the total yield. The increase in marketable yield with drip-irrigation was primarily a consequence of reductions in both culled and BER yields (Fig. 3 and Fig. 4). Drip-irrigation decreased culled yield by 1.4 Mg ha^{-1} and BER yield by 1.7 Mg ha^{-1}, which were respective equivalents of 61 and 92%, relative to the non-irrigation. The percentage of BER to total yield was 0.3 and 4.1% for the drip-irrigation and non-irrigation treatments, respectively. Clearly, drip-irrigation that timely supplied water to crops at the optimized rates enhanced the formation of marketable yield through the increased remobilization of carbohydrates, products of photosynthesis, from vegetative organs to reproductive organs and the uniformity of fruit maturity, while it, to a greater extent, developed yield potential of processing tomatoes.

Compared with 2007, total fruit yield in 2008 was 58% and 46% less for drip-irrigation and non irrigation treatments, respectively. The cumulative rainfall in the first week of fertilizer application was 58.2 mm. Such heavy rain could have caused substantial nutrient loss in a sandy loam soil, especially N. The minimum temperature in August, 2008 was 15.3^{o}C, which was 2.6^{o}C lower than that in 2007. Both of these factors would have caused unexpected yield loss in 2008. In addition, the dry weather from late July to early September would have been another major factor causing the low yield in non-irrigation plots.

Fertilizer P effects: Total fruit yield responded quadratically to the addition of fertilizer P (Fig. 5). Total fruit yield reached its maximum of 52.3 Mg ha^{-1} at 54.5 kg P ha^{-1} fertilizer P added.

Response of marketable fruit yield to the addition of fertilizer P followed the same pattern as did the total yield (Fig. 6). Quadratic relationship indicated that marketable fruit yield reached its maximum of 44.4 Mg ha^{-1} at 53.5 kg P ha^{-1}. The soil was started with a relatively low value of soil test P, Olsen P of 65 mg P kg^{-1}, for processing tomatoes in 2008. The low initial value of soil test P might have been the main reason causing positive response of fruit yields to the fertilizer P added. However, it would be surprise enough when the quadratic relationships between yield, either total or marketable, and the fertilizer P rate were observed, as a quadratic plateau curveship is normally expected for yield response to P. Over-application of fertilizer P might have resulted in an increased proportion of early matured fruits which would have been fully dried and not collectable, when harvesting was conducted. However, this needs to be determined.

Fruit yield with BER showed a decreasing trend with increases in fertilizer P rate (Fig. 7). BER fruit yield decreased from 3.4 to 1.1 Mg ha^{-1}, or from 3.3 to 1.0% of the total yield, when fertilizer P rate increased from 30 to 90 kg P ha^{-1}. This can be explained as that increased P addition enhanced crop resistance to water deficiency and thus improved Ca uptake. Ca deficiency has been considered the key factor causing formation of BER fruits for processing tomatoes. Relative low BER fruit yield in the zero-P plots might have been the result of low water demand due to smaller size of fruits.

Stover yield

Among all the treatment factors, drip-irrigation was the only one that affected stover yield in 2008 (Fig. 8). Stover yield with drip-irrigation decreased by 0.6 Mg ha^{-1}, an equivalent of 28%, relative to the non-irrigation. Formation of fruit yield is not only a function of total photosynthetic assimilates, but also of the assimilate partitioning between vegetative and reproductive organs of the crop. With drip-irrigation, a larger amount of assimilates would have rapidly translocated to fruits. As a result, a higher fruit yield with a decreased stover yield was formed, when compared to the non-irrigation treatments.

Fruit Quality

Both fruit size and soluble solids content were influenced by drip-irrigation, but not by any other experimental factors, including additions of fertilizer P and K and their interactions with drip-irrigation.

It is normally expected that additional water supply would cause the formation of large fruits, which are low in content of soluble solids. In the current study, the content of soluble solids with drip-irrigation decreased by 12% (Fig. 9), while fruit size increased by 25% (Fig. 10), when compared with the non-irrigation. Irrigation determines, to some extent, the amounts of water that is available to crops and the water in fruits where solids are dissolved in. However, increased total yield with drip-irrigation might have diluted the synthesized solids, thus resulted in decreased solids content. As mentioned earlier, increased fruit yield with drip-irrigation (26% higher) can well compensate the decreased soluble solids content. Therefore, sufficient water in the drip-irrigation treatment should have been the main reason enlarging both source and sink, which resulted in larger average fruit weight.

There were quadratic relationships between soluble solids and fertilizer K addition, but the curveships varied depending on the irrigation treatment (Fig. 11). With drip-irrigation, content of soluble solids reached the maximum of 5.0^{o}Brix at the fertilizer K rate of 346 kg K ha^{-1}. Under non-irrigation circumstances, however, soluble solids content reached the maximum of 5.8^{o}Brix at the fertilizer K rate of 286 kg K ha^{-1}. Consequently, increased fertilizer K addition is required to maximize the soluble solids content, when high yield of processing tomato is to be produced with sufficient water supply.

In 2007, soluble solids content was linearly and positively related to the fertilizer K rate applied. The different response curves of soluble solids to K addition between 2007 and 2008 would have been due to the relatively high initial value of soil test K in 2008. These two-year results indicate that soluble solids content could be increased with fertilizer K application, but can be reduced if excessive K is applied. It appears that fertilizer K rate have to be optimized with consideration of the levels of soil test K to maximize the soluble solids content of processing tomatoes.

Vitamin C in 2007 and 2008

Contents of vitamin C increased with addition of fertilizer P in 2008, while in 2007 contents of vitamin C were not affected by any of the treatment factors. Contents of vitamin C averaged across all of the fertilizer P rates increased by 12%, compared with the zero-P plots (Fig. 12).

Fruit nutrient (N, P, K) removals and plant nutrient uptake

Both fruit removal and plant uptake of N, P, and K were affected by irrigation, but not by P and K additions and the interactions between P and K applications and between drip-irrigation and P or K addition, except for plant P uptake which responded quadratically to fertilizer P rate.

Fruit removals of N, P, and K with drip-irrigation were respectively 25, 34, and 29% greater than those without irrigation (Fig. 13; Fig. 15; and Fig. 18). Crop uptakes of N, P, and K with drip-irrigation increased by 7, 21, and 14%, respectively, compared with non-irrigation (Fig. 14; Fig. 16;and Fig. 19). Greater increases in crop nutrient removals relative to crop total uptake indicate that sufficient water supply with drip-irrigation enhanced nutrient translocation from vegetative organs, stover, to reproductive harvest organs.

Crop P uptake responded quadratically to fertilizer P rate, with the maximum plant P uptake of 20.3 kg P ha^{-1} obtained at 61.3 kg P ha^{-1} fertilizer P applied (Fig. 17).

Nutrient use efficiency

Partial factor productivity (PFP) of fertilizer P

In 2007, partial factor productivity (PFP) of applied fertilizer P was affected by drip-irrigation, P and K addition, and the interaction between irrigation and fertilizer P addition, but not the interactions between fertilizer P and K and between irrigation and fertilizer K. PFP of fertilizer P decreased linearly with increases in P rate, ranging from 1322 to 3741 kg kg^{-1} in the drip-irrigation plots and from 516 to 1464 kg kg^{-1} in the non-irrigation plots (Fig. 20). On average, PFP of fertilizer P increased by 62% in the drip-irrigation plots (2304 kg kg^{-1}) compared with the non-irrigation plots (879 kg kg^{-1}).

PFP of fertilizer P with fertilizer K added, averaged across all the four K rates, was 24% higher than the control plots (1648 kg kg^{-1} with fertilizer K vs. 1328 kg kg^{-1} without fertilizer K) (Fig. 21). As a result, both drip-irrigation and fertilizer K addition enhanced the productivity efficiency of fertilizer P.

In 2008, PFP of fertilizer P was a function of drip-irrigation, P rate, and the interactions of drip-irrigation with P rate. PFP of fertilizer P decreased linearly with increases in fertilizer P added, regardless of irrigation (Fig. 22). However, the coefficient of the regression for drip-irrigation was 57.6% greater than that with non-irrigation. PFP of fertilizer P with drip-irrigation ranged from 573-1752 kg kg^{-1}, with an average of 1067 kg kg^{-1}, while it ranged from 390 to 1139 kg kg^{-1}, with an average of 716 kg kg^{-1}, without irrigation. Values of PFP of fertilizer P were 796 and 1192 kg kg^{-1} for non-irrigation and drip-irrigation, respectively, when the maximum marketable fruit yield was produced.

Drip-irrigation in comparison with non irrigation increased PFP of fertilizer P, with an average of 111% (1684 kg kg^{-1} for drip-irrigation vs. 797 kg kg^{-1} for non-irrigation) over the two years of the study.

Partial factor productivity (PFP) of fertilizer K

Partial factor productivity (PFP) of fertilizer K was influenced by drip-irrigation, K addition, and the interaction between irrigation and K addition in 2007. However, the PFP of fertilizer K was not affected by fertilizer P addition and its interaction with drip-irrigation. The PFP of fertilizer K decreased linearly with increases in fertilizer K added, ranging from 199 to 608 kg kg^{-1} in the drip-irrigation plots and from 80 to 206 kg kg^{-1} in the non-irrigation plots within the range of fertilizer K applied (Fig. 23). The averaged PFP value of fertilizer K with drip-irrigation (354 kg kg^{-1}) was 63% greater than without irrigation (132 kg kg^{-1}), an indication that there was an increased need for K for processing tomatoes, when irrigation was not applied, if the same level of yield production is to be obtained as with drip-irrigation. On the other hand, the greater declining rate of PFP in the drip-irrigation plots, as indicated by the coefficient of the regression, implies that the rate of fertilizer K must be optimized to maximize investment profits.

In 2008, the PFP of fertilizer K was only affected by irrigation and K addition. None of the effects of P addition and the interactions between drip-irrigation and K or P addition were found. The PFP of fertilizer K with drip-irrigation averaged across all the P and K rate treatments (155 kg kg^{-1}) increased by 28% relative to the non-irrigation treatments (112 kg kg^{-1}) (Fig. 24).

The PFP of fertilizer K averaged across both non-irrigation and drip-irrigation decreased linearly with the increases in fertilizer K rate applied, ranging from 72 to 221 kg kg^{-1} (Fig. 25).

The PFPs of applied nutrient P and K was generally lower in 2008 than in 2007, presumably due to the lower marketable fruit yield in 2008, which was caused mainly by low-temperature during the peak of production period in the middle of season, as discussed earlier.

