Introduction to the Workshop

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The unprecedented growth in world food production from 1950 until the middle of the 1980s was accompanied by a B-fold increase in the use of mineral fertilizers. Although this fertilizer—yield relationship will be played out in many underdeveloped countries, there is no such certainty as far as the advanced agricultural countries are concerned. In the latter, crop responses to ever-increasing fertilizer rates will likely be lessspectacular, as one can deduce from crop yield curves found in many soil fertility textbooks. Therefore, continuousattempts to maximize crop yields by means of increasing fertilizer rates may prove wasteful or, at best, inefficient. One can already detect a leveling-off trend in fertilizer use in the United States, Western Europe, and other countries.

Excessive fertilizer rates may not only be profligate, but, potentially, can also pollute watercourses with plant nutrients in general, and nitrates in particular. The public is increasingly concerned about the quality of drinking water. Potential for groundwater pollution appears particularly troublesome, because slow water movement in underground aquifers assures that contaminants may persist for long periodsof time. The danger of pollution seems to be especially high under irrigated agriculture.

Horticultural crops commonly are fertilized heavily with N and other plant nutrients. At present the data appear too scarce to assess what role fertilization of horticultural crops may play in polluting water sources. Nevertheless, the ASHS Mineral Nutrition Working Group, in cooperation with the Ornamental/Landscape and Turf, Pomology, and Temperate Tree Nut Crops Working Groups, initiated a review of fertilizer management strategies aimed at maximizing fertilizer-use efficiency in horticultural crops while minimizing the potential for water pollution. Fruit orchards, vegetable fields, turf, and greenhouse-grown plants each constitute a unique situation and, thus, were treated separately on the pages that follow.

I hope that these papers will provide a useful summary to those involved in the practical aspects of horticultural crops, the scientific community, and the students of agriculture in general and horticulture in particular. Also, these workshop proceedings may serve to stimulate research that will answer currently unanswered questions.

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TECHNOLOGY & PRODUCT REPORT

Causes and Consequences of Overfertilization in Orchards

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Summary. Over-fertilization (i.e., the application of fertilizer nitrogen (N) in excess of the tree or vine capacity to use it for optimum productivity) is associated with high levels of residual nitrate in the soil, which potentially contribute to groundwater and atmospheric pollution as a result of leaching, denitrification, etc. Overfert-ilization also may adversely affect productivity and fruit quality because of both direct (i.e., N) and indirect (i.e., shading) effects on flowering, fruit set, and fruit growth resulting from vegetative vigor. Pathological and physiological disorders as well as susceptibility to disease and insect pests also are influenced by the rate of applied N. Over-fertilization appears to be more serious in orchard crops than in many other crop species. The perennial growth habit of deciduous trees and vines is associated with an increased likelihood of fertilizer N application (and losses) during the dormant period. The large woody biomass increases the difficulty in assessing the kinetics and magnitude of annual N requirement. In mature trees, the N content of the harvested fruit appears to represent a large percentage of annual N uptake. Overfertilization is supported by a) the lack of integration of fertilizer and irrigation management, b) failure to consider nonfertilizer sources of plant-available N in the accounting of fertilizer needs, c) failure to conduct annual diagnosis of the N status, and d) the insensitivity of leaf analysis to over-fertilization. The diversity of orchard sites (with climatic, soil type, and management variables) precludes the general applicability of specific fertilization recommendations. The lack of regulatory and economic penalties encourage excessive application of fertilizer N, and it appears unlikely that the majority of growers will embrace recommended fertilizer management strategies voluntarily.

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Of all the essential elements, N is most commonly applied in orchards and at the greatest rates. The extent to which applications of fertilizer N areactually based on need, however, is lessclear.

Nitrogen over-fertilization is the application of N in excess of the tree/vine capacity to use it for optimum productivity. Data for many crop species (Broadbent and Carlton, 1978) including almond (K. Uriu and WC. Micke, Dept. of Pomology, Univ. of California, Davis, unpublished data), indicate that fertilizer N applied in excess of that needed to support optimum productivity accumulates in the soil and becomes increasingly vulnerable to a variety of loss mechanisms, including leaching and denitrification.

Nitrogen is naturally present in groundwater and soil profiles as a result of nitrates from indigenous deposits; although more recently, N contamination of groundwater resulting from human activities (e.g., domestic sewage effluent, fertilizers, and animal wastes from large feedlot operations) is increasing in regions of intensive agriculture (Miller and Smith, 1976). Estimates of residual soil N resulting from fertilizer N applications in excess of N removed from the field in the edible portion of harvested crops in the San Joaquin Valley of California are presented in Table 1. In both 1961 and 1971, estimates of N removal in the harvested crops, expressed as a percentage of the fertilizer Napplied, was lowest in fruit trees (<20%), followed by grapes (37%), vegetable crops (≈50 %), field crops (≈55%) and hay (>70%) (Miller and Smith, 1976). In a study area of 334 square miles of intensively irrigated land within Fresno County, California, a field evaluation of N fertilization of several crop classes (grapes, orchard crops, truck crops, row crops, and no crops) indicated greater frequencies of high soil nitrate concentrations below the root zones of orchard crops than at similar depths in other crop classes (Nightingale, 1972). Nightingale (1972) suggested that deep

Table 1. ***Estimated fertilizer and residual soil N use and removal by crops in the San Joaquin Valley (1961 vs. 1971) (Miller end Smith, 1976).***

Crop	Area (ha) 1961	Area (ha) 1971	N applied (kg•ha⁻¹) 1961	N applied (kg•ha⁻¹) 1971	N removed (metric tons)[z] 1961	N removed (metric tons)[z] 1971
Field	642,400	648,400	117	120	42,900 (57)	41,700 (54)
Hay	95,100	92,300	57	105	6,900 (100)	7,100 (73)
Vegetable	51,400	57,300	150	181	4,000 (52)	4,500 (43)
Tree	65,400	115,100	114	122	1,300 (17)	2,600 (19)
Vine	105,600	116,200	38	49	1,500 (37)	2,100 (37)
Total	959,800	1,029,300			56,600	58,000

[z]Percentages of N removed are in parentheses and are based on the amount of N applied and that removed in harvested crops, Nitrogen contents of the edible portion of the crops were obtained by laboratory analyses and local sources.

soils (those more likely to support orchard crops) were more sandy. For example, under orchards in the 4- to 6-m-depth interval, 95% of the soil samples had coarse textures (sands to sandy loams). As a consequence, at depths below 1.5 m, orchard soils more typically had lower water-holding capacitiesand higher hydraulic conductivities which may require more frequent irrigation and greater amounts of fertilizers. Such conditions are generally favorable for loss of nitrate by deep percolation (Nightingale, 1972). In recent years, with an increased awareness of the ecological impact of agriculture on the environment, it has become clear that the agricultural community mustassess the long-term sustainability of current agricultural practices. In this paper we examine one aspect of orchard management—N fertilization.

Fruit tree response to overfertilization

Besides environmental concerns, overfertilization may adversely affect tree growth, productivity, and fruit quality as a result of both direct and indirect effects. For example, excess N increases vegetative growth (direct effect), which accentuates shading within the tree and negatively affects flower bud development, fruitset, fruit quality, and shoot survival (indirect effects).

Excessive vegetative growth is probably the least-disputed effect of overfertilization (Claypool et al., 1971; Taylor and van den Ende, 1970). This may lead to increased yield, especially in young trees, due to a greater bearing surface and higher fruit set. We have observed young peach trees growing in good soils under optimum irrigation conditions that have grown extremely vigorously when supplied with high and continuous rates of N. Yield may increase (Taylor and van den Ende, 1970) decrease (Claypool et al., 1971) or remain unchanged (Embleton et al., 1975) due to overfertilization. However, with heavy pruning in the tops of the trees and shading-out of lower fruiting wood, yields often decrease (Claypool et al., 1971). Embleton et al. (1975) reported a slight increase in fruit number for citrus, which was offset by a decrease in fruit size and resulted in no change in yield.

Fruit size also has been reported to either increase (Bramlage et al., 1980; Williams and Billingsley, 1974) or decrease (Claypool et al., 1971; Embleton et al., 1975) with overfertilization. In general, apples tend to be larger with overfertilization (Bramlage et al., 1980; Williams and Billingsley, 1974), while oranges (Embleton et al., 1975) and peaches (Claypool et al., 1971) are often smaller. With nectarines we have observed a slight decrease in fruit size when trees are hand-thinned to equalize fruit loads. Increased shading within the canopy may be partly responsible for this effect (Claypool et al., 1971). Different species and cultivars (Benson et al., 1957) vary in their vegetativegrowth potential and would beexpected to respond to high N rates differently. Pistachios showed very little response to N fertilization (Ferguson et al., 1988). On the other hand, peaches are one of the most responsive species to N. As will be discussed later, responsiveness to applied N will vary not only among species (which vary in their use of N), but also with the availability of nonfertilizer sources of N in the soil.

In stone fruit species, fruit maturity is delayed by overfertilization (Albrigo et al., 1966; Claypool et al., 1971; Proebsting et al., 1957). This delay can be as long as 2 weeks for peaches (Proebsting et al., 1957). The effect appears to be directly due to N, since there isevidence it starts in the early stages of fruit growth before excessive vegetative growth and shading have occurred (Albrigo et al., 1966). High N also increases the variability of maturity among fruit on a tree and even among different parts of a fruit (Claypool, 1975). For example, in apricots the stylar end may be ripe while the stem end is still green. Olives exhibit a similar problem termed “blue nose,” which has been attributed to high N levels (Hartmann et al., 1980). This effect of delaying maturity makes it very difficult to evaluate other fruit quality parameters, since the fruit needs to be picked at different times and may not be at the same level of physiological maturity. Fruit color is influenced by excessive applications of fertilizer N in almost all fruit species. Peaches and red apples exhibit less red coloration (Bramlage et al., 1980; Claypool, 1975; Weeks et al., 1965) and ‘Golden Delicious’ apples tend to be more green with less yellow (Williams and Billingsley, 1974). Valencia oranges show a greater degree of regreening as leaf N increases (Embleton et al., 1975). These responses often are due to chlorophyll retention in the skin until the fruit begin to soften. High N applications reportedly do not influence fruit color in lemon (Jones et al., 1970).

Several pathological and physiological disorders in fruits are accentuated under high levels of applied N. Apples can develop several disorders, including cork spot and bitter pit before harvest and a higher incidence of scald (Weeks et al., 1965) bitter pit, internal browning, and internal breakdown after storage (Bramlage et al., 1980; Terblanche et al., 1980). However, other reports have shown a reduced or unchanged incidence of bitter pit with increasing N (Goode et al., 1978; Weeks et al., 1965). Rind-staining is a storage problem of navel oranges that is intensified by high N applications (Embleton et al., 1975). Some apricot varieties are susceptible to a disorder on the tree called “pit-burn.” It isassociated with high temperatures in the field but isexacerbated by high N (Claypool, 1975). A greater occurrence of split pits have been reported in peaches under high N conditions (Claypool et al., 1972).

Susceptibility to diseaseand insect pests is reportedly influenced by N level. In citrus heavy N fertilization increased fruit scarring by citrus thrips *(Scirtothrips citri* Moulton) but reduced the density of citrus red mite *(Panonychus citri* McGregor) (Hare et al., 1986). Heavilyfertilized nectarinesare more susceptible to infection by brown rot *[Molininia fructicola* (Wint.) Honey] (Michailides and Johnson, 1991) and to peach twig borers *(Anarsia lineatella* Zeller) feeding on fruit (Daane and Johnson, unpublished data). Vigorous growth stimulated by high N is correlated with fire blight *(Erwinia amylorova* Burr) infection in apples and pears (Van der Zwet and Keil, 1979). Infection of grapevines by *Phomopsis viticola* Sacc. is increased by high N (Kast, 1991).

Fruit quality includes many different characteristics. Besides color and size mentioned above, other measures of quality include soluble solids, firmness, texture, flesh color, acidity, tannin content, and flavor. Since each of these parameters may be affected differently by N, it is difficult to assess the overall effect of overfertilization on quality. As a general rule, apples have poorer quality at high N levels (Bramlage et al., 1980, Williams and Billingsley, 1974). Inaddition to the problems already mentioned, apples also tend to be less firm at harvest and after storage with high N levels. Oranges also exhibit poorer quality because several quality factors are negatively affected (Embleton et al., 1975).

