Response of Soil and Irrigated Fruit Trees to Fertigation or Broadcast Application of Nitrogen, Phosphorus, and Potassium

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SUMMARY. Traditionally, broadcast or foliar fertilizer applications have been used to improve or sustain the nutrition of many irrigated, deciduous fruit tree orchards in western North America. Recent developments, including adoption of low-pressure microirrigation systems and planting at higher densities [especially for apple (*Malus domestica* Borkh.)], have increased interest in controlled application of fertilizers directly with irrigation (fertigation). Recent fertigation research in western North America is reviewed, emphasizing results from high-density apple orchards. Fertigation and traditional broadcast application methods are examined with respect to mobility of N, P, and K in the soil and response of fruit trees to application of these nutrients.

Irrigation is widely practiced in western North America where $\approx 75\%$ of the continents 62 million irrigated acres (25 million ha) is located (Reaves, 1997). Virtually all

fruit crops in this region are irrigated, and irrigation systems range from gravity flow (flood irrigation) to a variety of sprinkler, low-pressure-microsprinkler or drip-distribution systems. Low-volume irrigation systems are well suited to the high-density apple orchards that are increasingly important in the Pacific Northwest. In British Columbia, for example, new apple cultivars, like 'Gala' and 'Fuji', are propagated on dwarfing rootstocks such as 'Malling 9' (M.9) and 'Malling 26' (M.26) and planted at tree densities that vary from ≈ 240 trees/acre (600/ha) (some traditional central-leader plantings) to nearly 800 trees/acre (2,000/ha) (slender-spindle plantings) and even $>2,400$ trees/acre (6,000/ha) (super spindle plantings) (Quamme et al., 1997). At present, low volume irrigation systems comprise $\approx 20\%$ of the 25,000 acres (10,000 ha) of irrigated fruit trees in British Columbia but are being installed in nearly all of the new, high- and very-high-density orchards. Applying nutrients with irrigation (fertigation) is the most efficient method of nutrient delivery in this type of irrigation system.

Fertigation offers increased flexibility in managing orchard nutrition programs because of the potential for more closely synchronizing nutrient application with plant demand (Haynes, 1985). There is a need, however, to assess effectiveness of any new fertilization strategy relative to traditional methods. In the irrigated fruit growing regions of western North America, the traditional method of meeting fruit crop nutrient requirements has involved a combination of soil and foliar applications (e.g., British Columbia Ministry of Agriculture, Fisheries and Food, 1996). However, this review will focus on the major nutrients N, P, and K, which, when required, traditionally have been applied via broadcast or banded application to the soil. The emphasis will be on comparing and contrasting fertigation and broadcast fertilizer application as they affect the mobility of N, P, and K in orchard soils and response of fruit trees to their application. The discussion will focus on high-density apple orchards on dwarfing rootstocks with low-volume irrigation systems.

Nitrogen broadcast application

SOIL MOBILITY. Remarkably few

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(1989) observed decreased fruit color which resulted in delayed harvest for 'Starking Delicious' apple when fertigated N applications exceeded 223 lb/acre (250 kg·ha⁻¹). Both NH₄-N and NO₃-N forms have been effectively used to fertigate fruit trees. Klein and Spieler (1987a) found no evidence to indicate that fertigating NH₄-N inhibited apple growth on agricultural soils as has sometimes been observed in sand culture (Shear and Faust, 1971). Urea, ammonium nitrate, and calcium nitrate have been found to be acceptable N sources for fertigation with use of calcium nitrate being advantageous when soil pH is low and Mn toxicity a potential problem (Neilsen et al., 1993).