Agronomic Efficiency (AE) of fertilizer P

In 2007, the calculated AE values of fertilizer P were not statistically different, although they tended to decline with increases in fertilizer P rate within each irrigation category (Fig. 26). The initial value of soil test P in 2007 was relatively high, and might have provided plant with sufficient P. Consequently, response of yield to fertilizer P applied was subtle within the same irrigation category.

The AE of fertilizer P in the non-irrigation plots (104.8 kg kg^{-1}) increased by an average of 39% compared with that in the drip-irrigation plots (74.9 kg kg^{-1}). The pattern reverses the one determined using PFP. Nutrient use efficiency measured using AE can be more accurate than one using PFP, as the later may confound with the soil background fertility. The decreased AE with drip-irrigation indicates that the diffusive movement of soil original P would have been largely enhanced when additional water was available, and consequently there was a decreased demand for fertilizer P in the drip-irrigation plots. However, in the non-irrigation plots fertilizer P has added supplemental P to satisfy crop needs, with a consequence of greater increase in yield production. The results suggest clearly that fertilizer P addition is a mandatory practice to increase the yield of processing tomatoes when drip-irrigation is not applied, even if the initial soil test values are high.

In 2008, AE of fertilizer P was linearly and negatively related to fertilizer P rate, but at a greater scale with drip-irrigation than without irrigation (Fig. 27). AE of fertilizer P with drip-irrigation ranged from 72 to 276 kg kg^{-1}, while it was from 31 to 123 kg kg^{-1} in the non-irrigation plots, when P rates varied from 30-90 kg P ha^{-1}. On average, AE of fertilizer P increased by 51% in the drip-irrigation plots (157.8 kg kg^{-1}), compared with that in the non-irrigation plots (77.1 kg kg^{-1}). Values of AE of fertilizer P were 86.3 and 180.8 kg kg^{-1} for non-irrigation and drip-irrigation, respectively, when the maximum marketable fruit yield was produced. Increased AE with drip-irrigation indicates increased role of fertilizer P, when soil test P is limited to meet the production needs of processing tomatoes.

Agronomic Efficiency (AE) of fertilizer K

In both 2007 and 2008, AE of fertilizer K decreased linearly with increases in K addition, but the coefficients of regression varied depending on the irrigation treatment (Fig. 28 and Fig. 29). The AE of fertilizer K with drip-irrigation ranged from 17 to 86 kg kg^{-1}, while it ranged from 20 to 28 kg kg^{-1} without irrigation in 2007. On average, AE of fertilizer K increased by 45% in the drip-irrigation plots (24.5 kg kg^{-1}), compared with non-irrigation plots (44.3 kg kg^{-1}). In 2008, AE of fertilizer K ranged from 8 to 26 kg kg^{-1} in the drip-irrigation plots and from 3 to 22 kg kg^{-1} in the non-irrigation plots. The AE of fertilizer K was averaged 39% lower in the non-irrigation plots (10.8 kg kg^{-1}) than that in the drip-irrigation plots (17.8 kg kg^{-1}). Clearly, drip-irrigation improved AE of fertilizer K which however can be reduced if over-applied.

Agronomic efficiency of applied nutrients was partially determined by the background soil fertility. With the lower level of background soil test P in 2008, marketable fruit yield had larger responses to applied fertilizer P, in comparison with that in 2007. As a result, the values of AE for fertilizer P were higher in 2008. In contrast, lower background of soil test K in 2007 resulted in higher AE of applied fertilizer K than in 2008.

Post-harvest soil test N, P, and K

Post-harvest soil mineral N, including both NO_3- and NH_4-N, in the top soil layer (0-20 cm) was significantly affected by irrigation. However, none of the effects of P and K addition and their related interactions were found on soil mineral N. Content of soil mineral N with drip-irrigation decreased by 2.3 mg N kg^{-1}, an equivalent 37%, compared with non-irrigation (Fig. 30). The decreased post-harvest soil mineral N might have been caused by the increased N uptake with increased yield production.

Post-harvest soil test P (Olsen P) in the top soil layer (0-20 cm) was affected by irrigation and fertilizer P application, but the effects of fertilizer K addition, interactions between drip-irrigation and fertilizer P or K addition were found not significant. Soil test P in the drip-irrigation plots was 5.0 mg P kg^{-1}, an equivalent of 8%, lower than that in the non-irrigation plots (Fig. 31), presumably due to the increased P uptake with high yield.

Soil test P after harvest was linearly related to fertilizer P rate (Fig. 32). Each kg of fertilizer P input resulted in an increase of 0.1077 mg P kg^{-1} in soil test P.

Post-harvest soil test K in the top soil layer (0-20 cm) varied with irrigation, fertilizer K application, and the interaction between drip-irrigation and K addition. As expected, there were no effects of fertilizer P addition, as well as the interaction between fertilizer P and drip-irrigation on post-harvest soil test K. Content of post-harvest soil test K was quadratically related to fertilizer K rate, when drip-irrigation was applied (Fig. 33). Levels of soil test K reached its maximum at the K rate of 492 kg K ha^{-1}. Any K added above this rate would have been leached out of the surface soil layer, in addition to crop uptake. When the plots were not irrigated, content of soil test K responded linearly to the amount of fertilizer K applied. Each kg of fertilizer K added increased soil test K by 0.787 mg K_2O kg^{-1}. Post-harvest soil test K stays mostly in soil over the non-growing season, and can be available to next crops.

Post-harvest water extractable P in soil profile

Post-harvest water extractable P in soil varied remarkably with irrigation, fertilizer P addition, and soil depth. In addition, water extractable P was also a function of interaction between depth and fertilizer P addition or between depth and irrigation.

Water extractable P declined gradually with soil depth in the 0-100 cm soil profile (Fig. 34). Drip-irrigation decreased water extractable P in the top 40cm soil depths by 1.5 mg P kg^{-1}, an equivalent of 14%, relative to the non-irrigation treatment. Given the amount of water extractable P in the soil depth below 40 cm remained unchanged in the drip-irrigation than the non-irrigation treatments, the reduction with drip-irrigation in the soil layers above 40 cm would have been caused by the increased crop P uptake. This suggests that drip-irrigation reduced potentials for soil P loss, and thus reduced adverse impacts on water quality.

Water extractable P in soil profile remained similar when fertilizer P was added at the rates below 60 kg P ha^{-1} (Fig. 35). However, when the rate of fertilizer P increased from 60 to 90 kg P ha^{-1}, water extractable P increased, especially in the depth of 0 to 40cm.

Consequently, increases of soil residual P caused by either excessive addition of fertilizer P or decreased crop P uptake without irrigation can result in increased soil P loss potential, and hence the increases in damage on water quality.

Summary

Drip-irrigation in 2008 increased the marketable fruit yield (by 42%) through the increases of total fruit yield (by 26%) and fruit size (by 25%), and the decreases of BER (by 92%) and culled fruit yields (by 61%). Accordingly, drip-irrigation improved nutrient NPK removals, uptake, and PK use efficiency determined by either partial factor productivity (PFP) or agronomic efficiency (AE). As a result, drip-irrigation decreased post-harvest water extractable P in soil profile, thus, reduced the potential for adverse effects of soil residual P on water quality.

Addition of fertilizer P quadratically affected the fruit yields of processing tomatoes, with the maximum total yield produced at 54.5 kg P ha^{-1} and the maximum marketable yield at 53.5 kg P ha^{-1}, regardless of irrigation. Use efficiency of fertilizer P, measured by either PFP or AE, decreased linearly with increases in fertilizer P rate. Values of fertilizer P use efficiency were 796 and 1192 kg kg^{-1}, determined by PFP, and 86.3 and 180.8 kg kg^{-1}, determined by AE, for non-irrigation and drip-irrigation, respectively, when the maximum marketable fruit yield was produced.

Fertilizer K had no effects on fruit yields, because of the unexpected low yield in 2008 as a result of climatic disadvantages.

Fertilizer P addition increased vitamin C content. Drip-irrigation caused a decrease in the content of soluble solids of fruits, but it would be compensated with the significantly increased fruit yield. The best fitted curves between soluble solids contents and fertilizer K rate were quadratic because of high level of background soil test K.

Post-harvest soil test P and K increased linearly with increased fertilizer rates, regardless of irrigation, except for soil test K which responded quadratically to fertilizer K rate when drip-irrigation was applied.

This study is to be continued in 2009.

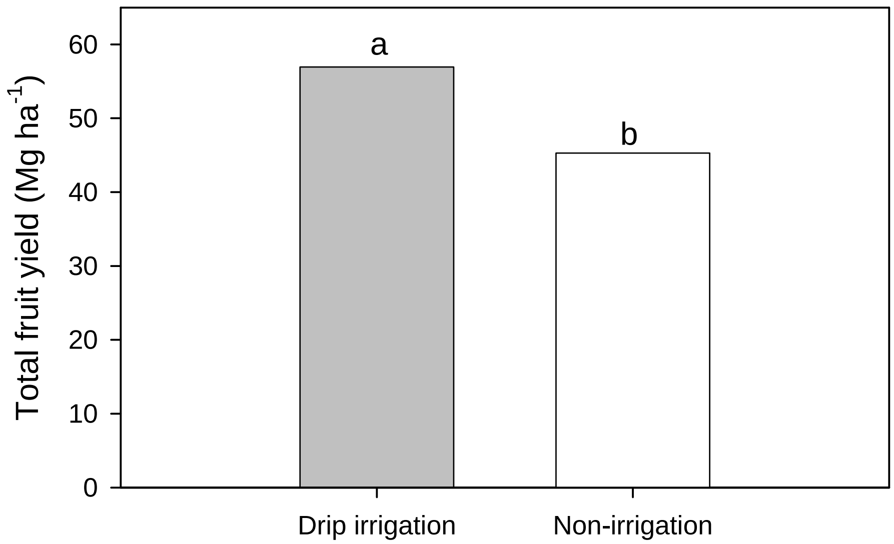

Fig. 1. Response of total fruit yield of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