The effect of overfertilization on peach and nectarine fruit quality is not as evident. For the fresh market, high N generally is considered to be a problem because of loss of color. We have found inconsistent effects on firmness and soluble solids. For canning, where surface color is less important, both better (Carter et al., 1958; Proebsting et al., 1957) and worse flavor (Stembridge et al., 1962) have been reported. Claypool (1975) suggests the best flavor in pears and peaches occurs at moderate N levels, with a decrease in quality at both very low and very high levels.

The widely held notion that N fertilization increases the likelihood of winter freeze damage to trees does not appear to have been substantiated experimentally (Pellett and Carter, 1981).

Factors contributing to overfertilization

Excessive application of fertilizer N in orchards occurs because growers have a limited awareness of tree N use, soil N availability (which includes both fertilizer and nonfertilizer sources of N), tree N status, and the relationship between tree N status and tree capacity for N uptake. The lack of proper soil moisture management and the nonresponsiveness of trees to excessive N fertilization are integrally related to N pollution of the environment. The perception that annual applications of significant amounts of fertilizer N represent cheap insurance against the economic risks associated with insufficient N availability is common among growers.

Fertilizer nitrogen use efficiency (NUE). NUE may be defined as the amount of fertilizer N recovered by the plant divided by the total amount of fertilizer N applied. There is great opportunity for improvement in NUE, because it is generally considered to vary between 25% to 50% in crop plants (Bock, 1984; Feigenbaum et al., 1987; Haynes, 1986; Newbould, 1989). Levin et al. (1980) suggested that it is appropriate to apply double the amount of fertilizer N that is actually removed from the land by the fruit-to accommodate an estimated 50% efficiency of fertilizer N recovery. Yet many California fruit growers currently apply more than four times the amount of N removed from the land by the crop. Tree use of fertilizer N is only one of the possible fates of fertilizer N. Cover crops and weeds also may compete with the trees for N (Delver, 1980; Stevenson and Neilsen, 1990) but N in cover crops usually is recycled in the orchard ecosystem. Nitrogen losses from agricultural ecosystems can occur via several pathways: a) in soil solution (leaching), b) as particulate material transported by wind and water (erosion), and c) as gasses (volatilization, denitrification). Fertilizer N also may be immobilized in soil organic matter or remain (at least temporarily) as residual nitrate in the soil. These loss mechanisms have been discussed in detail elsewhere (Horung, 1980; Stevenson, 1982).

Site-specific (Le., soil, crop, climatic) and management (N fertilizer sources, rates, and application methodology; irrigation method and frequency; etc.) variables will affect the magnitude of each of these processes (Craswell and Godwin, 1984; Embleton et al., 1973; Rosen and Carlson, 1984; Stevenson, 1982; Weinbaum et al., 1984).

Reviewing a number of studies conducted in commercial citrus orchards, Dasberg et al. (1984) reported that 22% to 68% of recently applied fertilizer N could not be accounted for in the harvested fruit or in the leachate. A substantial proportion of recently applied N fertilizer may be rapidly incorporated into soil organic matter (Embleton et al., 1980; Feigenbaum et al., 1987; Legg and Meisinger, 1982). At high N application rates, the amount of N leached increased and the amount of unaccounted fertilizer N was two to three times higher than the amount of unaccounted fertilizer N following low annual fertilization rates (Dasberg et al., 1984). Positive correlations exist between N fertilization rates and NO_3-N concentrations in the soil solution (Nightingale, 1972).

NUE is inversely related to the level of applied fertilizer N. The percent recovery of fertilizer N has been reported to be ≈ 40% higher in mature, lightly fertilized orange trees than in heavily fertilized trees (Feigenbaum et al., 1987). In contrast, the amount of potentially leachable residual fertilizer N recovered in the NO_3 fraction of the soil has been shown to be considerably larger following high, as compared with low, N fertilizer application rates (Feigenbaum et al., 1987; Klein et al., 1989; Nightingale, 1972).

Splitting fertilizer N applications (i.e., more frequent applications of smaller amounts of fertilizer N) can reduce the leaching of nitrate and improve NUE relative to the amount lost when all N is applied in a single application (Ingestad and Lund, 1986; Mohtar et al., 1989; Stanford and Legg, 1984). In citrus culture, Embleton et al. (1986) suggested that supplementing a low N application rate to the soil with foliar-applied N results in a lower nitrate pollution potential than an all soil-applied fertilization program.

The amount of N leached to groundwater varies positively with the amount of nitrate dissolved in the soil water and the volume of water percolating per unit time (Nitrate Working Group, 1989). Overirrigation, particularly in coarse-textured soils, creates a situation that almost forces the grower to apply high rates of fertilizer N. That is, the greater the loss of fertilizer N from the field—whether by leaching, runoff, denitrification, or volatilization—the more N must be applied to compensate for the N lost. Reasonable management goals include significant reduction in N inputs and the minimization of deep percolation. The latter is influenced by the water-holding capacity of the soil, frequency and amount of irrigation and rainfall, and the uniformity of irrigation. Information on evapotranspiration rates or soil moisture availability is required to schedule the time and amount of irrigation properly (Nitrate Working Group, 1989).

Nitrate leaching appears to be affected not only by the amount of rainfall and irrigation, but also by the method of irrigation (see Elfving, 1982). Williams (1991) reported that drip-irrigated grapevines (NUE = 42%) absorbed three times more fertilizer N than did furrow-irrigated vines (NUE = 14%). With furrow irrigation there is a limit to the amount of deep percolation that can be reduced without greatly reducing yield (Nitrate Working Group, 1989). Other researchers (Coston et al., 1979; Mohtar et al., 1989) also have reported that fertilizer application was very efficient when applied through the drip irrigation system. Sour cherry trees exhibited comparable growth and yield on half the amount of applied fertilizer N injected through drip irrigation as compared with conventional soil application of fertilizer N (Mohtar et al., 1989). A greater proliferation of roots in a relatively confined zone under drip irrigation (i.e., an increased root density) appears to improve the interception and recovery of fertilizer N (Blackand Mitchell, 1974; Williams, 1991; Willoughby and Cockroft, 1974). The plasticity of root growth in response to changes in the soil nutrient environment is well documented (Coults and Philipson, 1977; Embleton et al., 1973). In that context it is somewhat surprising that the interrelationships between N application methodology (rates, distribution, etc.), root proliferation (density), and fertilizer N recovery have received so little attention.

Orchardists in California, as well as in other fruit-growing regions, traditionally have applied fertilizer N during winterwhen deciduous trees are dormant. This practice was apparently carried over from the days of dry-land farming when growers depended on winter rains to carry the recently applied N into the rootzone. Fertilization could be conveniently delayed until winter when there was a reduction in the workload. Winter fertilization was also supported by the mistaken belief (Peacock et al., 1989; Weinbaum et al., 1978, 1980, 1984) that N applied during winter would be readily accessible for uptake by trees in early spring. The N absorbed from the soil and assimilated before leaf fall and remobilized from senescing leaves (while the leaves are still functional) is stored over winter in perennial tissues. This storage N is translocated to the developing blossoms during the early stages of growth resumption in spring (Deng et al., 1989a, 1989b; Oland, 1959; Roberts, 1921; Taylor and van den Ende, 1969; Titus and Kang, 1982; Weinbaum et al., 1978, 1980, 1984). Significant uptake of N from soil does not resume until the period of rapid shoot growth and leaf expansion in the spring (Weinbaum et al., 1978). Nitrogen uptake during the winter is limited both by the physiological inactivity of the tree (dormancy) and the low temperatures that accompany it. The predisposition for fertilizer N loss by leaching, etc., during winter also is increased (Atkinson, 1986; Embleton et al., 1980; Goh and Haynes, 1986; Grasmanis and Nichols, 1971; Peacock et al., 1989; Weinbaum et al., 1978, 1984).

Alternate bearing, i.e., cyclical variation in crop load, is widespread among tree fruit species. That is, heavy flowering and fruiting in one year typically is followed by a light bloom and crop load during the subsequent season (Monselise and Goldschmidt, 1982). Root growth (Head, 1969) the capacity for N uptake (Hansen, 1971, 1973, 1980) and even nitrate reduction (Golomb and Goldschmidt, 1987) appear to be limited in heavily cropping trees. Preferential mobilization of carbohydrates by the fruit appears to limit both root growthand the transport of photosynthates needed by the roots for active nutrient uptake (Atkinson, 1986; Bhat, 1983; Goldschmidt and Golomb, 1982; Golomb and Goldschmidt, 1987; Smith, 1976).

Soil management practices such as cultivation, herbicide applications, and mulching alter the soil environment and influence fertilizer N recovery as a result of effects on trees and soil (bulk density, organic matter content, water infiltration capacity, pH, etc.) (Haynes, 1980, 1980/81). The conversion of arable soil to sod culture usually restricts the growth of young trees as a result of competition for N and soil moisture by the grasses (Haynes, 1980, 1980/81; Glenn and Welker, 1989a, 1989b; Stevenson and Neilsen, 1990; Welker and Glenn, 1985, 1988). When fruit trees are grown in wide herbicide-treated strips with grass alleys (the inter-row areas used for machinery access) between the tree rows, two distinct root environments are created that influence root distribution, root activity, and the use of soil nutrients (Atkinson, 1986). In studies of uptake of ^{15}N placed either in the herbicide strip or in the grass alley, Atkinson (1977) and Atkinson et al. (1978) reported that preferential extraction of N by apple trees occurred from the herbicide-treated area. Atkinson (1986) concluded that tree root distribution and function are dynamic, and rates and sites of uptake vary greatly within a season. They can be modified by orchard floor management systems that influence both soil and root parameters.

Plant-available N. Plant-available N is defined as that fraction of soil N present within the root zone that is in a chemical form (principally NO_3 and to a lesser extent NH_4^+) and can be absorbed readily by plant roots. Nearly all (i.e., >97%) soil N is immobilized in the organic fraction and, therefore, unavailable to plants (Haynes, 1986).

Orchardists tend to ignore nonfertilizer sources of N in the orchard ecosystem and equate the amount of currently applied fertilizer N with the availability of N to trees. This scenario is misleading from several perspectives. First (as discussed previously), not all the fertilizer N applied remains available to the trees (Feigenbaum et al., 1987). Second, nonfertilizer sources of N may supply sufficient plant-available N to maintain tree productivity for extended periods (i.e., 4 to 6 years) without additional N supplements (Greenham, 1980; Jones et al., 1959; Richardsonand Meyer, 1990; Taylor et al., 1960). The data in Table 2 indicate conclusively that trees may have access to N sources other than currently applied fertilizer N.

Soils of the humid and subhumid regions of the United States typically contain 2000 to 4000 kg of N per hectare in theorganic matter of thesurface 15 cm of soil. About 1% (20 to40 kg N/ha) of total soil N is converted annually to soluble, plant-available forms (Bremner, 1965; Scarsbrook, 1965). Mineralization and nitrification in highly organic soils may release sufficient plant-available N to maintain the productivity of some tree and vine species without N fertilizer supplements (Greenham, 1976). Nitrogen may accumulate in soils as a result of excessive fertilization, particularly under a combination of dry climatic conditions and fine soil texture (Harding, 1954).

In the arid western United States, significant amounts of NO_3^--N may be applied to agricultural soils with the irrigation water. In the San Joaquin Valley, for example, the nitrate concentrations in wells used to irrigate orchards have been increasing over the past 20 years and commonly exceed the drinking water standard of 45 mg NO_3^-/liter, the amount considered unsafe for infants (Anton et al., 1988; Miller and Smith, 1976). As a result, 70 to 100 kg N/ha per year commonly is applied with the irrigation water (Table 3). Many wells have become significant sources of "free" fertilizer N. For vineyards, the nitrate content of irrigation water may be enough to satisfy vine N needs since grapevines require less N than do most other perennial crops (Bill Peacock, Tulare County farm advisor, personal communication). The N in irrigation water should be credited against tree fertilizer requirements.

Tree N use (demand). Determination of the seasonal periodicity and the amount of annual N uptake by woody perennials is more difficult than for herbaceous crop species. The large woody biomass of field-grown fruit trees discourages periodic plant excavation and nutrient analysis. The N *content* of mature deciduous fruit trees appears to be two to three times greater than the *annual influx* of N from the soil (Weinbaum et al., 1987; unpublished data).