As previously indicated (Fig. 2-4), it is possible to monitor variation in soil solution N concentrations using suction lysimeters. Less information is available concerning an optimum soil solution N concentration for apple tree growth. For example, there were few effects of either irrigation or fertigation

Table 1. Average quantity of N leached below 5 ft (1.5 m) depth in an orchard lysimeter planted to 'Macspur McIntosh' on 'Malling-Merton 111' rootstock with variable irrigation and 145 lb N/acre (162 kg·ha⁻¹) applied annually.²

Year	Irrigation (% of maximum)	Annual irrigation + precipitation [inches/yr (mm/yr)]	Leached N/yr [lb/acre (kg·ha ⁻¹)]
1	37	30 (763)	162 (181)
2	37	29 (728)	92 (103)
3	37	30 (760)	69 (77)
4	50	43 (1101)	200 (224)
5	50	36.5 (928)	38 (43)
6	60	45 (1141)	37.5 (42)
7	75	57 (1459)	96 (107)
8	100	69 (1750)	242 (271)
9	50	43 (1086)	89 (100)

²Data adapted from Stevenson and Neilsen (1990).

treatments on leaf N, tree growth and yield despite differences in soil solution NO₃-N concentrations observed in Fig. 2, implying the lowest [50 to 75 ppm (3.6 to 5.4 mM)] soil solution N concentrations were adequate for growth of young apple trees. Midsummer leaf N

concentration of trees receiving NH₄-N rather than NO₃-N was significantly lower (2.27% vs. 2.33%) only in the year following initiation of differential N-forms when fertigating despite differences in soil solution NO₃-N concentrations during the growing season (Fig.

Fig. 2. Predicted and measured soil solution NO₃-N concentration at 1 ft (30 cm) depth immediately below the drip emitter in response to (a) rate of fertilizer in a silt loam soil, (b) rate of fertilizer in a loamy sand soil, (c) rate of irrigation in a silt loam soil, (d) rate of irrigation in a loamy sand soil during the growing season. Vertical bars represent mean $\pm$ 1 SE. From Neilsen et al. (1998a). For NO₃-N 14 ppm = 1 mM.

Fig. 3. Soil solution $\text{NO}_3\text{-N}$ concentration at 1 ft (30 cm) depth below a trickle emitter during the growing season in response to daily N fertigation of 1 oz/tree (30 g) as $(\text{NH}_4)_2\text{SO}_4$ or $\text{Ca}(\text{NO}_3)_2$. Vertical bars represent mean ± 1 SE. From Neilsen et al. (1998a). For $\text{NO}_3\text{-N}$, 14 ppm = 1 mM.

3). The different soil solution N regimes illustrated in Fig. 4 resulted in leaf N concentration averaging 2.54% over 5 years for fertigated trees and 2.40% for trees receiving broadcast N fertilizer. Few measurable differences in growth and yield were observed however between the two treatments. In greenhouse experiments, Neilsen et al. (1995a) reported maximum vegetative growth of five apple cultivars on M.9 rootstock fertigated three times weekly for 12 weeks with 56 and 112 ppm (4 and 8 mM) calcium nitrate solutions. Bar-Yosef et al. (1988) found a 42 ppm (3 mM) $\text{NO}_3\text{-N}$ concentration (Hoaglund solution) to result in most efficient use of N by daily fertigated 'Golden Delicious' apple grown in outdoor pots, even though plant N-uptake continued to increase to 154 ppm (11 mM) N. With the capability of monitoring variation in soil solution N concentrations using suction lysimeters, additional research is required to determine a minimum soil solution N concentration and duration capable of supporting adequate tree growth and to determine the consequence to fruit production of maintaining optimum N concentrations at different times during the growing season.

Phosphorus broadcast application

SOIL MOBILITY. The mobility of

broadcast P fertilizer under sprinkler-irrigation has been reported for several soils by Lauer (1988). In this study, it was concluded that irrigation rather than P fertilization rate [27 to 214 lb/acre (30 to 240 kg·ha⁻¹)] affected movement of P into the root zone but that downward movement was not large even for coarse textured soils (Table 2). The effect of continuous irrigation was to move P somewhat deeper into the soil but the effect was small. Poor downward movement of broadcast P into the root zone of many orchard soils has long been recognized (Wander, 1947), and it is known that P mobility is reduced in finer-textured and other soils with a high P sorption capacity.