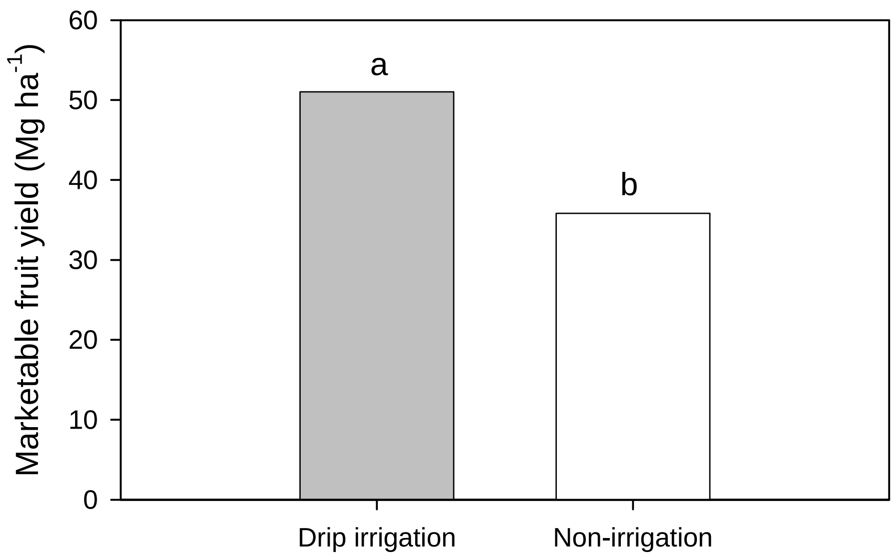

Fig. 2. Response of marketable fruit yield of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

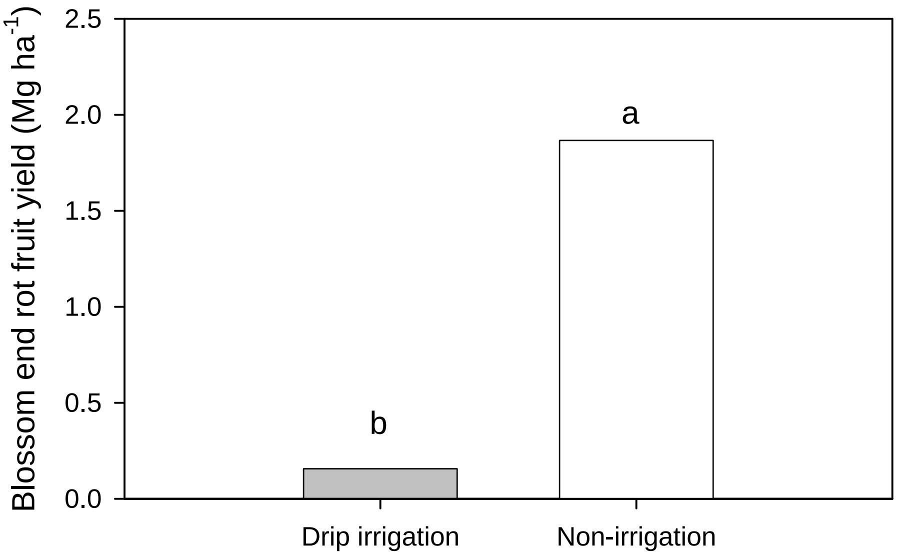

Fig. 3. Response of blossom end rot fruit yield of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

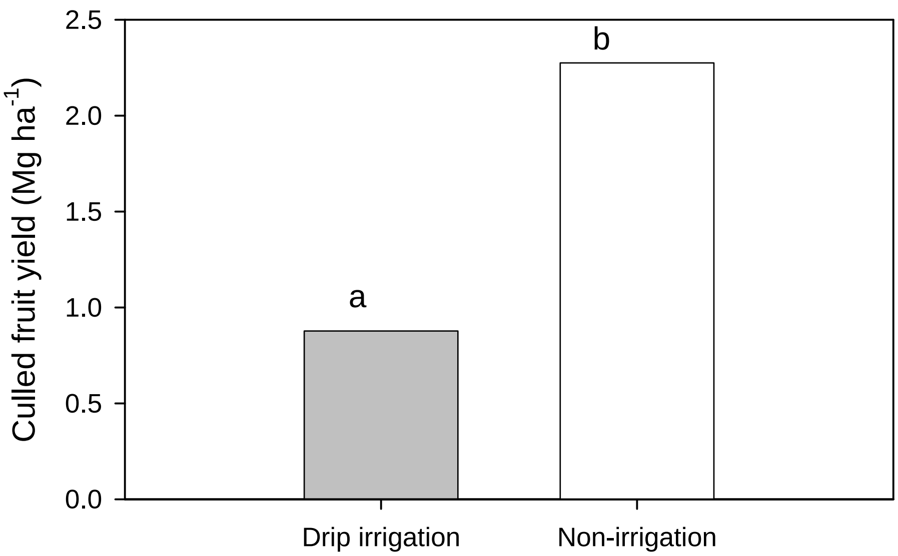

Fig. 4. Response of culled fruit yield of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

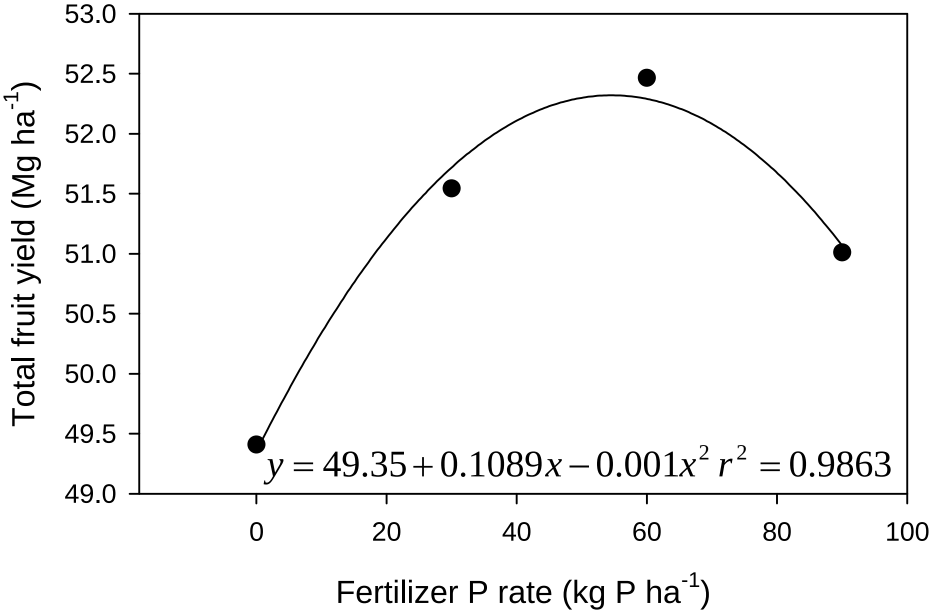

Fig. 5. Response of total fruit yield of processing tomatoes to fertilizer P rate on a sandy loam soil, Harrow, ON, 2008

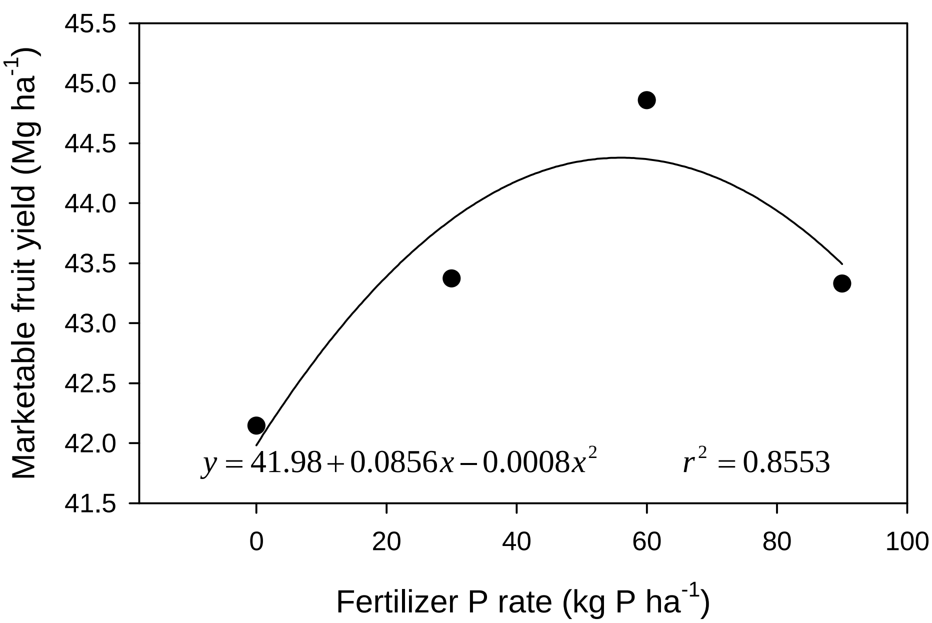

Fig. 6. Response of marketable fruit yield of processing tomatoes to fertilizer P rate on a sandy loam soil, Harrow, ON, 2008

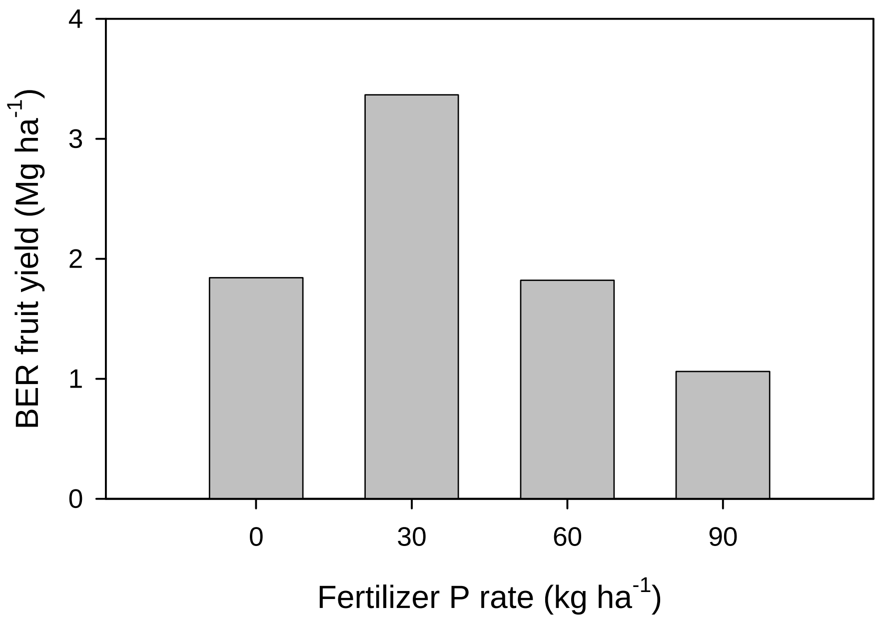

Fig. 7. Response of BER fruit yield of processing tomatoes to fertilizer P addition on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the $P \leq 5\%$ level.