Table 2. *Walnut yields[z] as influenced by fertilzation rates (adapted from Richardson and Meyer, 1990).*

Fertilizer N applied (kg•ha^{-1})	Air-dry nut wt (kg/plot) 1983	1984	1985	1986	1987	5-yr Avg
0	1536	955	1105	700	882	1036
87	1592	917	1040	699	890	1027
175	1588	932	1142	717	973	1068
262	1621	985	1074	730	940	1071
350	1602	1309	1164	764	1032	1120

[z]Yields did not differ statistically as a result of differential rates of fertilizer N applied in either March or August.

Table 3. *Amount of N applied in irrigation water as a function of nitrate (or N) concentration and the amount of irrigation wafer applied.*

Concn		Annual irrigation rate/unit area			
ppm N	ppm NO_3^-	0.76 m (2.5 ft)	0.91 m (3.0 ft)	1.1 m (3.5 ft)	1.2 m (4.0 ft)
		Amount of N applied (kg•ha^{-1})			
2.26	10	16.8	20.1	23.4	26.8
4.52	20	33.6	40.2	46.8	53.6
6.78	30	50.4	60.3	70.2	80.4
9.04	40	67.2	80.4	93.6	107.2
11.30	50	84.0	100.5	117.0	134.0
13.56	60	100.8	120.6	140.4	160.8
15.82	70	117.6	140.7	163.6	187.6

[z]Agricultural laboratories may report their results of water analyses as either NO_3^--N (ppm N) or ppm
The following conversion factors may be used to calculate the amount of N applied annually in the irrigation water for N concentr
or levels of applied irrigation water other than those listed above.
1 ppm NO_3^--N in the water = 2.72 lbs N/acre foot of water applied.
1 ppm of NO_3^- = 0.614 lbs N/acre foot of water applied.
Since the atomic weight of the N atom is 22.59% of the atomic weight of NO_3^-, ppm $NO_3^- \times 0.2258$ = ppm N.

In late winter and spring, a substantial decrease in the N concentrations of rootstock and trunk bark concomitant with shoot elongation is consistent with the role of storage N in the support of the growth flush before significant N uptake from the soil (Atkinson, 1986; Deng et al., 1989a, 1989b; Mason and Whitfield, 1960; Oland, 1959; Titus and Kang, 1982; Tromp, 1983; Weinbaum et al., 1978). Williams (1991) reported that the N stored over winter in the roots and trunks of grapevines supplied ≈33% of the N required for the new above-ground vegetative and reproductive growth. Stable N isotopes have been used to label the storage N pool of mature almond trees (Weinbaum et al., 1987). Assuming that the N content of mature trees remains relatively constant from year to year, a relatively constant annual dilution of labeled N in tree tissue samples indicates that 40% to 50% of tree N content is replaced annually as a result of current-year N uptake from the soil (Weinbaum et al., 1987). Sanchez et al. (1991) reportedsimilar results. The residual tree N content represents storage N, i.e., N absorbed and assimilated in previous years. Preliminary assessment of an experiment using isotopically labeled N fertilizer and conducted in two mature walnut orchards indicates that the N content of harvested fruit represents ≈75% of annual N uptake by the trees (S.A.W., unpublished data).

The amount of N removed in the crop depends on crop load and fruit N content and varies greatly among speciesand cultivars (Table 4). The amount of N removed in the fruit of several major California tree fruit species can differ by as much as 1000% (e.g., 15 vs. 147 kg N/ha for cherry and pistachios, respectively). An appreciation for these large differences in crop N removal is a key first step in understanding N demands of various tree crops.

Although using fruit N demands to determine crop fertilizer requirements may not guarantee maximum crop productivity because of other tree N requirements and the many factors that influence fertilizer NUE, it may be a step toward developing more ecologically sound fertilizer practices. Under optimal management practices, most of the N in leaves and prunings (except with almonds and walnuts, where 5 to 10 kg N/ha is removed from the orchard) are incorporated back into the soil N pool (i.e., recycled within the orchard ecosystem), and in the long term, the N removed in the crop is the primary legitimate N loss from the orchard ecosystem. Thus, N applications in excess of the crop demand are net increases to the orchard ecosystem and are potential environmental contaminants. Experimentation with several different orchard crops indicates that large applications of fertilizer beyond that removed in the crop are wasteful, because they result in little or no additional yield (Table 5). In the almond and nectarine experiments cited (Table 5) higher N application rates increased fruit N content and, thus, N removal rates. However, the amount of N

Table 4. ***Estimates of crop N removal in major California tree crops.***

Tree crop	Yield ranges[y] (MT/ha)	N removed[z]/ ton of crop (kg/MT)	N removed in crop ($kg \cdot ha^{-1}$)
Pome fruit			
Apple (Golden Delicious)[x]	45–67[w]	0.50	22–33
Pear (Bartlett)	45–67	0.65	29–43
Stone fruit			
Apricot (Tilton)	22–34	2.50	55–85
Cherry (Bing)	11–16	1.35	15–22
Nectarine (Royal Giant)	34–56	0.97	33–54
Peach, clingstone (Halford)	45–67	1.07	48–72
Peach, freestone (O'Henry)	34–56	1.28	43–72
Plum (Simka)	22–34	1.42	31–48
Prune (Improved French)	27–40	1.85	50–74
Nuts			
Almond (Nonpareil)	1.7–2.8[z]	35.3	60–99
Pistachio (Kerman)	3.4–5.6[v]	26.2	89–147
Walnut (Chico)	4.5–6.7[v]	17.9	80–120
Other			
Oranges (Navel)	28–39	2.10	59–82
Grapes (mean of several)	22–34	1.45	32–50
Kiwifruit (Hayward)	22–34	1.80	40–61
Persimmon (Fuyu)	27–40	2.01	54–80

[z]*Kernel weight with standard 5% moisture content*
[y]*Range of yields, considered very good to excellent under California conditions.*
[x]*All estimates, except for oranges andgrapes, are based on tissue analysis of all parts (including endocarp, pericarp, and seed) of fruit harvested from specified cultivars grown under semicommercial conditions in the Pomology Dept. orchards, Univ. of California, Davis, or the Univ. of California Kearney Agricultural Center, Fresno. Data for oranges and grapes are adapted from Birdsall et al. (1961) and Mullins et al. (1992), respectively.*
[w]*A11 values are for fresh weight, except for the nut crops.*
[v]*In-shell weight with standard 8% moisture content.*

Table 5. ***Estimates of fertilizer N applied in excess of crop N demand in fertilizer trials with apples (6-year study), almonds (5-year study), and nectarines (3-year study).***

Crop	N application rate ($kg \cdot ha^{-1}$)	Mean annual yield ($t \cdot ha^{-1}$)	Est. mean annual N removed in crop ($kg \cdot ha^{-1}$)	Est. mean N excess ($kg \cdot ha^{-1}$)
Apple[z]	50	47.7	23.8	26.2
	150	54.3	27.1	122.8
	250	45.1	23.0	226.9
	400	47.1	23.5	376.4
Almond[y]	0	1.89	72.1	–72.1
	60	2.35	94.7	–34.7
	120	2.58	114.7	5.3
	240	2.77	133.1	106.9
	480	2.75	132.6	347.4
Nectarine[x]				
Flavortop	0	35.7	58.9	–58.9
	112	41.9	69.1	42.9
	196	38.9	70.7	25.3
	280	42.7	90.4	189.6
	364	41.5	97.1	266.9
Fantasia	0	42.4	75.0	–75.0
	112	53.8	115.4	–3.4
	196	49.9	113.2	82.8
	280	53.2	147.7	132.3
	364	50.6	139.3	224.7

[z]*Adapted from Klein et al. (1989). Estimates of N removal are based on fruit N data in Table 5.*
[y]*Adapted from Uriu and Micke, unpublished data. Estimates of N removal are based on actual tissue analysis of fruit removed in each treatment.*
[x]*Adapted from Johnson, unpublished data. Estimates of N removal are based on actual tissue analysis of fruit in each treatment. Percent N content of fruit tissue increased with increasing N application rates.*

removed as a result of high application rates was minimal compared to the amount of excess N applied. Moreover, there were no horticultural advantages to having high fruit N contents (R.S.J., unpublished data).

Many growers and researchers apparently fail to distinguish between tree N *demand* (i.e., N use or N removal in the crop) and tree *response* to applied N. If tree N demand exceeds soil N availability, the tree will respond (in terms of growth and yield) to the addition of fertilizer N. If soil N availability exceeds tree N demand, trees will be unresponsive to applied fertilizer N, percent recovery of fertilizer N will be low, and losses to the environment (leaching, denitrification, etc.) will be large.

It is axiomatic that N uptake and tree response (i.e., vegetativevigor, yield, leaf color, and N concentration, etc.) decrease progressively with incremental increases in the levels of applied fertilizers and/or manures (Table 5) (Dasberg, 1987; Embleton et al., 1973; Goh and Haynes, 1986, Smith et al., 1985; Worley, 1990). A lack of response to fertilization in tree growth and productivity may be associated with luxury consumption of N. More typically, however, when maximum productivity and vegetative growth occur, plants exhibit a reduced capacity for N uptake, and nitrate accumulates in the soil (Broadbent and Carlton, 1978). Since nitrate does not react with soil clays, the total supply of nitrate in the root zone is potentially available to the trees. Conversely (and for the same reasons), nitrate is leached readily below the root zone with excessive irrigation or rainfall. Nitrate then becomes both unavailable to the plant and a potential groundwater contaminant (Broadbent and Carlton, 1978; Feigenbaum et al., 1987; Goh and Haynes, 1986).

It is conceivable that trees might *respond* to extremely high N application rates (e.g., 10 times higher than the amount of N actually removed in the crop) if poor management practices are used (e.g., very high N application rates during the dormant period in high-rainfall areas on coarse-textured soils, etc.).

On the basis of fertilization experiments conducted over a period of 30 years at 28 locations in the United States and Canada, Alderman (1919) reported that many orchards growing on a variety of soil types did not respond economically to theapplication of any form of commercial fertilizer. In many other situations, trees responded to relatively low N applications, but in the case of fertigated apple, no statistically significant increases in yield or vegetative vigor resulted from N applications above modest amounts such as 50 kg N/ha (Klein et al., 1989). In this case, trees receiving 400 kg N/ha produced more yield than trees receiving50 kg N/ha in only1 out of 6 years. Application of fertilizer N in soils already containing adequate amounts of plant-available N results in low NUE and is potentially damaging to the environment.

Diagnosis as a guide to fertilization

At present, there are no means to predict accurately the amount of fertilizer N required to support optimum productivity over diverse orchard sites. Estimation of appropriate fertilizer N application rates relates less to our lack of information, however, than to a common inclination of growers to ignore diagnostic possibilities and availablesources of relevant information concerning crop N use and soil N availability. Formulation and implementation of general, i.e., commodity- or county-wide, fertilizer rate recommendations ignore site-specific variables that influence both the annual need for fertilizer N application and the vulnerability of fertilizer N to the various mechanisms for loss. Arbitrary application of excessive rates of fertilizer N to ensure that N is nonlimiting is increasingly difficult to reconcile with current concerns of environmental degradation. Grower practices often are based on tradition, testimonials, and convenience. Thus, growers may fertilize during the winter despite advice to the contrary because of long-standing practice. A grower who applies 500 kg N/ha and obtains high yields is likely to assume a causal relationship and convince neighbors to do likewise.

Fertilization rates and managementstrategies should be based on judgment of tree N status, crop N demand, soil N availability, and other site-specific variables. Fertilizers typically are applied uniformly throughout a field. Many fields, however, consist of two or more soil types differing sufficiently in properties to influence crop yield potentials and tree N status (Carr et al., 1991). It is unlikely that orchard fertilization will ever be based on thedevelopment of accurate N budgets because of the difficulties in quantifying the various N inputs and outputs (Buwalda and Smith, 1988; Dasberg et al., 1984; Feigenbaum et al., 1987; Haynes and Goh, 1980) and their site-specific variation. Soil testing does not appear to be well suited for perennial horticultural crops (Jones, 1985). Spatial variability in soil nitrate concentrations, root distribution, and the (unknown) potential for soil N mineralization make it difficult to assess the amount of soil N available to the trees (Goh and Haynes, 1986; Robinson, 1980). Also, as a result of the presence and use of tree N reserves (Titus and Kang, 1982; Tromp, 1983) tree performance in the current year is not completely dependent on the availability of soil N. Nevertheless, evidence of high amounts of residual nitrate in soils might be legitimate cause for eliminating or at least reducing theannual application of fertilizer N. Visual symptomology of N deficiency, i.e., reduced growth (Drew and Saker, 1975) and restricted chlorophyll synthesis is only a qualitative indicator of tree N statusand is difficult to evaluate without standards for comparison.