PLANT RESPONSE. Provided there is sufficient movement of P into the main rooting zone in orchards, tree P status can be increased by broadcast applications of P. This is illustrated by increased leaf P concentration of apple

and pear (*Pyrus communis* L.) trees upon soil-surface applications of monoammonium phosphate fertilizer in a range of Pacific Northwest irrigated orchards (Raese, 1998). Lack of growth response of fruit trees to broadcast fertilizer application is common (Greenham, 1976), although recent studies have indicated improved initial growth of newly planted apple trees following application of high rates of P fertilizer in the planting hole, especially on fumigated, replanted orchard sites (Neilsen and Yorston, 1991) or in orchard soils low in available P (Cripps, 1987; Raese, 1998).

Phosphorus fertigation

SOIL MOBILITY. Increased mobility of P dissolved in irrigation water has been observed, especially for sandy soils (O'Neil et al., 1979) but also for fine-textured clay loams (Rauschkolb et al., 1976). The improved mobility has been attributed to movement of P in mass flow with irrigation waters after saturation of reaction sites near the zone of P application. The extent of P mobility is illustrated from a fertigation study carried out by Neilsen et al. (1997b). Trees in an orchard on a loamy sand soil received annual applications of 1.4 oz (40 g) N and 0.6 oz

Fig. 4. Soil solution $\text{NO}_3\text{-N}$ concentration during the growing season in response to 0.9 oz (25 g) N applied as either a single application of broadcast fertilizer (34N-0P-0K) subsequently irrigated via microsprinkler or periodic fertigation (28N-0P-0K) and drip irrigation. Vertical bars represent mean ± 1 SE. From Neilsen et al. (1998a). For $\text{NO}_3\text{-N}$, 14 ppm = 1 mM.

(17.5 g) P as mixtures of ammonium nitrate (34N-0P-0K) and ammonium polyphosphate (10N-15P-0K), through a single drip emitter. Extractable soil P values were measured at 1 ft (30 cm) depth frequently during the growing season at various distances from the emitter and perpendicular to the tree row. Increases in extractable soil P were measurable as far as 1 ft (30 cm) from the emitter, regardless of whether the same amount of P was applied as a single dose, four weekly doses or thirty daily doses in May (Fig. 5). Changes were most apparent directly beneath the emitter, (0 distance), with elevated extractable P concentrations at 1 ft (30 cm) depth immediately after application. This contrasts with the behavior of surface broadcast P fertilizer, which failed to penetrate below 3 inches (7 cm) depth for sandy soil after 16 irrigation applications totalling 6.3 inches (16 cm) (Table 2). This is a clear indication of the mobility of fertigated P.

PLANT RESPONSE. Fertigated P can efficiently modify the P status of fruit trees (Neilsen et al., 1994). Fertigating P increased leaf P concentration of apple in the first growing season (Table 3). Phosphorus-fertigated trees also exhibited increased yield in the first fruiting season. This supports the hypothesis that improving first year P nutrition will accelerate establishment and flowering of newly planted trees (Neilsen et al., 1990). Fertigation of P was less effective for increasing leaf P concentration beyond the first year although fruit P concentration was higher for fertigated trees in the second fruiting season (Table 3). Fertigation of P may therefore have a role in augmenting fruit P concentration. A possible benefit might be reducing low-temperature breakdown, a disorder associated with low P fruit (Johnson and Yogaratnam, 1978; Webster and Lidster, 1986).

Potassium broadcast application

SOIL MOBILITY. Mobility of potassium broadcast directly beneath a drip emitter on a K-fixing soil was high directly below the emitter but restricted at lateral distances 12 inches (30 cm) or more from the emitter (Table 4) (Uriu et al., 1980). Concentrating the fertilizer in a band directly beneath the emitter resulted in unit area K application rates more than 50 times usual

surface broadcast rates. However, it is generally recognized that moderate to heavy surface applications of K salts usually increases available K in the surface soil with adequate movement into the rooting zone of most orchard soils (Oberly and Boynton, 1966). The mobility of normal rates of surface applied K is highest in sandy soils, reduced for soils with high exchange capacity, and very limited for soils known to fix K (Uriu et al., 1980).