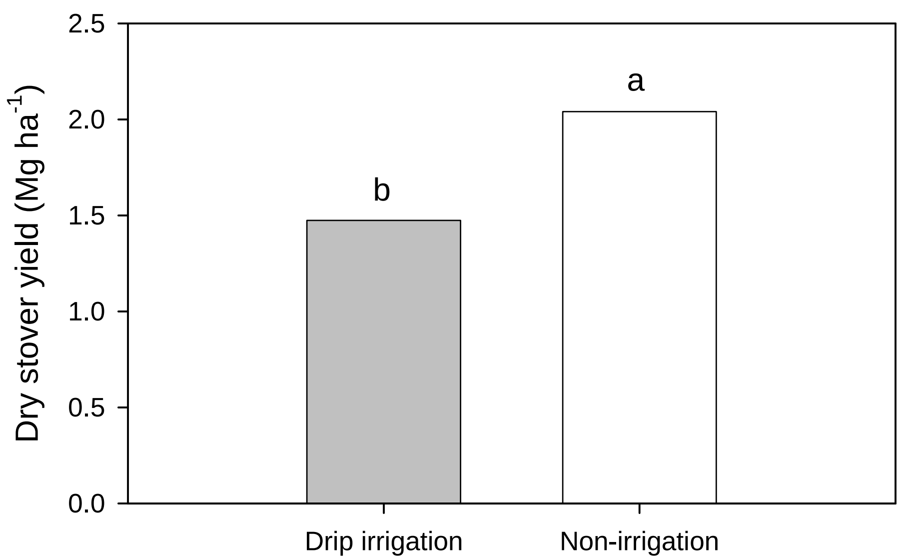

Fig. 8. Response of stover yield of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the $P \leq 5\%$ level.

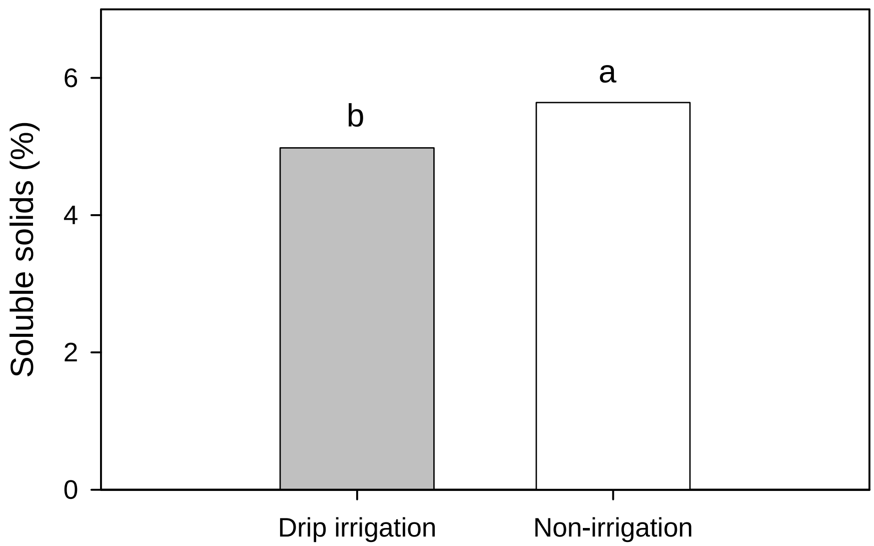

Fig. 9. Response of soluble solids of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

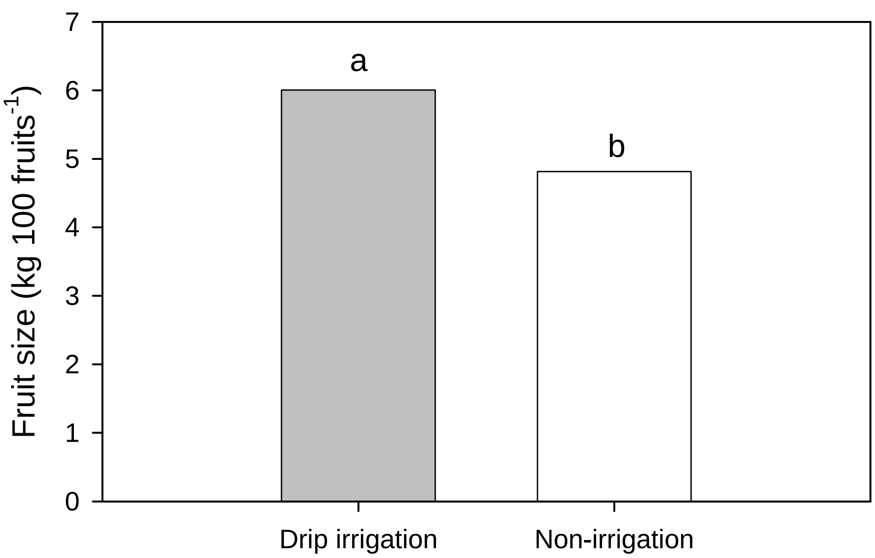

Fig. 10. Response of fruit size of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

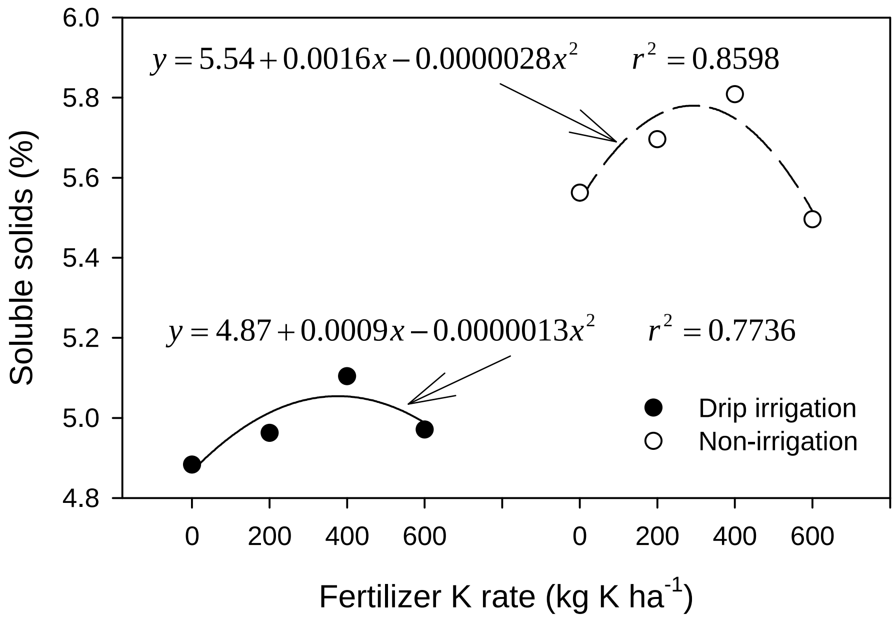

Fig. 11. Response of soluble solids of processing tomatoes to fertilizer K rate with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2008

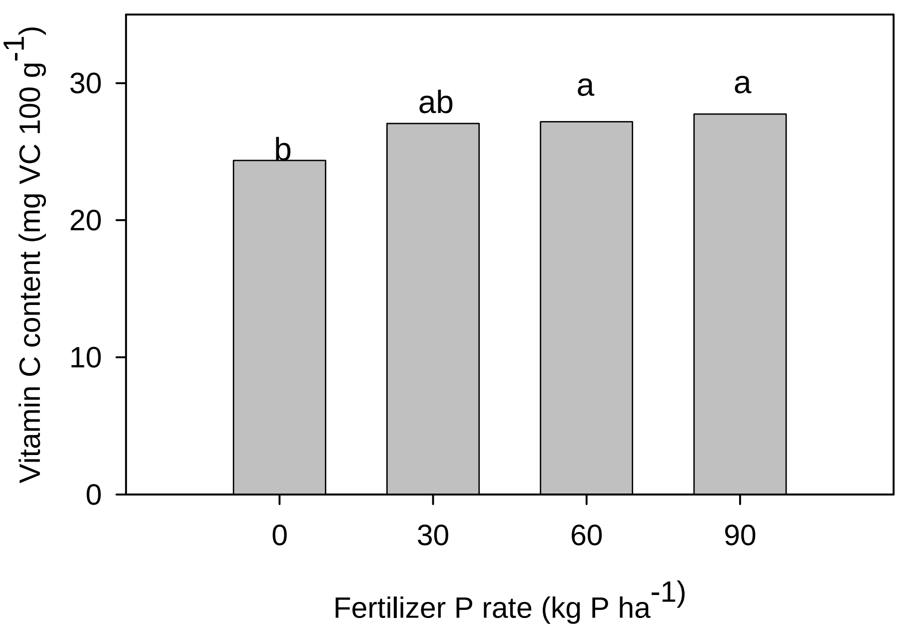

Fig. 12. Response of vitamin C content of processing tomatoes to fertilizer P rate on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

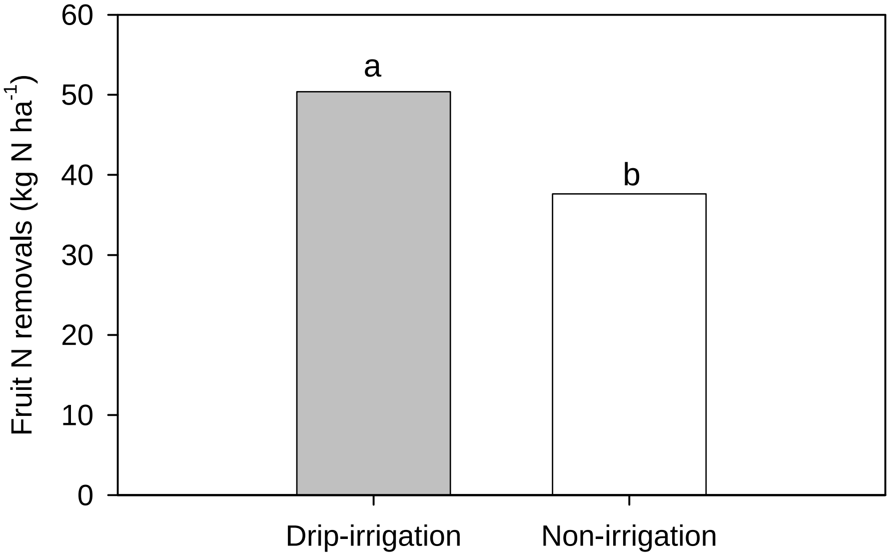

Fig. 13. Response of fruit N removals to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