In orchard culture, tissue tests [typically, total N concentration (percent dry weight) of leaves sampled in midsummer] are considered more indicative of N availability than are soil tests, because N uptake by the large tree root system integrates the spatial variability in soil nitrate concentrations over a relatively large soil volume (Cramer, 1986; Schaller, 1991). Analytical techniques used with most fruit tree species focus on reduced, i.e., organic N, compounds because nitrate reduction occurs primarily in the roots, and nitrate concentrations are very low in tracheal sap, as well as in the leaf petioles and blades (Bollard, 1957). Nitrate has been found, however, in the sap and petioles of several deciduous vines, i.e., kiwifruit (Ferguson et al., 1983) and grape (Bollard, 1957).

Although leaf analysis appears to represent a vital check of the validity of fertilizer management practices, an informal survey conducted in California indicated that <20% of fruit growers perform leaf analyses annually. Furthermore, the accuracy of leafanalysis, the basis of interpretation, and the recommendations purportedly based on these analyses may vary among analytical laboratories and advisers. Unfortunately, many commercial crop advisers also have a vested interest in selling fertilizer.

Embleton et al. (1974) have credited the use of leaf analysis for diagnosis of tree N status as the basis for a 50% reduction in N fertilization rates of orange trees in parts of California. Interpretation of the results of leaf analysis is usually based on comparison with previously published (if not firmly established) critical levels. Leaf N concentrations below these critical values are taken to indicate that the soil is unable to supply a sufficient amount of N to support optimum tree performance (Robinson, 1980). The use of leaf analysis to diagnose tree nutrient status is based on theassumption that leaf N concentration increases with soil N availability.

If tree N status is low, leaf N concentrations increase significantly with the application of fertilizer N (Tables 6 and 7). Tree response and the increase in leaf N concentration, however, are often insignificant at high fertilizer application rates (Embleton et al., 1974; Klein et al., 1989; Smith et al., 1985; Worley, 1974, 1990) (Tables 6 and 7). Thus, a doubling of the application rate of fertilizer N from 240 to 480 kg N/ha in almond (Table 6) or from 150 to 400 kg N/ha in apple (Table 7) generally did not increase leaf N concentrations significantly. The lack of increase in leaf N concentrations with increased rates of fertilizer N application may result from a) growth dilution, i.e., a dilution of leaf N within an expanded tree canopy volume orb) a lack of any additional uptake of soil N. In pecan studies conducted in Oklahoma, differences in leaf N concentrations were very small between trees receiving no applied N and those receiving the highest rate (2.13% to 2.35%; Table 8). These data (Tables 6-8) again indicate a relative insensitivity of leaf N concentration to rates of applied N that are in excess of the rates needed to maximize tree productivity.

Table 6. ***Relationship between fertilizer application rates and leaf N concentration in almond.***[z,y]

N application rate ($kg\bullet ha^{-1}$)	Sample year 1975	1976	1977	1978
	Percent dry wt			
0	2.03 a[x]	2.22 a	1.97 a	2.01 a
60	2.20 b	2.43 b	2.21 b	2.28 b
120	2.25 bc	2.45 b	2.32 c	2.33 b
240	2.30 c	2.58 c	2.45 d	2.47 c
480	2.38 d	2.64 c	2.54 d	2.54 c

[z]*K. Uriu and W. Micke, unpublished data.*
[y]*Leaf samples harvested in July.*
[x]*Values in columns sharing the same letter do not differ statistically at P = 0.05 by Duncan's multiple range test.*

Table 7. ***Leaf N concentration of unthinned 'Starking Delicious' apple trees fertigated with various fates of applied N***[z] ***[after Klein et al. (1989)].***

N application rate ($kg\bullet ha^{-1}$)	Year 1982	1983	1984	1985	1986
			Percent dry wt		
50	1.90 b	2.40 c	2.34 c	2.33 b	2.11 b
150	2.27 ab	2.86 b	2.84 b	2.78 a	2.65 a
250	2.46 a	3.01 ab	3.09 a	3.02 a	2.56 a
400	2.49 a	3.15 a	3.13 a	2.83 a	2.63 a

[z]*Mean separation between N rates by Duncan's multiple range test at P = 0.05.*

Despite these data, there has been almost no attempt to address the upper limit of the N sufficiency range, i.e., the portion of the soil N availability vs. leaf N concentration plot that is minimally responsive or nonresponsive to increases in the availability of soil nitrate. Worley (1990) has proposed that fertilizer N be applied only when leaf N concentration drops below the sufficiency threshold. In a long-term (16-year) study on pecans in Georgia, Worley (1990) tested sufficiency threshold leaf N concentrations of 2.25%, 2.50%, 2.75%, and 3.00% and compared these thresholds to the application of 224 kg N/ha annually, irrespective of leaf N concentration. After defining the sufficiency threshold for pecan in Georgia at 2.75% N, Worley calculated that optimum yields (comparable to those achieved with 224 kg N/ha applied annually) were obtained at ≈34.8% of the amount of applied fertilizer N (Table 9). Thus, it appears that high concentrations of total leaf N, i.e., above the sufficiency threshold, were indicative of overfertilization and probably accompanied by additional N losses to the groundwater and atmosphere.

Researchers in Oklahoma found that the minimum acceptable leaf N concentration of 'Western' pecan should be ≈2.25% N (Smith et al., 1985) whereas researchers in Georgia suggested a sufficiency threshold of 2.75% N (Worley, 1990) for 'Stuart pecan. Confirmation of currently accepted critical values and establishment of sufficiency threshold standards for the various species and cultivars (T. Embleton, personal communication) in the major geographical fruit-growing regions (Worley, 1990) may promote more environmentally responsible use of N fertilizers in orchard ecosystems.

Conclusion

Orchardists have emphasized economic profitability at the expense of environmental husbandry. High market value of fruit relative to the cost of fertilizer hasencouraged liberalapplication of fertilizer N that frequently exceeds the N removed in the crop by 300% to 400%.

To illustrate this point, data in Table 2 can be used to contrast the economic and N balance equationsassociated with overfertilization. The 5-year average yield associated with the application of 350 kgN/ha was 84 kg/plot (200 kgžha^{-1}) higher than the yield of trees receiving no fertilizer N over that period. The cost of 350 kg of fertilizer N (currently at $0.50/kg N) is $l75/ha. The return on 200 kg of 'Vina' walnuts (currently at $l/kg) is $200/ha (Ren Fairbanks, walnut grower, Gridley, Calif., personal communication), resulting in an additional net return of $25/ha. The N input of 350 kg N/ha resulted in the additional removal of only 3.9 kg N/ha in the fruit. This excessive net N input of 346 kg N/ha to the orchard ecosystem will likely appear in the groundwater and atmosphere. Ultimately, someone will pay the cost for measures to remedy excessive nitrate in the groundwater and the increase in atmospheric pollutants.

Economists have predicted that the price of fertilizer would have to increase >200% to stimulate more judicious fertilizer usage (Newbould, 1989). Newbould (1989) suggested the following steps to reduce nitrate leaching losses to groundwater: a) define sensitive soils, farming systems, and catchments; b) develop appropriate management systems and fertilizer strategies to suit both crops and soils in a range of climatic conditions; c) determine the profile of nitrate at depths under contrasted farming systems where these lie over aquifers used for public water supplies; and d) monitor the effect of changes in farming practices on the profiles of nitrate in the soil and on the appearance of nitrate in groundwater.

Aldrich (1980) listed several strategies to reduce N losses from the soil and increase plant recovery of fertilizer N. The majority of these means involved legislative action, presumably because voluntary compliance with best management

Table 8. ***The influence of N fertilizer application rates on leaf N concentration and yield of 'Western' pecan over a 6-year period [after Smith et al. (1985)].***

N application rate ($kg\bullet ha^{-1}$)	Leaf N concn (% dry wt)	Cumulative yield ($kg\bullet ha^{-1}$)
0	2.13[z] ± 0.02	2901
56	2.21 ± 0.03	3961
112	2.26 ± 0.03	3903
224	2.35 ± 0.02	3949

Table 9. ***Long-term (16 years) pecan productivity and vegetative vigor of 'Stuart' pecan as influenced by level of applied N [adapted from Worley (1990)].***

Basis of fertilization[z]: Leaf N (% dry wt)	Basis of fertilization[z]: Annual application (kg N/ha)	Relative N applied (%)	Relative Yield (%)	Relative Tree vigor (%)
N 2.25	---	3.2	75	92
N 2.50	---	11.2	83	93
N 2.75	---	34.8	100	100
N 3.00	---	40.6	92	97
---	224 (AN)	100.0	100	100

[z]*Nitrogen at 112 kgžha^{-1} was applied to each tree only when the previous season's leaf analysis was below the specified thresholds of 2.25% (N2.25) 2.50% (N2.50), 2.75% (N2.75). or 3.00% (N3.00) except that treatment AN received 224 kgžha^{-1} annually, regardless of leaf analysis*

practicesappeared unlikely. It is clear that agriculture must become more proactive in the development and integration of environmentally sound and economically viable fertilization management strategies. Horticulturists must recognize and accept their responsibility in these efforts.

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Concepts and Practices for Improving Nitrogen Management for Vegetables

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Additional index words. fertilizer management, pollution, water management

Summary. Efficient N management practices usually involve many potential strategies, but always involve choosing the correct amount of N and the coupling of N management to efficient water management. Nitrogen management strategies are integral parts of improved production practices recommended by land-grant universities such as the Institute of Food and Agricultural Sciences, Univ. of Florida. This paper, which draws heavily on research and experience in Florida, outlines the concepts and technologies for managing vegetable N fertilization to minimize negative impacts on the environment.

There are many sources of N, both man-made and natural, that can enter the soil N cycle, and once the N form is converted to nitrate, the N issubject to movementto the groundwater. The interconversions of N forms in the soil make it difficult to determine specific sources of N contamination. The maximum allowable level of 10 mg nitrate-N/liter in drinking water has been established (Council for Agricultural Science and Technology, 1985; U.S. Environmental Protection Agency, 1973). Concentrations of nitrate-N below 3 mg·liter^{-1} in groundwater usually are not considered to be man-made (U.S. Geological Survey, 1985). Although survey results show that most states have sites where the nitrate-N concentration in the groundwater exceeds the drinking water standard, there does not appear to be widespread contamination (Madison and Brunette, 1985; Olson, 1986). There are examples, however, of agricultural areas where ground water nitrate levels have been increasing (Council for Agricultural Science and Technology, 1985; Olson, 1986). Natural N sources, such as organic N deposited over recent geologic time, also can be sources of N contamination of groundwater (Hergert, 1986a; Olson, 1986).

Agricultural production sites at highest risk for groundwater contamination are those in humid, high-rainfall areas with highly permeable soils and shallow water tables. High-value, intensively managed crops, e.g., vegetables and other horticultural crops, and irrigated agronomic crops to which large amounts of N fertilizer are applied have the highest potential for contributing to groundwater contamination. Vegetable production on the sandy soils of the southeastern United States meets all of these criteria. The future of vegetable production in these areas depends on fertilizer management technologies that minimize the potential for groundwater contamination from N.

Crop nutrient requirement. Vegetables are high-value, intensively managed crops requiring inputs of fertilizer and water. Commercial vegetable growers, however, sometimes over-fertilize and overirrigate to minimize the chances of poor crop performance and reduced vegetable quality (Locascio, 1987; Locascio et al., 1984b). Florida tomato growers, for example, commonly apply more than 300 kg N/ha, although recent research reports showed no benefit from N rates above 180 kg·ha^{-1} (Everett, 1976; Hochmuth et al., 1989).

Different philosophies of making fertilizer recommendations complicate fertilizer management (Olson et al., 1982). Recommendations based on crop *removal* values rather than *requirements* are particularly questionable, because excess fertilizer recommendations are probable with the removal philosophy. This is because removal values used were often determined from crops grown under highly fertilized or high native soil fertility situations.

One reason for excessive N rates appears to be unrealistic yield goals set by some growers (Olson et al., 1986; Peterson and Frye, 1989; Schepers et al., 1986). Results of a 4-year study with corn growers in Nebraska showed that only 10% of growers reached their yield goal and only one-half reached 80% of their yield goal (Schepers et al., 1986). Vegetable growers fertilize for high

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yields and high vegetable quality, and goals for both factors are often set too optimistically, leading to overfertilization. Recent work with tomatoes and pepperers conducted on growers' farms in Florida showed that fertilizer rates could be reduced without sacrificing yields or quality (Hochmuth et al., 1987, 1989). Educational programs that increase growers' awareness of the value of groundwater resources and demonstrate production techniques that minimize the potential for N contamination should continue (Hubbard and Sheridan, 1989; Schepers et al., 1991).