PLANT RESPONSE. Broadcasting high rates of K directly beneath drip emitters (Table 4) increased leaf K concentration of prune trees throughout the growing season (Uriu et al., 1980). The high requirement of heavily cropping fruit trees for K and their response to broadcast K application when leaf K concentrations decline below 1% has long been recognized (Greenham, 1976). Few instances of K deficiency have been identified in the Pacific Northwest of North America. However, a single K broadcast application of 200 lb/acre (224 kg·ha⁻¹) as KC1 (0N-0P-50K) was sufficient to ameliorate K deficiency (leaf K concentration <1%) for 3 years in a soil with low available K, averaging 39 ppm (mg·kg⁻¹) throughout the surface 12 inches (30 cm) (Neilsen et al., 1989).

Potassium fertigation

SOIL MOBILITY. The mobility of fertigated-K is well documented and illustrated by changes in extractable soil K at selected depths and distances from an emitter through which K had been added (Table 4) (Uriu et al., 1980). At the end of a single growing season in a clay loam soil, expected to inhibit downward movement of fertilizer K, increases in NH₄OAc-extractable K could be discerned to depths of 2 to 2.5 ft (60 to 75 cm) and lateral distances as great as 2 ft (60 cm). Thus the distribution of soil K was similar in

depth but greater in lateral extent than similar changes previously cited after broadcasting K directly beneath the emitter at rates which exceeded by >50 times normal unit area surface broadcast rates under flood irrigation.

PLANT RESPONSE. As a result of the improved mobility of fertigated K in soils, increased leaf K concentration is a well documented consequence of K fertigation on a range of fruit crops, including apple (Klein, 1992), prunes (*Prunus domestica* L.) (Uriu et al., 1980) and tart cherry (*Prunus cerasus* L.) (Callan and Westcott, 1996). Amelioration of deficiency symptoms and occasionally increased yield can be consequences of fertigating K. However, the ready availability of fertigated K may adversely affect plant uptake of other cations including Ca and especially Mg (Callan and Westcott, 1996; Klein, 1992). The anticipated Ca-K antagonism in fruit, with adverse effects on quality and storage, has not been observed for apples when tree K status has been improved from deficiency conditions (Klein, 1992). In contrast, improvements in apple quality, including increased red coloration of fruit and increased titratable acidity, have been measured when fertigated K ameliorated K deficiency but not when leaf K values were adequate. (Neilsen et al., 1998b).

Direct comparison of broadcast fertilizer application and fertigation

Ideal information for assessing the relative performance of fertigated and broadcast-fertilized trees in irrigation regions would be side-by-side site comparisons with both treatments receiving the same fertilizer and irrigation regime and with experimental duration spanning a significant portion of an orchard's life cycle. Unfortunately, few such comparisons have been made

Table 2. Average depth of penetration of 54 lb P/acre (60 kg·ha⁻¹) applied as monoammonium phosphate or triple superphosphate in three different soils and subjected to sprinkler irrigation.^z

Irrigation applied [inches (cm)]	Soil [inches (cm)]		
	Quincy sand	Warden silt loam	Calcareous Warden silt loam
1.6 (4)	1.9 (4.9)	2.3 (5.8)	1.2 (3.1)
6.3 (16)	2.7 (6.9)	2.6 (6.6)	1.3 (3.3)
Significance	*	*	*

^zData adapted from Lauer (1988).