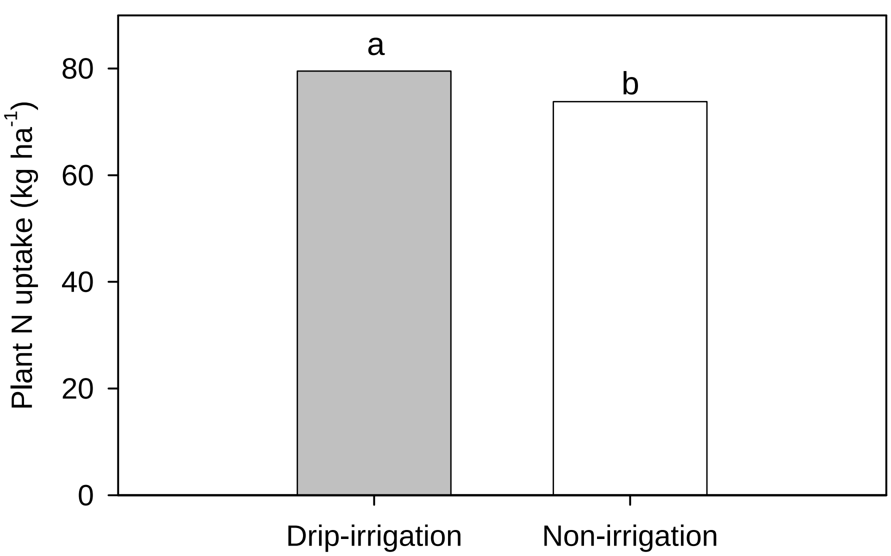

Fig. 14. Response of plant N uptake to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

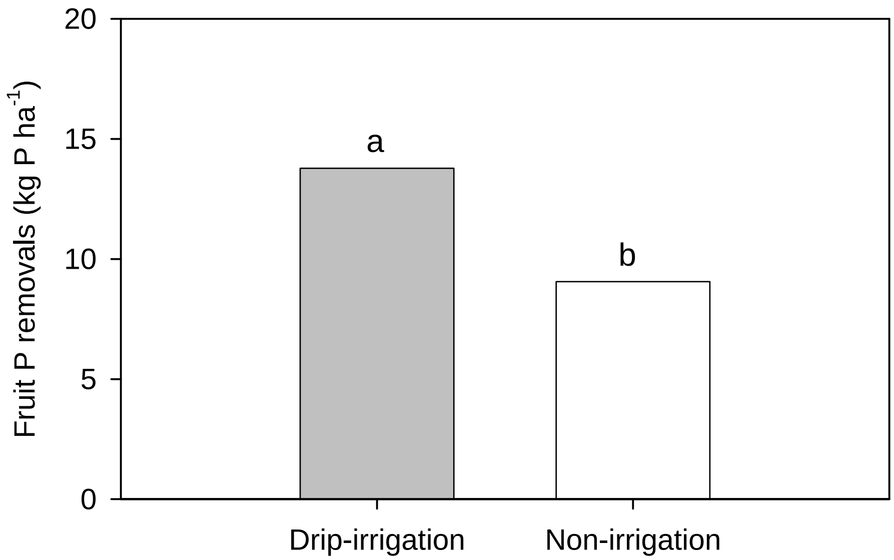

Fig. 15. Response of fruit P removals to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

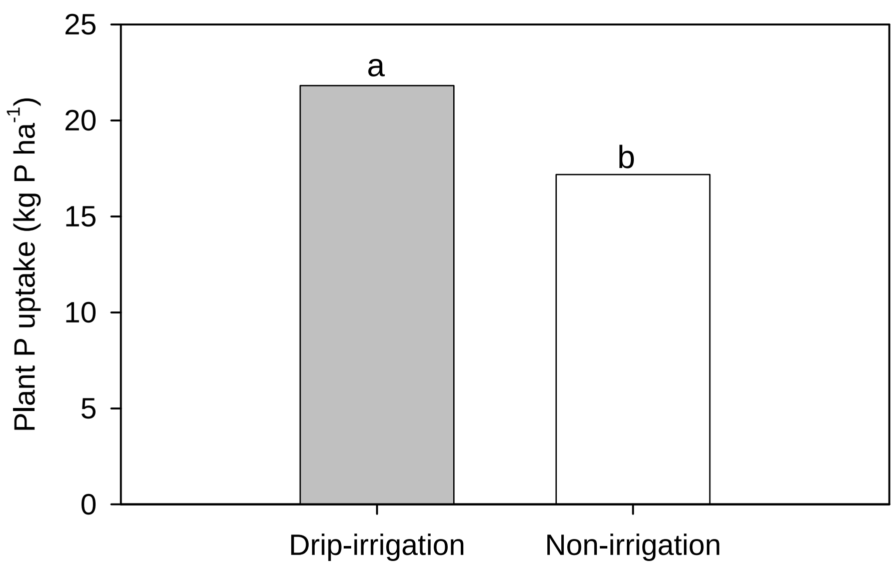

Fig. 16. Response of plant P uptake to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

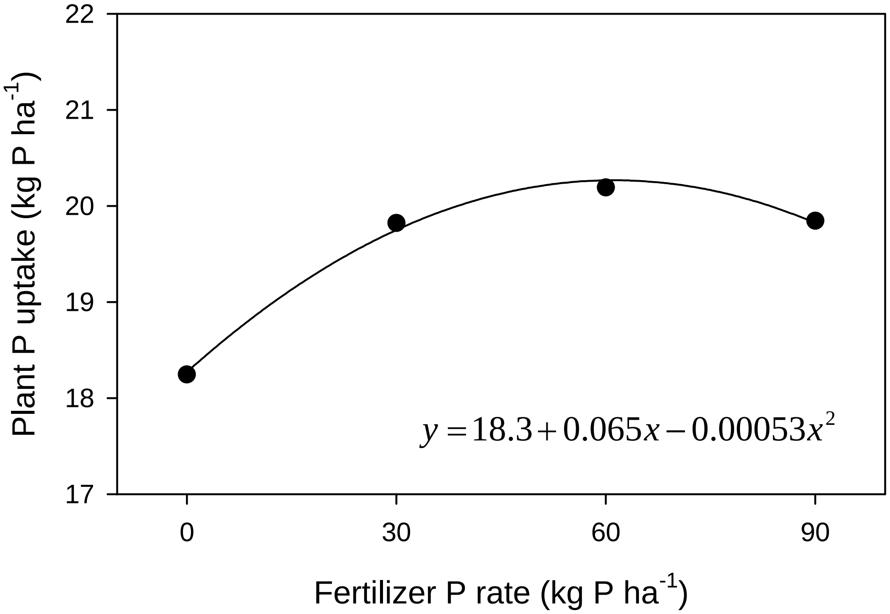

Fig. 17. Response of plant P uptake to fertilizer P rate on a sandy loam soil, Harrow, ON, 2008

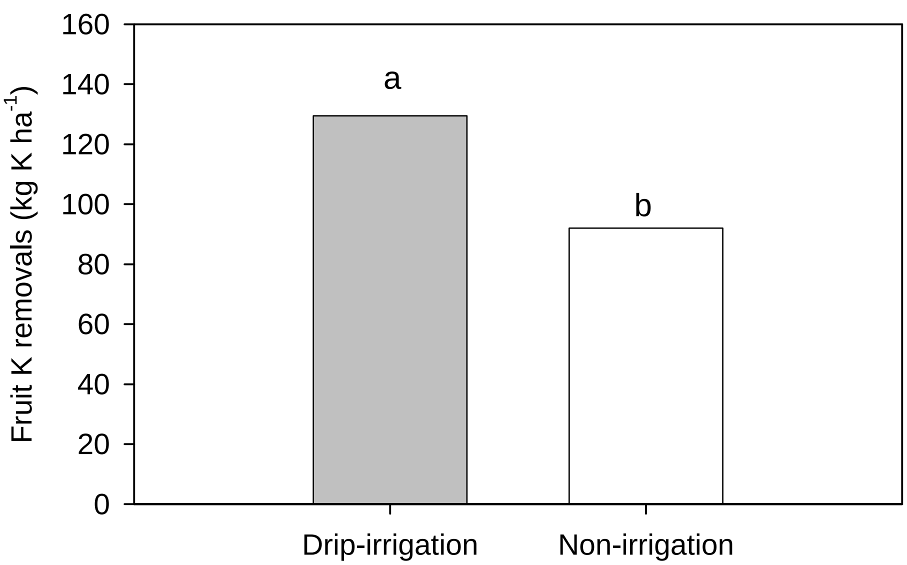

Fig. 18. Response of fruit K removal of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

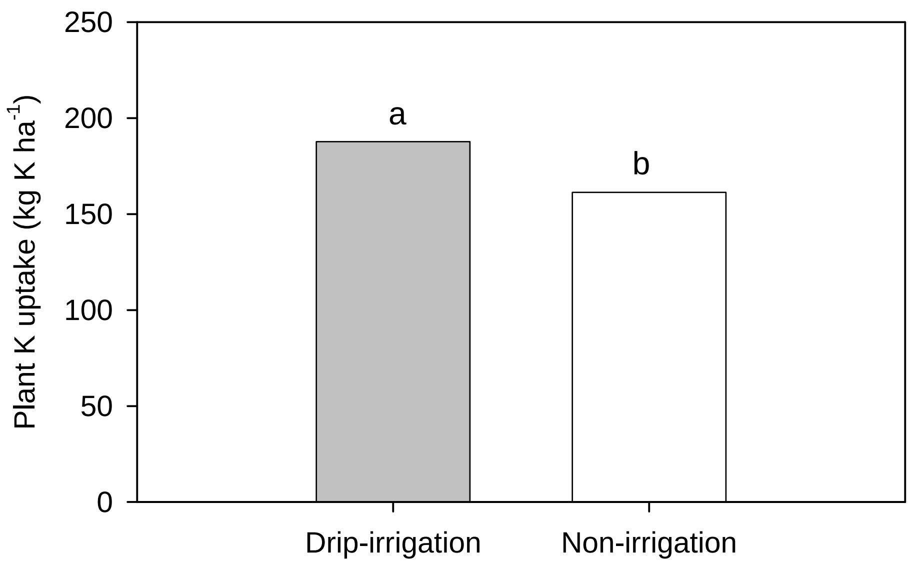

Fig. 19. Response of crop K uptake of processing tomatoes to drip-irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