Excessive N leaching occurs mainly when crops are fertilized at rates in excess of the crop nutrient requirement (Keeney, 1982). Of the vegetable crops, potato has been studied most widely. Research in Canada showed that N is leached from cultivated potato fields but that more work is needed to determine losses from dormant fields (Milburn et al., 1990). Studies in Wisconsin and New York showed that much of the N in groundwater could be traced to overfertilization and that growers could reduce fertilization rates to environmentally safe levels without sacrificing yields (Meisinger, 1976; Saffigna and Keeney, 1977; Saffigna et al., 1977). Results of several N balance studies with vegetables in California, summarized by Pratt (l984), showed N leaching losses ranging from 90 to 260 kgžha^{-1}.

Several states are using soil testing for N to aid in predicting N fertilizer rates (Blackmer et al., 1989; Magdoff et al., 1990; Olson, 1986; Olson et al., 1986; Randall, 1986; Roberts et al., 1980; Saint-Fort et al., 1990; Stanford, 1982) especially for agronomic crops in low-rainfall areas. This technology is not widely used in Florida or in other humid areas, because soil testing to predict N availability to a crop would be difficult under conditions of highly permeable sandy soils with low organic matter content and high rainfall. There might be a potential for soil N testing in polyethylene mulch systems where soluble N can be protected from leaching by mulch.

Water management. Irrigation is practiced on most vegetable crops in Florida to ensure high production and high quality. Proper water management is a prerequisite for efficient N management, since nitrate moves with the soil water and can leach from the root zone with excessive irrigation (Bar-Yosef and Sagiv, 1982; Ferguson et al., 1991; Martin et al., 1991; Pratt, 1984).

Soil moisture indicators, such as tensiometers, and crop evapotranspiration estimates are being incorporated into irrigation management decisions (Heermann et al., 1989; Martin et al., 1991). Nitrate-N leaching during the season can be reduced by matching irrigation amounts to evapotranspiration (Hergert, 1986b). Research with tomatoes showed that irrigation requirements for the season were 0.5 to 0.75 times the evaporation from a Class A Weather Bureau Pan (Bar-Yosef and Sagiv, 1982; Locascio et al., 1985b, 1989; Smajstrla and Locascio, 1990). The use of pan evaporation with proper crop coefficients (Clark et al., 1990) to estimate the volume of irrigation water, coupled with a tensiometer to indicate when to initiate irrigation, is currently recommended practice for vegetables and strawberries in Florida (Clark, 1992; Clark et al., 1990; Hochmuth and Clark, 1991).

Nitrogen forms and sources. Ammoniacal forms of N often are recommended for N fertilization due to lower cost and higher soil retention compared to nitrate sources of N. However, the soil needs a sufficiently high cation exchange capacity to retain significant amounts of ammoniacal N (Tisdale et al., 1985). Low cation exchange capacity of Florida's sands and warm soil temperatures lead to rapid nitrification, making long-term soil retention of ammoniacal N unlikely. Many studies with various vegetables have shown little yield difference between nitrate and ammoniacal N forms for vegetable fertilization in Florida (Locascio et al., 1982).

Slow-release (controlled-release) N sources also have been studied for their potential to increase N fertilization efficiency. Several studies showed that sulfur-coated urea and isobutylidene-diurea used as 25% of the N fertilizer produced higher or equivalent yields compared to treatments with all soluble sources of N (Locascio and Martin, 1985; Locascio et al., 1981, 1982, 1984a). It appears that slow-release N sources have highest utility for long-term crops, such as peppers, tomatoes, and strawberries, and for crops with high N requirements. Slow-release sources have the potential to increase N efficiency and reduce potential soluble salt injury.

Organic-N sources. Interest is high regarding the use of various organic materials, such as manures and sludges, as fertilizers and soil amendments. Part of the interest is from individuals and organizations that produce wastes, because they need a suitable disposal mechanism. Organic-N sources sometimes are touted as a type of slow-release N, but most of these materials are low in N concentration and must be used at high rates or in combination with synthetic or mineral N sources to satisfy N requirements of most vegetables.

Organic-N sources require proper management to minimize the risk of nitrate contamination of groundwater and surface water (Roth and Fox, 1990). Growers must have knowledge of the N mineralization rate so that management strategies can be developed to maintain N in the root zone and minimize the amount of residual N in the soil after the crop is harvested (Schepers and Fox, 1989). Organic-N applications at rates in excess of crop requirements run the risk of groundwater pollution when the N is converted to nitrate (Weil et al., 1990). Data on manure and irrigation management show that nitrate can appear in the subsoil of fields fertilized with manure at rates in excess of crop N requirements, especially when excess irrigation water is applied (Hubbard et al., 1987; King et al., 1990; Milburn et al., 1990; Weil et al., 1990). This could be a problem when high nutrient rates are applied to short-season crops in warm, high-rainfall areas such as Florida. It might be preferable in humid areas to use organic-N sources on perennial forage or tree crops that have an active root system year-round for nutrient uptake.

Organic-N sources also could present additional problems for vegetable growers. Manures are essentially low-analysis, mixed fertilizers; therefore, several nutrients, e.g., P, Ca, and K, are applied in addition to N (Sommers, 1984). The additional nutrients might not be needed on soils that already contain large amounts of these nutrients. Transportation and application costs can be high, making organic-N sources uneconomical for some growers. A portion of the cost could be borne by the producer of the waste material to improve the economic attractiveness of manures.

Nitrification inhibitors. Chemical means to interfere with the conversion of ammoniacal-N to nitrate-N have been studied for many crops, including vegetables. Vegetable research with nitrification inhibitors such as nitrapyrin (2-chloro-6-trichloromethyl pyridine) and DCD (dicyandiamide) have produced mixed results (Frye et al., 1989; Hendrickson et al., 1978; Rudert and Locascio, 1979; Torrey et al., 1982; Welch et al., 1985) Although nitrification inhibitors have shown some benefit for agronomic crops (Hoeft, 1984) and in some vegetable studies, the consistency of results and economics of their use compared to split application of N fertilizers appear questionable (Frye et al., 1989; Peterson and Frye, 1989).

Fertilizer application timing and mulching. Mixed results have been obtained from studies of split applications of N fertilizer compared to a one-time broadcast application (Evanylo, 1989; Locascio et al., 1970; Smith, 1984; Westermann et al., 1988). The positive responses usually have occurred on sandy soils, with long-term crops, and in wet seasons. Single applications of large amounts of N at planting may save application time and expense but are more prone to leaching losses, because these amounts exceed the N requirement of young seedlings. Split applications of N would be preferable over single applications for minimizing potential negative effects to the environment due to N leaching, because split N applications more closely match the plant N uptake function (Peterson and Frye, 1989; Scarsbrook, 1965).

In the polyethylene mulch production system, all fertilizers traditionally have been applied under the mulch at the beginning of the season. Polyethylene mulch reduces rain and sprinkler irrigation water infiltration into the soil in the bed and helps retain fertilizer in the root zone (Hanlon and Hochmuth, 1989; Hochmuth et al., 1990; Locascio, 1961; Locascio et al., 1985a). Leaching of nitrate is still possible from under the mulch in situations where beds were flooded from heavy rainfall, rising watertables, or excessive irrigation. Split application of N to minimize N losses is possible with the mulch system with the use of drip irrigation (Cook and Sanders, 1991; Locascio and Martin, 1985; Locascio and Smajstrla, 1989) or a liquid fertilizer injection wheel (Csizinszky et al., 1987; Locascio and Hochmuth, 1989).

Placement of N fertilizer. The two most commonly used fertilizer application methods for vegetables are broadcasting and banding. When considering placement options, one should be concerned with the N source, crop, and soil type (Randall, 1984). Ammonia volatilization can result in N losses when ammoniacal N sources are surface-applied to alkaline soils (Randall, 1984). Incorporation after broadcasting or subsurface banding would appear to be the best placement options for fertilizer N. With the full-bed polyethylene mulch system, broadcasting N in the bed area produced better results with some crops than banding (Locascio et al., 1970). Since nitrate is highly mobile, fertilizer placement should not be so deep as to risk leaching, especially from high water tables.

Cultivars. Strains of several vegetable species have been identified that have improved N uptake or usage efficiencies (Barker, 1989; O'Sullivan et al., 1974). Although the idea of nutrient-efficient cultivars has been around for many years, breeding programs have not focused heavily on the incorporation of N efficiency into new cultivars. Incorporation of nutrient efficiency into new cultivars of vegetables would not be simple due to the complex inheritance of many nutrient efficiency traits. Genetic characterization and breeding will require the integrated efforts of classical breeders, molecular biologists, and physiologists (Sussman and Gabelman, 1989). Nutrient-efficient cultivars of vegetable species may offer, in the future, an additional level of efficiency of N management above that available today.

Rotation and cover crops. The use of cover crops, especially N-fixing legumes, has been a common rotation practice for vegetable producers in much of the United States. In Florida, only a few legumes are adapted for use as rotation crops, so grasses such as rye, millet, and sorghum-sudan hybrids are used more widely. Legume rotation crops can fix large amounts of N, on the order of 150 to 200 $kg \cdot ha^{-1} \cdot year^{-1}$ (Power and Doran, 1984). These large amounts of fixed N, however, will be subject to mineralization and subsequent leaching losses unless the vegetable crop production system incorporates technology such as polyethylene mulch to minimize N losses.

Benefits and disadvantages of cover crops have been summarized (Kurtz et al., 1984; Russelle and Hargrove, 1989). Many of the positive aspects of cover-cropping can be used by vegetable growers. Cover crops reduce soil erosion and can use some residual N fertilizer that becomes available to the next vegetable crop upon tillage and decomposition of the cover crop. However, cover crops in high-rainfall areas might not be able to tie up large amounts of residual N rapidly. Estimates have been made that only 20 to 30 $kg \cdot ha^{-1}$ of residual N is tied up in grass cover crops (Aldrich, 1984) so that the practice of cover-cropping to reduce N leaching might have limited value. In addition, the short cycle between spring and fall crops and the lack of suitable, nonweedy species makes cover crop selection difficult in some warm areas of the southeastern United States.

Double-cropping. With the polyethylene mulch system, economic benefit can be realized by producing two or more successive crops on the same mulched beds (Brown et al., 1985). The second crop is often of lower value compared to the first crop, such that mulch ordinarilywould not be used on that second crop if it were grown alone. In a double-cropping sequence, watermelons (a lower-value crop), for example, can follow tomatoes and takeadvantage of the mulch, any residual fumigant effects, and residual fertilizer.

Double-cropping usually offers the potential to increase N efficiency in a multicrop sequence because the successive crops benefit from the residual N of the first crop (Clough et al., 1990; Kalmbacher et al., 1982). In the multicrop systems, supplemental N can be added by drip irrigation (Clough et al., 1990) or a liquid fertilizer injection wheel (Csizinszky et al., 1987).

Drip irrigation. One of the best examples of a production tool with potential for increasing N efficiency is drip irrigation. Drip irrigation has the potential for improving two of the most common contributing factors to N leaching—overfertilization and overirrigation. Irrigation applications can be reduced by 50% to 80% with drip irrigation compared to subirrigation or overhead sprinkler (Locascio and Martin, 1985; Locascio et al., 1989). Better management of water by frequent applications of small, calculated amounts during the growthcycle helpsmaintain N in the root zone and improves N efficiency (Miller et al., 1981). Research with application of N through drip systems (fertigation) showed that yields were improved in most cases by the split applications compared to a single preplant application of N (Cook and Sanders, 1991; Locascio and Smajstrla, 1989).

Fertigation holds the most promise for vegetables produced in humid, high-rainfall areas with sandy soils. Weekly applications of N were equal to daily applications as long as water amounts were managed properly to maintain previously applied N in the bed (Locascio and Smajstrla, 1989). On finer-textured soils, single preplant applications were as good as any fertigation program (as long as subsequent irrigation applications were properly managed) (Cook and Sanders, 1991). With computer controllers, frequent N applications are possible, and more-frequent small applications would seem preferable to less-frequent large applications when leaching potential is high.

Seasonal scheduling of N with drip irrigation makes it possible to maximize crop response while minimizing N input, because N additions can be scheduled to coincide with crop demand. Schedules for N application have been summarized for many vegetables produced in Florida (Hochmuth and Clark, 1991).