*Significantly different at *p* = 0.05.

in irrigated regions. In humid regions, as in the Netherlands, trials established at four locations in 1986 on both 'Jonagold' and 'Elstar' compared single time broadcast N [0.5 oz/tree (15 g)] to the same rate of N broadcast with daily trickle irrigation or fertigation for 3 months (Kipp, 1992). Increases in first year shoot growth were observed from irrigation alone for both cultivars. Additional increases from fertigation for 'Jonagold' and for yield for both cultivars in the first fruiting year were measured. Yield differences from fertigation tended to decrease as trees matured. In New York, similar trials were designed to compare broadcast, broadcast and irrigation, and fertigated treatments (Robinson and Stiles, 1993). Broadcast fertilization at high rates of N, P, K, Mg, B, and Zn was applied three times over a 9-week period while fertigated applications were made in 10 weekly applications to 'Redchief', 'Oregon Spur', 'Mutsu', and 'Empire' on the more vigorous 'Malling-Merton 106' (MM.106) rootstock. Similar growth and yield responses to irrigation were observed as in the Netherlands, whereas responses to fertigation were less dramatic with yield increases occurring early (years 2 to 4) but not later for fertigated trees.

Short term comparisons in mature orchards between broadcast and fertigated fertilizer applications usually emphasize the ability to achieve similar yield, growth or N uptake at lower N rates when fertigating (Coston et al., 1978; Dasberg et al., 1988; Smith et al., 1979). Limited comparisons have been made of the effects of fertigation on fruit quality (Ericson, 1993) despite the ease of altering the timing of nutrient application via fertigation. Lack of knowledge of the seasonal and crop load variation in the nutritional requirements of fruit trees at different growth stages probably limits optimum use of the flexibility inherent in fertigation (Haynes, 1985). Such information is not easily generated by comparisons of broadcast and fertigated nutrient applications due to the many combinations of fertigation scheduling available.

Root distribution in relationship to fertigation

A range of plant, environmental and orchard management factors are known to affect the distribution of

fruit tree roots (Atkinson, 1980). Concentration of fruit tree roots occurred around drip emitters not delivering nutrients (Levin et al., 1979) and near emitters for newly fertigated mature trees (Goode et al., 1978). Roots were shallower and closer to the emitter for 'McIntosh' apple on M.26 and M.9 rootstock, relative to 'Malling 7' (M.7) rootstock after daily N and P fertigation through drip emitters in a 4-year

Fig. 5. Average extractable P during the 1989 growing season for single dose, four weekly and thirty daily fertigation treatments of 0.6 oz/tree (17.5 g) per season as measured at 4 to 8 inches (10 to 20 cm) depth directly beneath (0 inches), 6 inches (15 cm), 1 ft (30 cm) or 2 ft (60 cm) perpendicular distance from the emitter. P extracted in solution of 0.25 M acetic acid + 0.015 M ammonium fluoride. For P, 1 ppm = 1 mg·kg⁻¹.

Table 3. Comparison of leaf and fruit P concentration and fruit yield for Summerland 'McIntosh' apple trees on 'Malling 26' rootstock receiving various rates of fertigated P and adequate N for the first three growing seasons.^z

P rate ^v	Leaf P (% dry mass)			Fruit P (ppm fresh mass) ^x		Fruit yield [lb (kg)/tree]	
				Year			
	1	2	3	2	3	2	3
P1	0.19	0.18	0.15	131	72	3.3 (1.5)	11.7 (5.3)
P2	0.23	0.17	0.15	119	84	5.3 (2.4)	10.8 (4.9)
P3	0.20	0.19	0.16	129	97	5.7 (2.6)	11.5 (5.2)
P contrasts							
Linear	***	NS	*	NS	****	***	NS
Quadratic	NS	NS	*	NS	NS	NS	NS

^zData adapted from Neilsen et al. (1994).

^vP1 = 0, P2 = 0.6 oz (17.5 g), and P3 = 1.2 oz (35 g) P/tree annually as ammonium polyphosphate (10N-15P-0K).