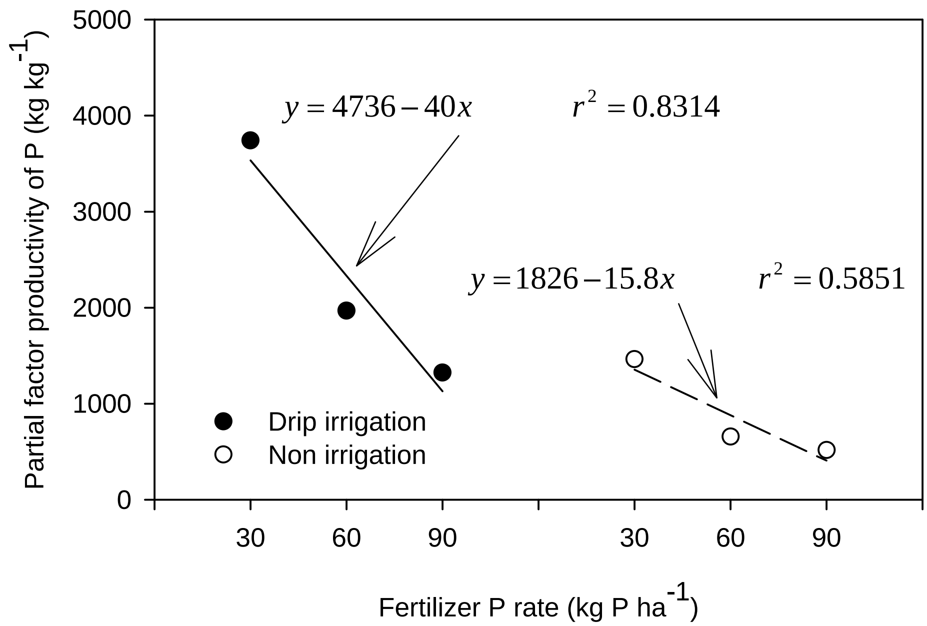

Fig. 20. Response of partial factor productivity of fertiliser P to fertilizer P rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2007

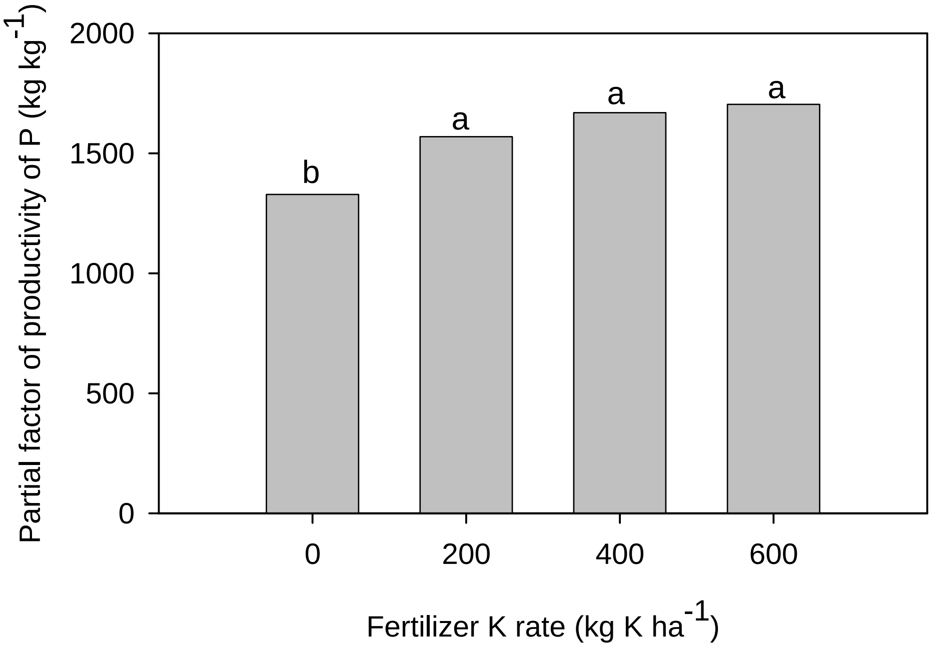

Fig. 21. Response of partial factor productivity of fertiliser P to fertilizer K rate in processing tomato production on a sandy loam soil, Harrow, ON, 2007. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

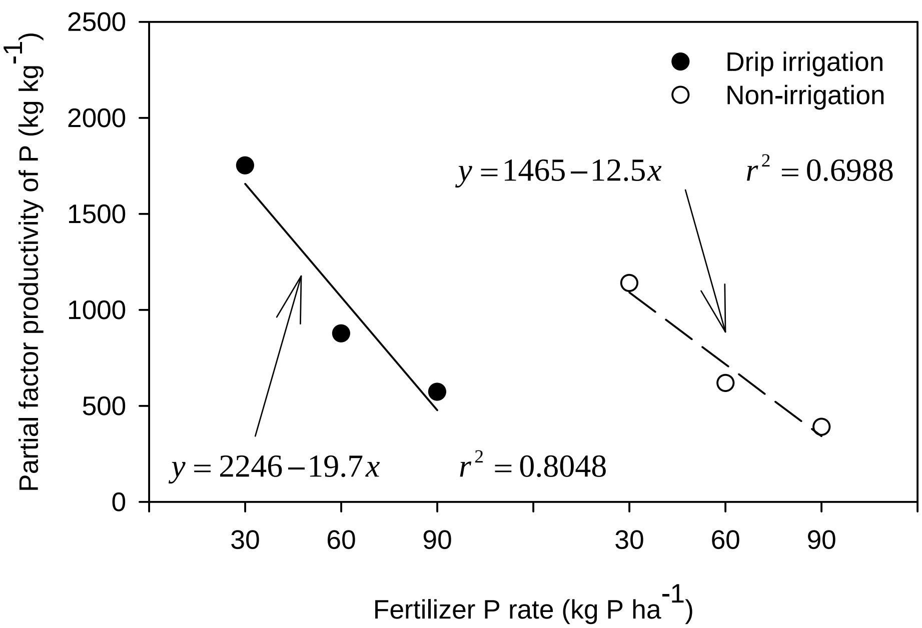

Fig. 22. Response of partial factor productivity of fertiliser P to fertilizer P rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2008

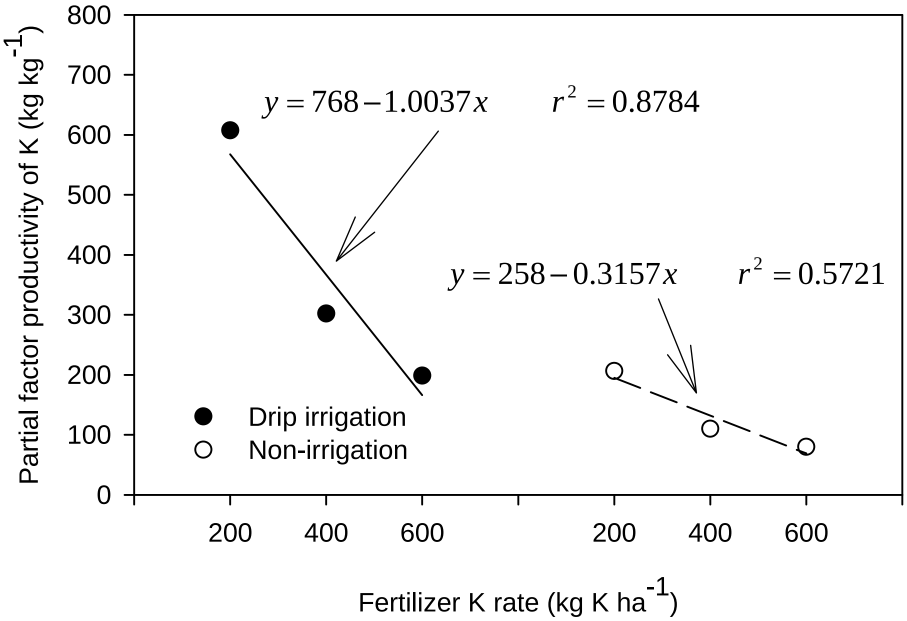

Fig. 23. Response of partial factor productivity of fertiliser K to fertilizer K rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2007

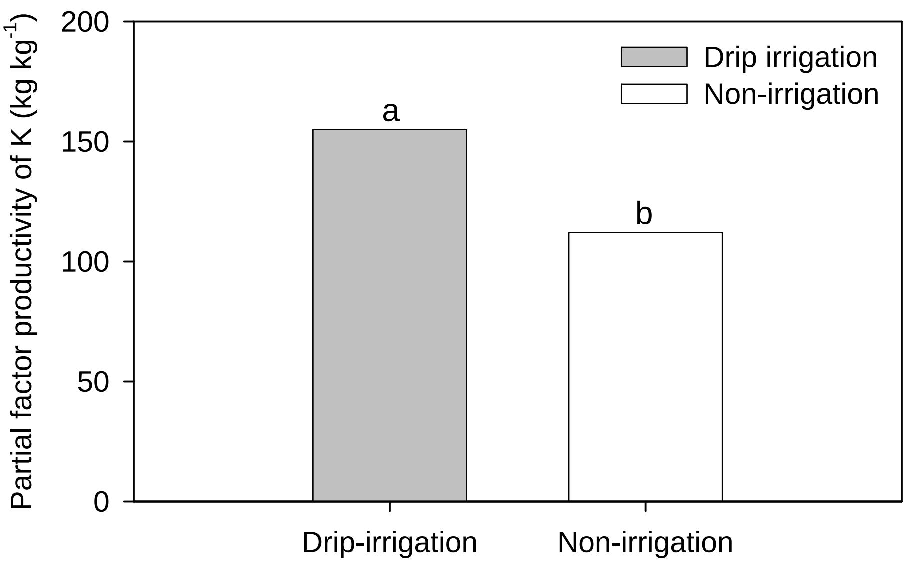

Fig. 24. Response of partial factor productivity of fertiliser K to irrigation in processing tomato production on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