Plant analysis. Nitrogen fertilizer management programs can be monitored by plant analysis (Geraldson et al., 1973; Hochmuth et al., 1991; Jones, 1985; Jones et al., 1991). Forseveral vegetables, detailed critical nutrient levels have been summarized for various stages of crop growth (Hochmuth et al., 1991). Plant analysis can improve N efficiency by aiding in thedecision-making process for determining amounts and timing of additional N applications.

Standard laboratory analytical procedures based on analysis of dried whole leaves or petioles are very accurate but time-consuming and costly for routine grower use. Recently, several colorimetric quick-test kits have been calibrated for nitrate-N determinations made on fresh sap (Coltman, 1988; Hochmuth et al., 1991; Prasad and Spiers, 1985; Scaife and Stevens, 1983). Critical nitrate-N concentrations for plant sap have been determined for tomatoes. Growers with drip irrigation are finding the plant sap quick-tests useful in the field for managing N. Small, handheld, battery-operated ion-selective electrodes are also available for nitrate-N or K determinations, and calibration work has begun for these instruments

Proper N fertilization of crops is a significant factor in efficient food and fiber production, yet N has the greatest potential for negative environmental and health effects (Keeney, 1982, 1986). Nitrate contamination of groundwater has become one of the major environmental concerns during the past 20 years. Irrigated agriculture frequently has been viewed as a primary source of contamination because of large inputs of N and the potential for leaching of N (Keeney, 1982; Schepers and Martin, 1986).

Improving N management by farmers should play a large role in the search for sustainability and profitability on modern vegetable farms. Costs of N fertilizer undoubtedly continue to rise, and there is increased concern over N fertilizer use regulations resulting from environmental concerns (Aldrich, 1984). Research in the United States indicates that N leaching results mainly from poorly managed fertilization and irrigation programs. Risks to the environment are minimized when realistic yield goals are set and when best current production technologies are used to their fullest extent. Continued educational programs are needed to increase farmers' awareness of the value of groundwater resources and to demonstrate production techniques that minimize potential for N contamination.

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Technology & Product Report

Effects of Nutrients Applied to Turf on Runoff and Leachate

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Additional index words. turfgrass, nutrient management, nitrate-nitrogen, water quality

Summary. A paucity of data exists on the water quality impacts of fertilizer nutrients used for turfgrass management. The primary macronutrients N and P have been shown to cause the eutrophication of surface water bodies, and excessive nitrate (NO_3^-) concentrations in drinking water have been linked to methemoglobinemia in infants. Several studies have indicated that runoff quantities from high-quality turf areas are minimal; therefore, nutrient transport by this mechanism should not be a major concern. The leachability of N is favored by the presence of soluble forms in permeable soils receiving rainfall or irrigation in excess of field capacity. Most of the factors contributing to this condition are manageable. However, a wide range of turfgrass types, uses, and management expertise make it difficult to generalize the overall impact of turfgrass fertilization on water resources. While research has demonstrated the ability to minimize nutrient loading, characterization of nonresearch sites is critical to gain a legitimate understanding of environmental impacts. Once developed, best management practices can be effective only if understood and adopted by applicators.

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The impact of agricultural fertilizer (and pesticide) use on water quality has commanded much scientific and political attention during the past decade. An impressive volume of literature has been published on the topic by agricultural researchers, and U.S. agricultural producers are currently undergoing a critical examination of practices and policies that have the potential to have an impact on water quality (Office of Technology Assessment, 1990). More recently, the use of agricultural chemicals for residential and commercial turf management has come under even more vociferous attacks than conventional agriculture (Code, 1991). Unfortunately, only a few studies examining the effects of this particular use pattern have been completed to date. In addition, I am aware of no studies that have fully accounted for the environmental fate of fertilizers or pesticides in situ as part of the total turf system. Thus, the ability to determine the contribution of turfgrass systems to nutrient-loading of surface or groundwater is limited to the interpretation of numerous independent studies and the extrapolation of their conclusions to the wide variety of existing conditions.

Among the primary macronutrients, only N and P have played a major role in the degradation of the United State's water resources. Enrichment of surface water with both N and P has been linked to the eutrophication of numerous receiving bodies, and excessive levels of nitrate (NO_3^-) in drinking water have been associated with methemoglobinemia in infants (National Research Council, 1978). Both of these nutrients are used widely in conventional agricultural production systems. Contamination of surface water by agricultural runoff that contains significant concentrations of N and P has been a well-recognized problem for decades. A number of recent studies (Gross et al., 1990; Harrison, 1989; Morton et al., 1988) have suggested that runoff from high-quality turfgrass occurs mostly in insignificant quantities. Thus, the transport of nutrients into surface water when applied to well-managed turf should be minimal.

Turfgrass fertilizers generally include a lower percentage of P relative to N-anywhere between 2 and 6 parts N to 1 part P—except during initial establishment. Phosphorus is relatively insoluble in the soil matrix (Brady, 1974), and I am not aware of its role as a groundwater contaminant. Nitrate, on the other hand, is quite soluble and is not adsorbed onto soil colloids, causing it to be readily leached. A maximum contaminant level of 10 mgžliter^{-1} has been established for NO_3^--N in drinking water (U.S. Environmental Protection Agency, 1990). Legislation is pending in Pennsylvania that will require the development of agricultural nutrient management plans to reduce losses to drinking water and the Chesapeake Bay (Pennsylvania General Assembly, 1991). In some instances, fertilizer use on lawns, athletic fields, and golf courses has been implicated by association as a major contributor to the problem. In fact, a paucity of data exists on this topic. Nitrogen is one of the most ubiquitous and dynamic elements in the biosphere. It comprises nearly 80% of the atmosphere, is naturally present in rainfall, and is a basic building block of the amino acids and proteins that are integral to all living things and their waste products. Attempts at regulating its behavior will prove to be a challenge.

The effect of N applied to turfgrass on water resources depends on: the form of N applied and its subsequent fate in the environment; the turf type and use and associated maintenance practices; inherent site characteristics: and the interaction among these components of the system. Nitrogen exists in numerous chemical forms that range in complexity, solubility, and mobility from simple inorganics such as atmospheric N_2, NH_4^+, and NO_3^-; to simple organics such as urea and short-chain methyl ureas; to complex organics such as proteins, amino acids, and synthetic fertilizers such as isobutylidene diurea (IBDU). Nearly all of these forms are available to turf managers as naturally occurring or commercially marketed fertilizer products. The dynamic cycling of these N compounds can lead to their gasification and loss to the atmosphere, uptake by plants, soil storage, runoff, and/or leaching. Plant uptake is primarily through root absorption of the fully oxidized NO_3^- form, which is also the most leachable. Thus, an environmentally sensitive N-management plan looks to make NO_3^- available during periods of optimum plant uptake in quantities that do not exceed plant needs and to minimize NO_3^- availability during the remainder of the year. This is accomplished either by timely, low-rate applications of soluble forms or through the use of slow-release organic forms. The conditions favoring the various N forms and pathways have been well studied and recently reviewed by Petrovic (1990). He concluded that the major factors affecting the aqueous transport of N, such as soil texture/organic matter content, irrigation/rainfall, fertilizer source/rate, and season of application, are manageable under most circumstances,

The situation is complicated, however, by the range of uses for which turfgrass is employed and the variability in management practices for each. Turfgrass established for golf and professional athletic uses tends to be the most intensively managed. Residential and commercial lawns, parks, and scholastic athletic fields vary widely in management inputs. Turfgrass for commercial sod harvest is generally maintained at low to moderate levels, and utility turf such as that in cemeteries and on utility or roadside rights-of-way receives few inputs beyond occasional mowing. In addition to mowing, management practices may include clipping removal, irrigation, fertilization, pest control, and mechanical cultivation. All of these activities can have an impact on the availability and mobility of nitrate in the system. The range of expertise of individual site managers can also be a factor.

Turfgrass managers range from untrained and disinterested homeowners to home hobbyists and commercial novices to scientifically literate and innovative professionals. In fact, the effect of nutrients applied to turf on runoff and leachate can depend as much on the function of the site and the expertise of the manager as on the chemical, physical, and environmental characteristics of the system.

A number of recently conducted field studies (Harrison, 1989; Gross et al., 1990; Morton et al., 1988) has demonstrated that NO_3^- concentrations in suction and zero-tension lysimeter samples were either not elevated or were generally well below the 10 $mg \cdot liter^{-1}$ standard. In all cases, the researchersconcluded that the turf ecosystem was able to absorb and cycle the nutrients. In addition, Cohen et al. (1990) observed that elevated NC_3^- in golf course wells was related to excessive application rates of soluble N formulations, supporting thecontention of Petrovic (l990) that N leaching is a manageable phenomenon.

What these studies demonstrate is not that turf fertilization makes no contribution to surface or groundwater contamination, but only that these practices do not have to contribute to the problem if they are managed carefully. A number of management considerations and research priorities are suggested by these results.

Management considerations

Cleanliness. As with pesticides, the greatest risk of contamination occurs during the transfer of bulk quantities of concentrates. Individuals involved with training need to emphasize that even small spills should be cleaned up immediately. Applications near the edges of turfgrass areas also should be performed with precision. Impervious surfaces, such as sidewalks or driveways, often are linked directly to storm water collection systems. Chemical products should be kept off of these surfaces.

Reduction of maintenance levels. Traditional management objectives are driven, to a large extent, by aesthetic standards that exceed the functional and agronomic needs of the turfgrass. Maintenance programs that aim to produce lush growth during the height of summer increase the demand for fertilizer and irrigation inputs and predispose grasses to infestations of pathogens. Such programs may be appropriate for heavily trafficked turf, such as golf courses and athletic fields, but are unnecessary for most lawns or parks. Education of clientele about the functional requirements of healthy turf and its ability to respond to environmental stress is needed.

Consideration of economic vs. environmental tradeoffs. Soluble N products are cheaper and their effect on plants is more predictable than slow-release forms. However, their use must be carefully monitored to avoid leaching losses. When management objectives include the "convenience" of infrequent maintenance inputs, the use of more expensive slow-release products should be considered.

Research priorities

In his review of N fate in turf, Petrovic (1990) noted, "The distribution of fertilizer N applied to turfgrass has generally been studied as a series of components rather than a complete system." While the pathways into which applied N will enter have been studied carefully, the behavior of the total system under field conditions has not.

Studies such as those conducted by Morton et al. (1988) Gross et al. (1990) and Harrison (1989) must be conducted under actual use conditions common to the golf courses, athletic fields, and lawns to which they are being extrapolated. Hydrologiccharacterization of such sites iscritical to understanding their chemical transport potential.

Low-maintenance approaches to turf management need to be developed and adopted. Politically driven actions on nutrient use are likely to supersede research findings in some locales.

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TECHNOLOGY & PRODUCT REPORT

Root-zone Management of Greenhouse Container-grown Crops to Control Water and Fertilizer

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Greenhouse production of plants and flowers in the United States is valued at more than $2.5 billion, up from about $1 billion in 1980 (U.S. Dept. of Agriculture 1989 Floriculture Crops Statistics). The majority of these crops is produced by 8500 operations in 16,300 acres (6596 ha) of greenhouses and shade structures. To obtain the nearly $150,000 per acre production value requires intensive methods, including frequent irrigation and fertilization, growth-regulating chemicals, and thorough pest-management programs.

Like other agricultural producers, greenhouse operators have realized that practices once commonly used are no longer acceptable due to the potential detrimental impact on water quality. As early as 1983 a report from California identified potential environmental contaminants from greenhouses (Jones, 1983). In recent years trade publications and associations have highlighted this topic (Biernbaum, 1990a, 1990c; Biernbaum et al., 1988a; Scott, 1990; Walker and Dreesen, 1990; Wilkerson, 1990) and research to address the problem is in progress.

Protection of groundwater and surfacewaters from percolationand runoff of nutrients from greenhouses is the primary concern. Controlling or decreasing nitrate nitrogen fertilization is the first priority, but soluble phosphate and heavy metal trace elements also are used extensively, more so than in field crop production (Nelson, 1990). Fertilization in greenhouses is done not

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only at higher concentrations than field crops, but also on a year-round basis rather than seasonally. These rates are not necessary but have evolved with irrigation and fertilization practices based on frequent, heavy leaching of the root media. Heavy leaching of water and fertilizer is no longer acceptable, and methods of irrigation and fertilization based on zero runoff must be implemented. The technology and irrigation systems exist to stop runoff, but the fertilization strategies need to be developed.