^x1 ppm = 1 mg·kg⁻¹.

study on a sandy loam soil (Neilsen et al., 1997a). Nearly half the number of root intersections observed for 'Gala' apple on M.26 rootstock were measured within 1 ft (30 cm) depth and lateral distance from drip emitters after 5 years of annual N and P fertigation (Fig. 6). Roots were more widely distributed for similar trees fertigated through microjet emitters, which were estimated to wet a 6 ft (2 m) wide strip in the loamy sand soil.

The development of a more restricted root zone in orchard planting systems, subjected to frequent fertilizer and water additions offers a potential for improved control and manipulation of the main rooting zone. However, it will be necessary to maintain optimum soil conditions in this smaller root volume.

Soil acidification

A problem which has arisen from continued fertigation of ammonium-containing N fertilizers into restricted soil volumes is soil acidification result-

ing from nitrification of the applied NH₄-N. Declines of 2 pH units have been measured in fertigated orchards within a single year. This parallels declines in soil cation concentrations (Haynes and Swift, 1986) and increases in solubility of toxic elements such as Al (Edwards et al., 1982). The result may be reduced tree growth and induced nutrient deficiencies, such as for K, which have not previously been observed in that orchard (Neilsen et al., 1994). The sensitivity of orchard soils to fertigation-induced acidification varies with the buffer capacity of the soil and can be estimated by an acidification resistance index to assess soil susceptibility to acidification (Neilsen et al., 1995b). Soils with little resistance to acidification should receive N fertigated in NO₃ rather than NH₄ forms.

Conclusion

Comparisons drawn from N, P, and K fertilizer experiments carried out under irrigated growing condi-

tions, typical of western North America fruit orchards indicate that N is very mobile in the soil, regardless of whether it is broadcast or fertigated. An advantage to fertigation is increased flexibility in application with similar plant response possible at reduced N rates and a potential for multiple reduced rate applications timed to more closely coincide with plant N demand. The timing of N application can be readily modified. The more controlled application of N through fertigation thus offers potential to reduce the leaching of excess N and contamination of groundwater, providing excess irrigation can also be avoided. A more sophisticated understanding of the plant's N demand will be required to take maximum advantage of the flexibility of fertigation. The mobility of P and K is much greater when fertigated than broadcast, increasing the potential to apply these nutrients rapidly when required. Caution will be needed to avoid luxury uptake of these nutrients. Fertigation through low-pressure irrigation

Table 4. Average NH₄OAc-extractable K concentration in a Colusa clay loam soil at the end of a single growing season at various depths and distances from emitters through which 2.47 lb (1.12 kg) K had been broadcast beneath the emitters or fertigated or not over the irrigation season.^z

Soil depth inches (cm)	NH ₄ OAc-extractable K (ppm) ^v							
	Distance from emitter [ft (cm)]							
	0			1 (30)		2 (60)		
	Broadcast ^x	Fertigated	Broadcast	Fertigated	Broadcast	Fertigated	Fertigated	
	K	K	no K	K	K	no K	K	no K
0-6 (0-15)	2131	520	270	164	512	250	164	289
6-12 (15-30)	2714	414	141	137	395	137	141	98
12-18 (30-45)	3284	332	113	109	258	102	121	70
18-24 (45-60)	3288	230	74	78	407	70	78	94
24-30 (60-75)	1634	100	70	74	228	66	74	106
30-36 (75-90)	176	66	90	86	90	82	98	86

^zData adapted from Uriu et al. (1980).

^v1 ppm = 1 mg·kg⁻¹.

^xSingle time application at start of irrigation.

Fig. 6. Percent of total number of root intersections for 'Gala' apple on 'Malling 26' rootstock occurring at various depths and distances from drip or microjet irrigation emitters after 5 years of N and P fertigation on a loamy sand soil.

systems, such as drip and microjet, concentrates root development in smaller soil volumes, increasing tree reliance on fertigated nutrients and requiring optimum soil quality in the root zone. An important aim must be to minimize rapid and excessive acidification which can result from the fertigation of $\text{NH}_4\text{-N}$.

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