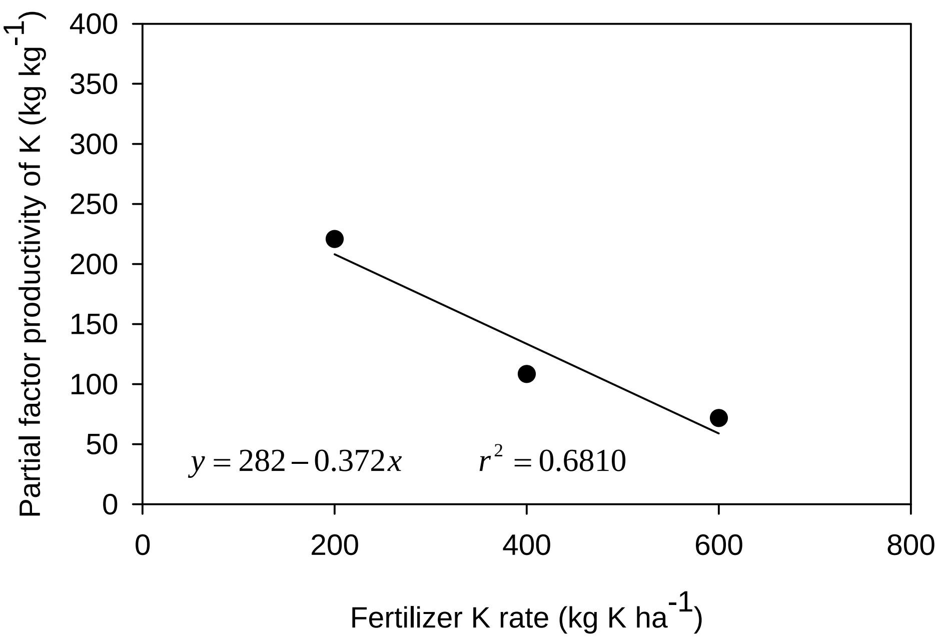

Fig. 25. Response of partial factor productivity of fertiliser K to fertilizer K rate in processing tomato production on a sandy loam soil, Harrow, ON, 2008

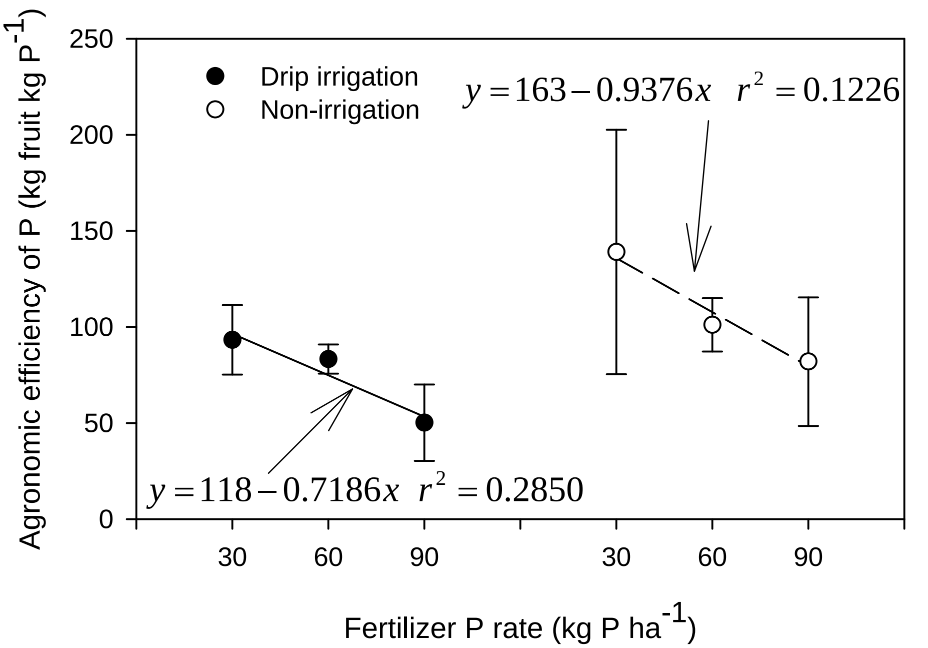

Fig. 26. Response of agronomic efficiency of fertiliser P to fertilizer P rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2007

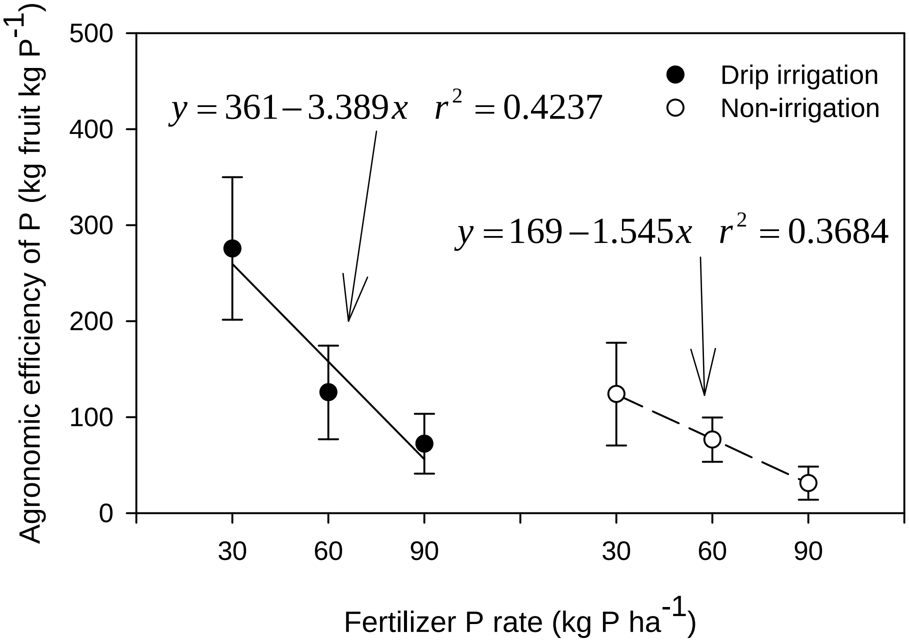

Fig. 27. Response of agronomic efficiency of fertiliser P to fertilizer P rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2008

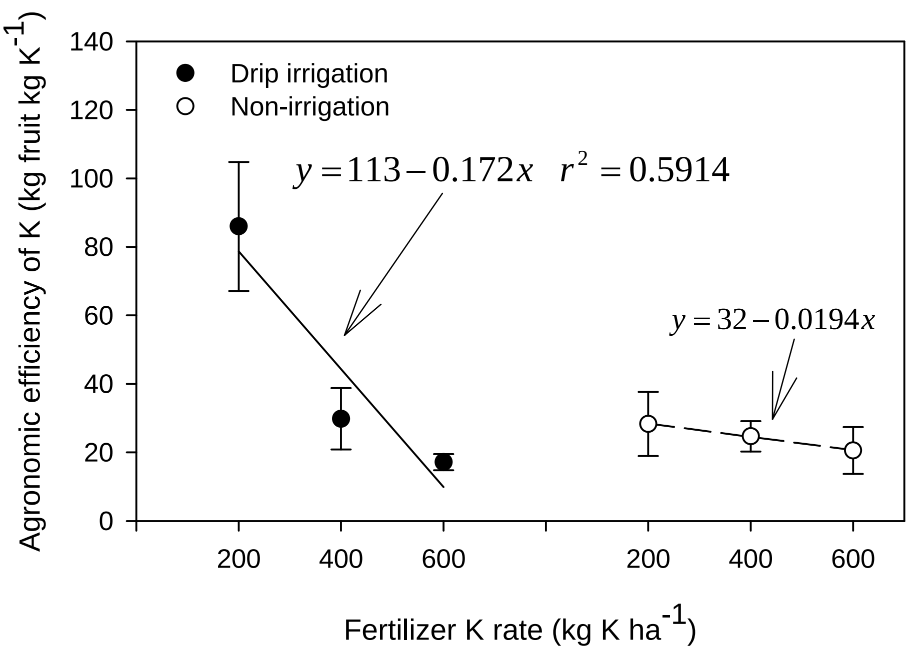

Fig. 28. Response of agronomic efficiency of fertiliser K to fertilizer K rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2007

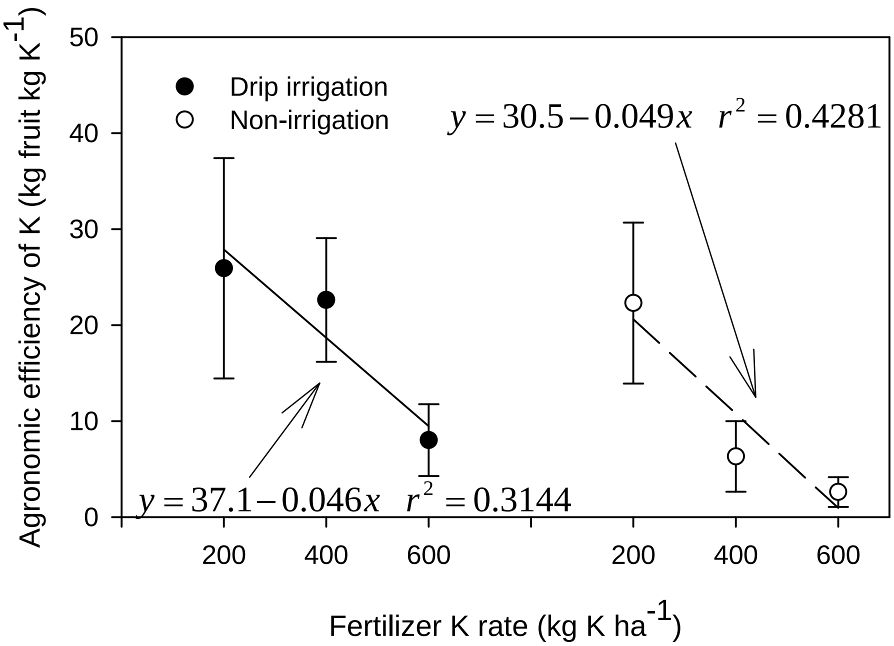

Fig. 29. Response of agronomic efficiency of fertiliser K to fertilizer K rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2008

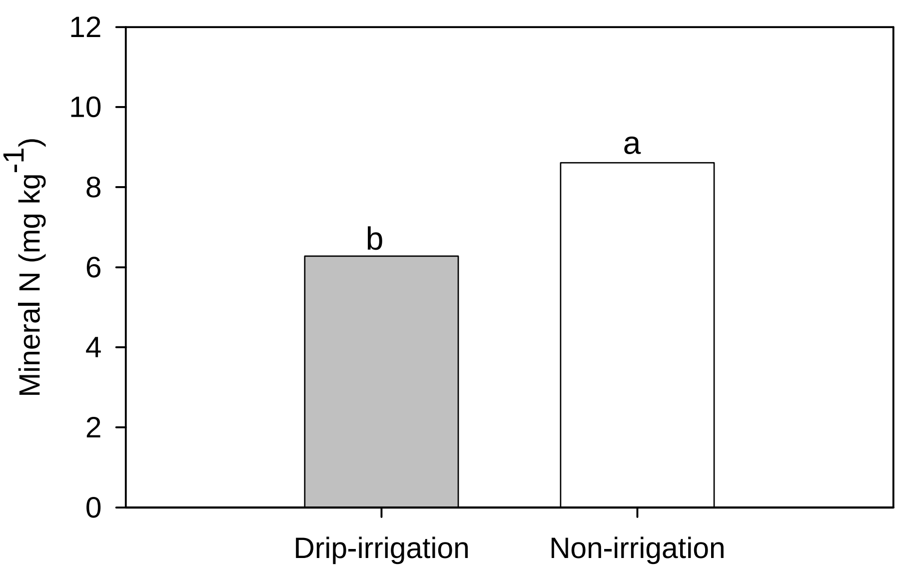

Fig. 30. Response of post-harvest soil mineral N to irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the *P* ≤ 5% level.