A historical perspective

The potential problem with water and fertilizer runoff or percolation from greenhouses producing ornamental plants is the result of basic cultural practices that have been used for more than two decades. Methods that made sense in the mid-1960s when they were developed are no longer good enough. Taking the time to understand the basis for our current methods can help us to identify ways to deal with runoff now and as we develop systems for the future.

Several important developments occurred during the late 1950s and early 1960s that dramatically influenced greenhouse production. We often hear how the development of plastic films changed greenhouse structures and also led to the production of new irrigation systems. Spaghetti-tube drip systems for pots and spray lines for beds made rapid application of large volumes of water very easy.

With the new irrigation systems, watering required less labor. There was also less grower control over the volume of water applied. Some of the new systems did not make uniform applications of water. The lack of uniformity of application often was managed by watering until the driest spot was wet, resulting in over-application in most areas.

Development of totally automated irrigation systems became a priority, and the problem of the best way to schedule irrigations was addressed. Much like today, media moisture content could be measured with a tensiometer, plants could be put on a scale with built-in switches, or light levels could be monitored and used to determine watering frequency. At that time, however, the method chosen to automate irrigation was to water at a regular time interval with clocks. This was the easiest and most efficient method for most growers.

The key to success of timed irrigations was that the root media had to be well drained so it would not be over-watered. Well-drained root media made it easy for even untrained growers to grow crops as long as large amounts of water were applied regularly. The well-drained root media also benefited greenhouse operations still using hose-watering because it was harder to over-water. All pots that did not dry uniformly could be watered and brought to a uniform moisture level.

The porous root media made use of components like peat, bark, vermiculite, perlite, and sand. Perlite and sand, which were often added to increase drainage, have little or no nutrient-holding capacity. Root media components like peat and vermiculite appear to have a high cation exchange capacity (CEC), but not in comparison to the field soil being replaced.

The nutrient-holding capacity of peat vs. soil is a comparison that can be confusing. It is important to realize that CEC often is expressed per unit of weight. A peat : vermiculite mixture has seven times the nutrient-holding capacity of field soil per unit of weight. However, since the peat: vermiculite mixture has such a low bulk density, when equal volumes are compared there is twice the nutrient-holding capacity in a pot of soil (Table 1). This was an important point when considering changes in fertilization practices as peat-based media were adopted.

At the same time current watering and media recommendations were developed, it was determined that frequent applications of water-soluble nutrients were needed to compensate for the high volumes of water applied and the low CEC of the root media. High levels of fertilizer were considered necessary to maintain an adequate level of fertility. Frequent applications of fertilizer were also a result of the increasing use of fertilizer injectorsand water-solublefertilizers. Fertilization was easy, as it should be, but this lead to unnecessary applications.

Growers were instructed to apply fertilizer and water in excess of container capacity to reduce the potential for soluble salt accumulation and nutrient imbalances. Excess application and leaching were easier than testing the media to see if nutrients were present. The rates of leaching that were recommended, 10% to 20% per watering, have had little effect on preventing soluble salt accumulation in the peat-based media tested in our research. As many growers found, it takes 40% to 60% leaching with constant liquid fertilization of 200 ppm (mgžliter^{-1}) to keep fertilizer levels from increasing (Fig. 1). In some cases concentrations of 300 ppm (mgžliter^{-1}) or more were being recommended, so high rates of leaching were even morecritical. Recommendationsfor leachingwere not refined to account for differences in irrigation water quality.

The irrigation and fertilization practices and the root media that evolved over the past 25 years have enabled many greenhouse operators to be successful. They also have created a potential problem of water and fertilizer runoff and percolation from greenhouses. The previous examples are illustrations of the importance of understanding how root-zone management is defined by the interaction of the root medium, water use and availability, and fertilization practices. The goal should be to develop economical irrigation and fertilization methods that optimize the root zone and are environmentally sound.

Stopping runoff of water and fertilizer from open systems

There are many different methods for management of water, fertilizer, and media. Some are very simple and inexpensive, while others require significant investments. Closed systems with recirculation and subirrigation can eliminate the runoff problem, but many greenhouse operations are not ready for closed subirrigation systems. The first step in water management for these operations is to limit or eliminate the waste or runoff so there is little or nothing to collect and recycle.

Irrigation scheduling. Scheduling irrigation frequency based on environmental conditions and careful control of the irrigation duration will control water and fertilizer runoff. Most greenhouse operations currently do not have the ability to control irrigation automatically based on environmental conditions. However, a variety of computers and irrigation schedulers with this capability are available and easy to use. Cost seems to be the major constraint. Labor savings as well as the limited availability of qualified labor should be considered when investing in irrigation systems.

If a grower cannot buy a system to control irrigation, or is not ready for sophisticated technology, there is an easier way. The most common way of determining when to water is to lift a few pots and check the weight. However, when a pot should be watered is strongly influenced by individual opinion and the rule of thumb is often, "When in doubt, water." One inexpensive solution to variable watering practices is to buy a portable scale. Even with little or no experience, growers should be able to learn how to tell when to water by simply weighing a few plants. All they have to do is learn how to let plants dry out to a target weight. The target weight is determined by weighing several plants that are at the point of requiring water. This point can be moist or dry, depending on the grower's preference, but now it can be reproduced regularly. The drier the plant, the fewer the number of irrigations over time. Another method of setting a target weight is to let some established plants dry out to very near the wilting point and check the weight. The difference in weight between a watered plant at container capacity and a plant near wilting is an estimateof the available water in the pot. If the goal is to minimize irrigation frequency, most plants should be watered when 60% to 70% of the

Table 1. ***A comparison of the nutrient-holding capacity of a pot of field soil with a pot of peat : vermiculite medium.***

Measurement	Field soil	Peat : vermiculite
Medium CEC (meq/100 g)	20	141
Density (g•cm^{-3})	1.3	0.1
Pot volume (cm^3/pot)	1250	1250
Medium CEC (meq/pot)	325	176

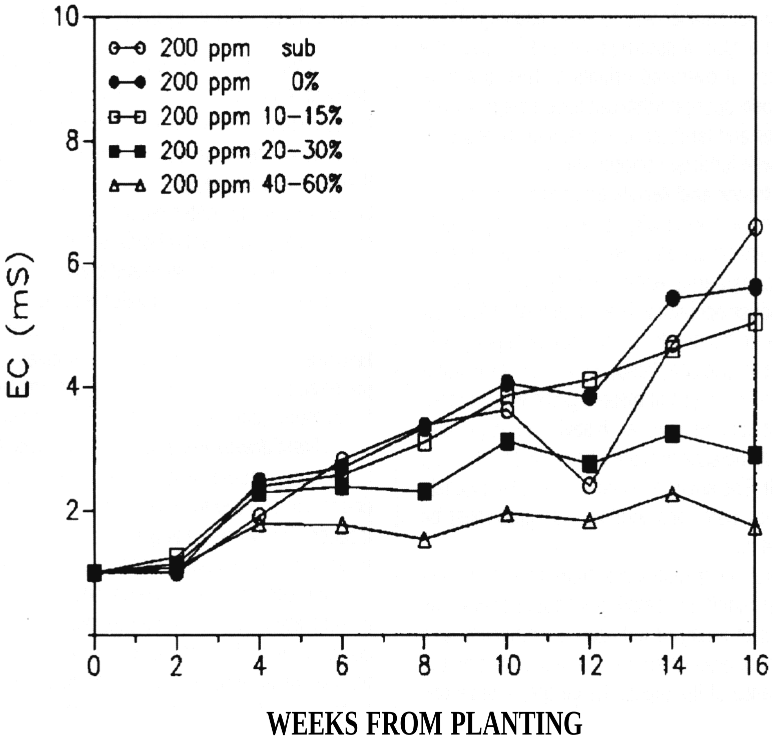

Fig. 1. ***The effect of 200ppm (200 mgžliter[-1]) N and K applied to 6-inch poinsettias with subirrigation (sub) or various leaching fractions (%) on root media electrical conductivity (EC). Leaching at 40% to 60% was needed to maintain a near constant EC.***

available water is used. This target for an average plant allows for faster-drying plants to be near but not at the wilting point at irrigation. The target weight may have to be increased as the crop grows, but not by much. With root system development and acclimatization, the plant will adapt and grow well with the drier, but consistent, moisture cycle.

Controlling the duration of application to limit leaching can be accomplished in every greenhousewith minimal investment. The key is to realize that *seconds* of irrigation time, not minutes, are important when it comes to limiting water use. Accurately measure the length of time the plants are watered.

Root media selection. To improve the efficiency of water applications, root media can be selected for higher water-holding capacity (Biernbaum et al., 1989a). Forexample, compared to polystyrene, rockwool or vermiculite add water-holding capacitywhen blended with peat. Growers must remember, however, that higher water-holding capacity means the frequency of watering must be reduced. The media should be allowed to dry to avoid over-watering problems. As pointed out later in this paper, leaching also must be minimized if there is to be any advantage from higher water-holding capacity. One medium may hold up to twice the available water of a second medium, and this could cut the number of irrigations needed in half. However, the amount of runoff will be the same if the leaching fraction is kept constant.

In some cases, just filling the pot with more medium will increase water-holding capacity and decrease irrigation frequency. Careful watering to reduce medium shrinkage also will help. Hose-watering goes faster with higher flow rates, but more water and medium end up out of the pot. It is easy to see that, with concerns about runoff, the person watering with a hose becomes even more important. Sometimes high flow rates are used to get a fertilizer injector to work properly, and a mixing tank may be needed to decrease flow rates.

The current information about CEC of soilless potting media and the effect on fertilization requirements and runoff is not very detailed. Higher nutrient-holding capacity may not be needed if fertilizer is applied regularly at low levels and with reduced leaching, or if resin-coated fertilizers are used. The most important effect of nutrient-holding capacity or buffering in peat-based media is probably the effect on pH management rather than on macronutrient availability.

In our research, wetting agents have increased water absorption of many peat-based media. Increased water absorption translates to increased efficiency of applied nutrients. We have not found superabsorbent polyacrylamide gels to be effective under our normal watering practices, primarily because there is not enough time for the gel to absorb water, and soluble salts and fertilizer limit uptake of water by the gels.

Fertilize when needed. Based on research with bedding plants, poinsettias, and Easter lilies, in many cases too much fertilizer is applied. These crops require relatively little fertilizer as long as nutrient levels are maintained in the media at the proper level. The key is regular application, controlled leaching, and weekly analysis of media electrical conductivity (EC). Many species can be grown with low nutrient concentrations if the supply is constant. Many growers do not know the level of nutrients available in the root media. It has become easier to leach heavily with a known concentration then to test the media and find out what is needed. The lack of media analysis in the greenhouse is possibly a result of too little time and labor to do the job or a lack of expertise in how to do it. Weekly checking of pH and EC will prevent most nutritional problems experienced by growers. Weekly media analysis for pH and EC is one of the first things greenhouse and controlled plant environment operators should learn. A conductivity or soluble salt meter is a tool they can use to determine how much fertilizer is present and whether more is needed. Fertilizing only when needed based on media analysis and graphical tracking of EC can greatly reduce the amount of fertilizer applied and, in many cases, result in better crops.

One of the other problems leading to over-fertilization is that currently recommended root media analysis levels or targets may be too high. Some growers are working very hard to reach levels recommended on a root media analysis. Not only are the recommended high levels not needed, but, with heavy leaching, they may never be attained; not even with 400 ppm (mgžliter[-1]) N applied constantly. A good recommendation for now is that growers should try to maintain the “acceptable” media analysis levels rather than the normal target of the “optimum” level.

Reduce leaching. Over the past 25 years, growing plants in containers has been based on the basic premise that frequent leaching is required. Why should growers leach? Many times, applying water with no leaching can allow time for the fertilizer in the media to be used by the plant rather than washed away. In many cases in the United States, water quality is good enough that leaching should almost never occur. If salt levels are high due to fertilization, fertilizing should be stopped. There are greenhouse operations that would be out of business if they stopped leaching because of poor water quality. How does a grower know what to do? Water and media analysis will furnish the answer.

Excess leaching can be avoided with a variety of techniques. Irrigation systems need to be designed to provide uniform pressure and water flow at all locations. With uniform water application, a pulsed application of water (e.g., two applications of 1 min instead of one application of 3 min) will use less water and reduce or stop leaching. Low-volume drip applicators will help if water quality is acceptable and the drippers do not clog. Use of wetting agents to assure rapid wetting of dry root media and to reduce channeling of water down the sides of pots also can reduce leaching and the volume of water applied.