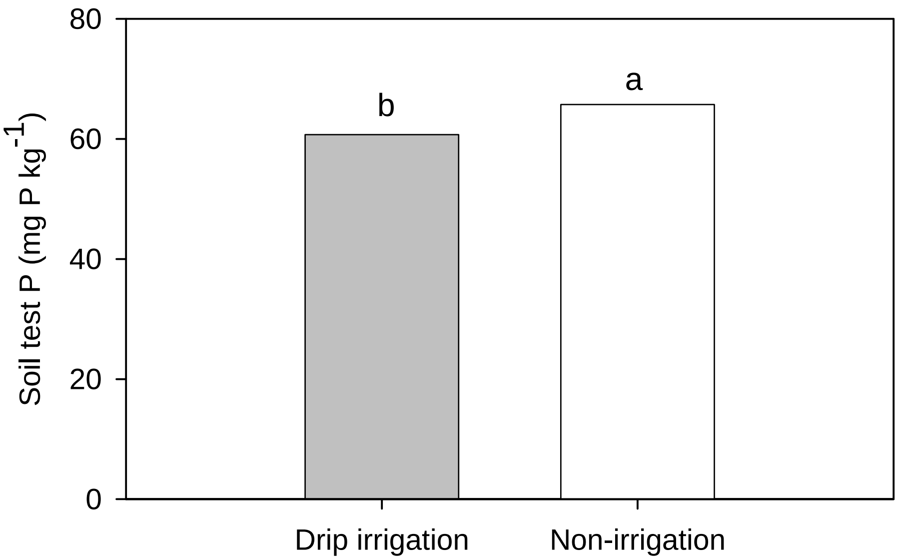

Fig. 31. Response of post-harvest soil test P (Olsen P) to irrigation on a sandy loam soil, Harrow, ON, 2008. Vertical bars marked with the same letters are not significantly different at the $P \leq 5\%$ level.

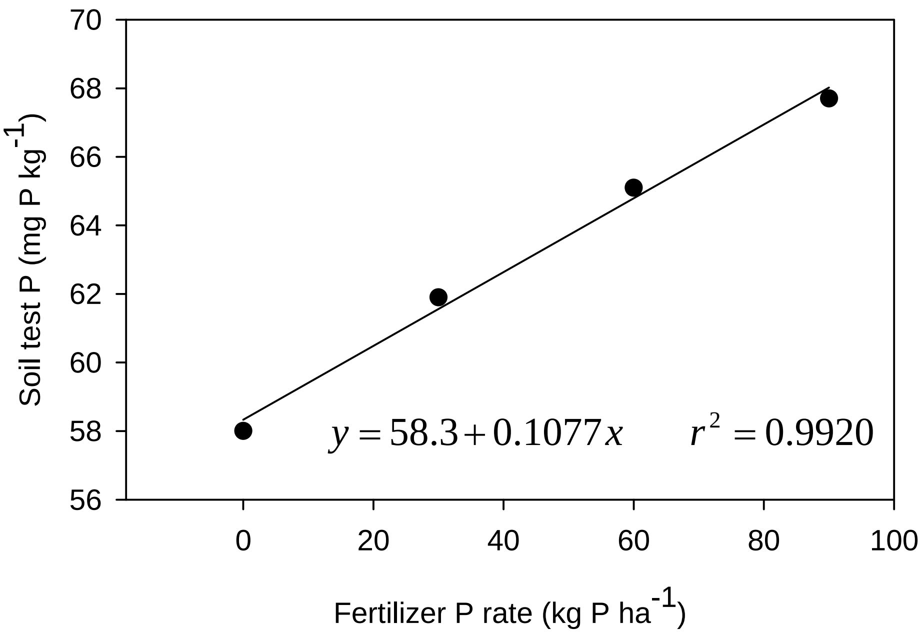

Fig. 32. Response of post-harvest soil test P to fertilizer P application rate in processing tomato production on a sandy loam soil, Harrow, ON, 2008.

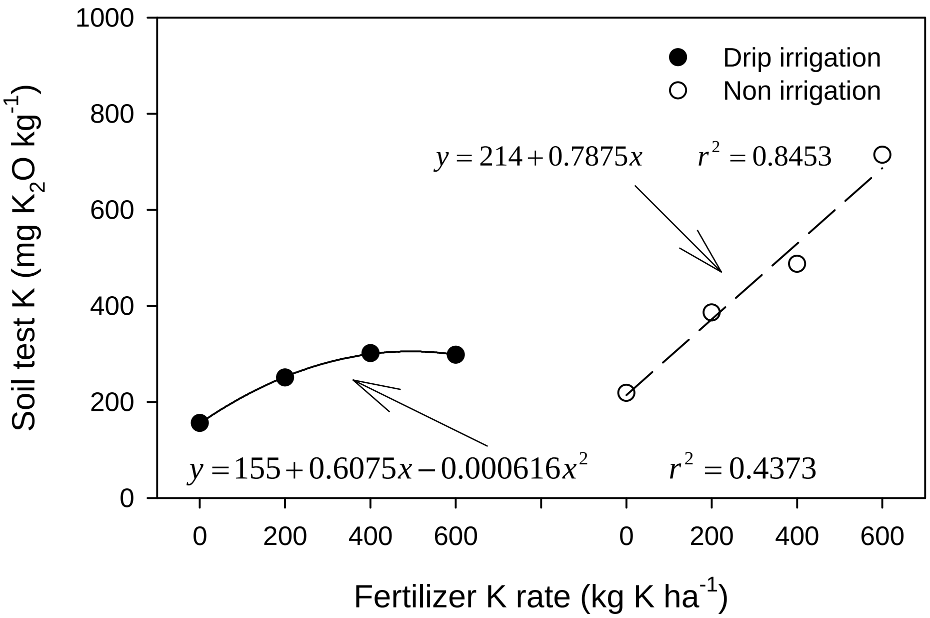

Fig. 33. Response of post-harvest soil test K to fertilizer K rate in processing tomato production with and without drip-irrigation on a sandy loam soil, Harrow, ON, 2008

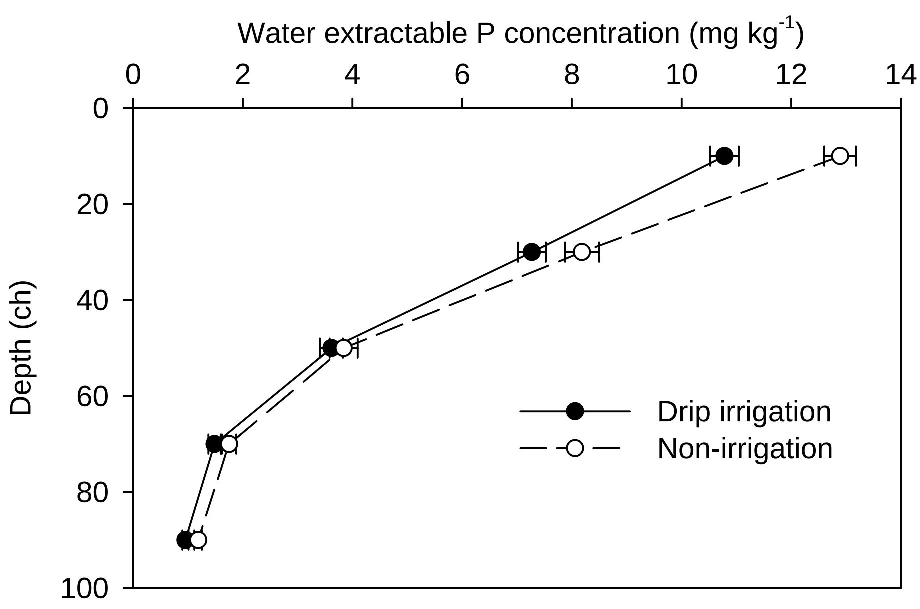

Fig. 34. Post-harvest soil profile water extractable P (0-100 cm) as affected by drip-irrigation under processing tomatoes on a sandy loam soil, Harrow, ON, 2007.

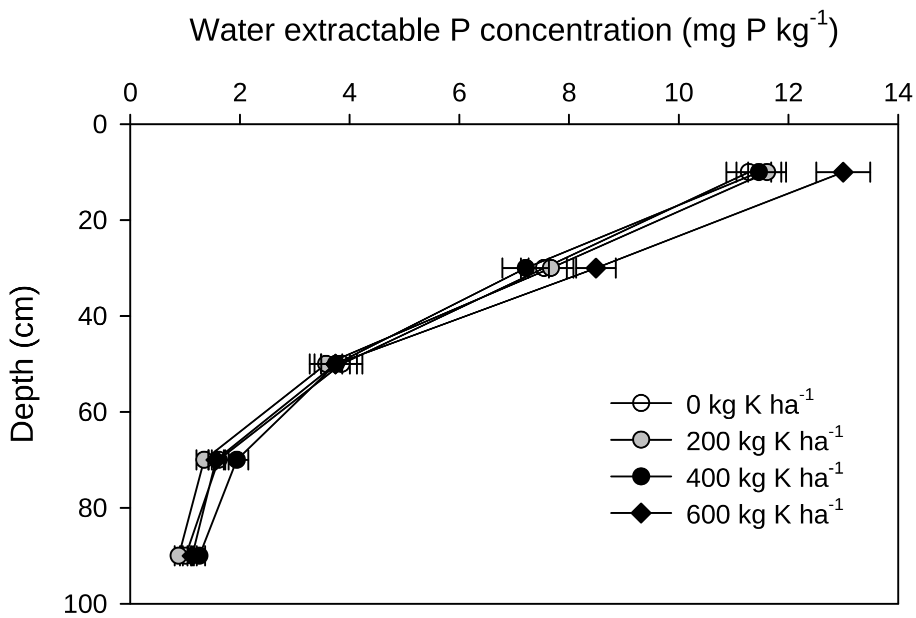

Fig. 35. Post-harvest soil profile water extractable soil P (0-100 cm) as affected by drip-irrigation under processing tomatoes on a sandy loam soil, Harrow, ON, 2007.