Fertilizer concentrations also can be reduced so less leaching is needed. Another way of looking at this is to recognize that if the leaching is reduced, the amount of fertilizer will have to be reduced. The root media availability of nutrients and soluble salts is a function of both the concentration and the volume leached. Poinsettia fertilization with 200 ppm (mgžliter^{-1}) N with 12% leaching [e.g., 16 fluid ounces (0.475 liter) applied and 2 oz (0.06 liter) leached] or 400 ppm (mgžliter^{-1}) N with 50% leaching [e.g., 40 fluid ounces (1.884 liters) applied and 20 oz (0.59 liter) leached] was evaluated. There was a 5-fold difference in fertilizer applied. Both strategies resulted in a similar EC level in the root media (Fig. 2) and both provided more nutrients than were needed to grow a good poinsettia in a 6-inch (15-cm) container. Only 100 ppm (mgžliter^{-1}) with 12% leaching was needed for good growth and quality (Biernbaum et al., 1989b; Yelanich and Biernbaum, 1990).

If water quality is poor or saline (EC > 1.25 mS) instead of or in addition to leaching, irrigation water EC may be reduced by changing water sources, using rain water, blending water sources, or using water treatments such as reverse osmosis. More growers need to consider collecting and using rainwater, particularly when alkalinity is a problem.

Water collection trays under plants can be used with overhead irrigation or hand-watering systems as another way to stop leaching. Trays provide a type of subirrigation and increase the efficiency of overhead irrigation. This is a low-investment approach that can have a major impact on water and fertilizer use. Leaching is reduced, along with fertilizer concentrations.

Water and fertilizer costs. Since water and fertilizer costs make up only a small percentage of total production costs, conservation has not been considered economically important to greenhouse operators. The actual cost of fertilizer is <1% to 2% of total production cost per pot in mostcases (Nelson, 1990). Small savings in water and fertilizer cost can mean significant increases in profit per unit however. A saving of l¢ per unit is a 10% increase in profit when total profit is 10¢ per unit. The environmental and regulatory costs of excess water and fertilizer use also must be considered.

Not all greenhouses have problems with fertilizer runoff. For small greenhouse operations the cost of a bag of fertilizer is significant, and fertilizer is used when it is needed, based on the appearance of the plants. Large greenhouse operations that buy fertilizer by the pallet ortruckload tend to use fertilizer more liberally. Fertilizer cost is not highly important to them. These operations usually fertilize regularly based on recommended rates—rates that frequently are too high. The potential for problems is much greater in these cases.

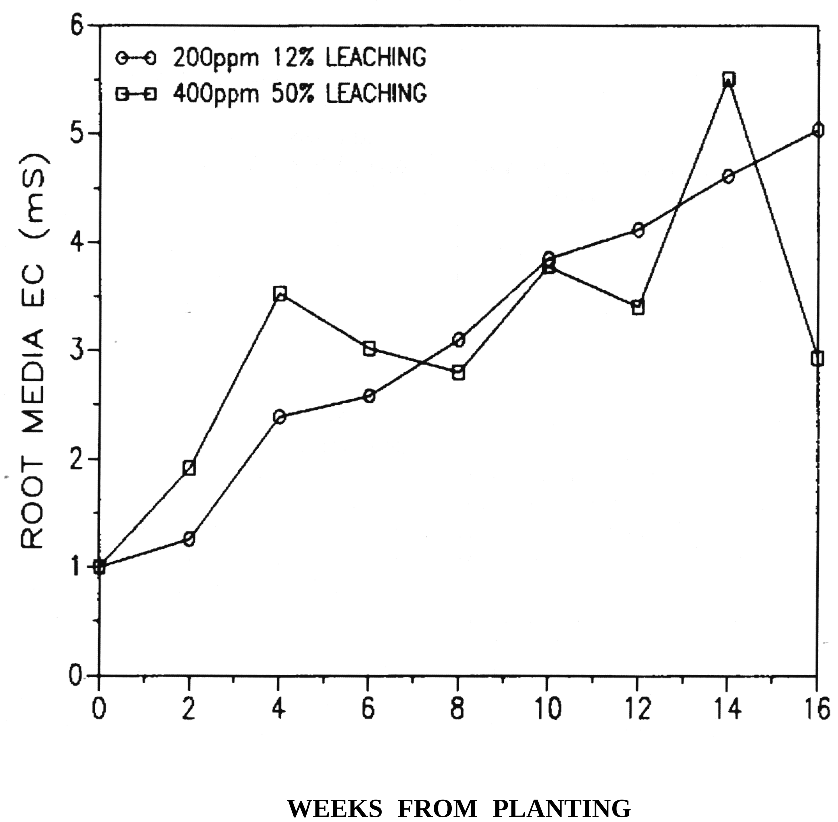

Fig. 2. *Comparison of root media electrical conductivity (EC) for samples from 6-inch pottedpoinsettias with 2OOppm (mgžliter^{-1}) N applied with 12% leaching or 400ppm (mgžliter^{-1}) applied with 50% leaching.*

Collecting and recycling runoff

Most of the suggestions so far have been directed at limiting runoff, or the need to collect excess water. Initially, for most greenhouse operations, it will be more economical to limit runoff than to collect and reuse it. However, runoff can be collected and the water reused. This water may contain significant levels of fertilizer (Walker, 1990). The type of watering system and greenhouse floor will determine how excess water is collected. For some operations water collection from floors or field drains will be necessary in the short term. The preferred method involves closed systems where the solution does not contact the floor or soil.

Field drains and noncement floors. With heavy, clay subsoils beneath the greenhouse, field drains can be used to collect runoff into a central location. The water-holding area can be an earthen pond, a vinyl-lined pond, or an in-ground cement reservoir similar to a manure-holding tank. Above-ground water silos are available, but they require pumping and lifting of the water. Only a limited number of greenhouse operations in the United States currently are collecting runoff in an open system. With very porous soils that allow water to percolate quickly, cement floors probably are required. Cement floors are not considered economically feasible for many greenhouse operations, but that attitude may be changing. If floors are poured, they should probably be floors suitable for subirrigation so that runoff is no longer a problem.

Closed-loop systems and subirrigation with recirculation. Rather than using open systems that allow for contamination of the water, the use of subirrigation with recirculated solutions provides the most efficient and thorough method of controlling water and fertilizer runoff. Several methods are available, the main ones being flood benches, flood floors and flowing water in troughs (Biernbaum, 1990b; Biernbaum et al., 1988b). There is no doubt that all of these methods work, but cost may be a barrier. We have done experiments with subirrigation of poinsettias, Easter lilies, chrysanthemum, geranium, and bedding plants. Despite the many advantages, investments should only be made with careful planning to cover the costs. Flood floors may be the most affordable answer for many growers.

Controlling pathogens. Based on the literature, the primary bioticconcern is with Pythium and Phytophthoraspecies (George, 1989; Molitor, 1990; Staghellini, 1990). The environmental conditions (particularly temperature), as defined by the geographic area and the species prevalent in a geographic area, will be the major factors influencing pathogen populationsand the rate of infection. The temperature and aeration level of the water during storage may also be important. Bacteria also can be dispersed by water, but root damage is often necessary for the pathogens to enter roots. This is not true for foliar penetration if leaves come in contact with the water.

Based on information available from greenhouseoperators, there has not been the problem of rampant diseasespread that often is expected with open collection of runoff water (George et al., 1989). Where the water goes and how it is collected will determine the potential for pathogen problems. Some important differences in recirculated solution systems are illustrated in Fig. 3. Hydroponic solutions moving through inert media with exposed roots have the greatest potential for spreading pathogens. Waterpassed through organic media in containers will also have a significant potential for picking up and spreading pathogens. One difference in this system is the probable presence of a wide variety of nonpathogenic, competitive organisms. Water that is used for subirrigation of container-grown plants has little potential for being contaminated because the water that goes in the pot usually does not come out.

Water treatment. Some form of water treatment may be desired when the water is recirculated. The type of crop being produced will define what, if any, treatment is needed. One key management approach is to keep the volume of stored water at a minimum so that it turns over quickly. Small reservoirs and cycling of irrigation zones result in rapid solution replenishment and turnover. The key here is the ability to make up fresh nutrient solution rapidly. For example, if there were five beds to water, rather than having a reservoir large enough to water all five at once, the reservoir might handle two beds, and by the time the second bed was irrigated and the third ready to start, water drained from the first bed would be available. Fresh nutrient solution would be added regularly, and turnover would be quicker.

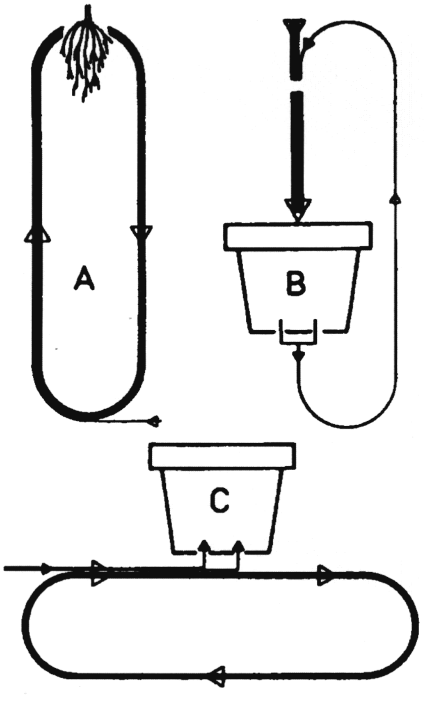

Fig. 3. *Three types of water recirculation systems;* ***(A)*** *solution constantly passing over the roots, as in hydroponics;* ***(B)*** *top-watered container-grown plants where leachate is collected and reused; and* ***(C)*** *subirrigation with recirculated solutions. The risk of pathogen dispersal is greatest with A and B (Molitor, 1990).*

Some horticultural operators havechosen to treat recirculated water with chlorine. The other alternative that is available and used by some greenhouses is the bromine biocide, Agribrom (George, 1989). Agribrom has been shown to be safe to plants, and, when used properly, it will kill algae and other organisms in recirculated water. There are some greenhouse operators treating fresh, nonrecirculated irrigation water with Agribrom. Agribrom has not been used in systems without organic media and with direct solution contact with roots. There are limited options for hydroponically grown food crops, and management is often the key for pathogen control. Heat treatment of water to 95C is another potentially economical alternative that is being attempted in Europe. Ozonation, ultraviolet irradiation, and ultrafiltration are not used in commercial flower production in the United States, but they can work and may be viable for some operations (Bulk, 1990; Molitor, 1990; Staghellini, 1990).

Looking to the future

Defining water and fertilizer requirements. How much water does it take to produce a rose, a poinsettia plant, a pound of tomatoes, or a head of lettuce in a greenhouse or controlled environment? How much N is required? These are the questions that must be addressed to stop runoff. Whether we use traditional watering systems and stop leaching or use subirrigation with no leaching, we need to know the amount of nutrients needed to produce plants in controlled environments. Appropriate irrigation and fertilization methodsand technology exist, but new fertilization strategies to stop water and nutrient runoff are needed.

Controlling evaporation. While working toward this goal of defining how much fertilizer is required to produce a given plant in a given container, an observation was made that may partially explain why nutrient applications are so high in container-grown plants. Significant amounts of soluble fertilizer and salts accumulate at the surface of the root media of container-grown plants. This salt layer has been recognized for subirrigated plants for many years but only recently for surface-watered plants. The surface layer of the medium can contain three to six times more fertilizer salts than the rest of the medium. This salt layer is due to movement of water and salt to the surface and the evaporation of water from the medium.

Evaporation barriers or pot covers can be designed to control water and fertilizer use and to increase uniformity and efficiency of water application to containers. In experiments where evaporation of water from the media of container-grown plants has been stopped, water use has been reduced by 20% to 50% and fertilizer requirements have been reduced, because the fertilizer salts stay in the rootzone ratherthan moving to the surface (Biernbaum et al., 1991). With further research, commercial application of evaporation barriers for container-grown plants could have an important impact on water and fertilizer use by greenhouseand landscape nurseries. Management strategies would also have to be altered, since high concentrations of fertilizer that are normally considered safe have reduced the growth of poinsettias grown with evaporation barriers (Biernbaum et al., 1991).

There are several areas for improvement with our current approaches to fertilization and irrigation. Many of the new ideas being suggested are contrary to what has been recommended for the past 20 years. Implementing these ideas will require training growers and greenhouse workers.

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