ABSTRACT

Title of dissertation: WATER AND NUTRIENT DYNAMICS IN CONTAINER-NURSERY PRODUCTION SYSTEMS

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Water quality remains a predominant issue within the Chesapeake Bay watershed, and nutrient loading continues to undermine the progressive recovery of this ecosystem. Until recently, the ornamental plant industry has had little information to develop better management practices to increase the efficiency of water and nutrient applications. This research used an integrated approach to examine container- production systems, to develop recommendations to increase nutrient uptake efficiency and reduce runoff.

A 40-month field study examined the effects of various cultural practices on irrigation and nutrient uptake efficiencies. Under cyclic scheduling, drip irrigation applied 3 to 4.5 times less water than overhead irrigation and had significantly less runoff when plants were spaced at low densities. While drip irrigation is significantly more efficient, overhead irrigation is more practical and economically feasible for most small container-nursery stock. Time Domain Reflectometry (TDR) was examined as an alternative to cyclic scheduling and when used with overhead irrigation, water applications were half that of cyclic irrigation scheduling. .

This research simultaneously documented nitrogen (N) and phosphorus (P) dynamics by examining nutrient applications, uptake and leaching over the forty months. In most cases, N and P uptake efficiency and runoff was negatively affected by overhead irrigation, particularly when soluble nutrients were applied via fertigation and at low plant densities. Nitrogen and P efficiencies ranged between 10 and 30% and were dependent upon methods of irrigation and fertilization, plant density and water use. The use of both drip and TDR-scheduled overhead irrigation reduced nutrient runoff to half that of the overhead irrigation program

Intensive spring nutrient uptake studies showed that N influences the total growth of *Rhododendron* (azalea) and P uptake is a function of P fertilization rate and growth, influenced by N rate. Moderate N rates maintained optimal growth, while total P was only required at 1/20 of this N rate. Periodicity in nutrient uptake suggests seasonal timing of fertilizers may increase N and P uptake efficiency.

Novel management strategies in the area of irrigation, fertilization, and cultural practices should be adopted by the ornamental industry to improve upon low efficiencies and reduce nutrient pollution in our watersheds**.**

WATER AND NUTRIENT DYNAMICS IN CONTAINER-NURSERY PRODUCTION SYSTEMS

By

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To Gia,
who, with her enduring patience
and constant praise, made this work possible.

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Chapter 1

Literature Review

1.1 Introduction

Nutrient loading into the Chesapeake Bay is a predominant problem that undermines the progressive recovery of this large ecosystem. Nutrient inputs include both point- and non-point sources from agriculture, industry, and public use within the Chesapeake Bay watershed (Taylor and Pionke, 2000). Nitrogen (N) and phosphorus (P) are critical nutrients, each affecting different aspects of surface water eutrophication. The role of N and P in surface water eutrophication continues to be controversial, confounding the debate over which nutrient is most important to regulate (Fisher et al, 1992; Caraco, 1988; Howarth, 1988; Webb, 1988; Smith, 1984). However, recent research suggests that both nutrients play important roles in the Chesapeake Bay's pollution issues (Boynton, 2000). In Maryland, agricultural industries that apply nutrients are now required to create nutrient management plans to record and assess the efficiency of nutrient applications (Lea-Cox et al., 2001a). This includes the ornamental nursery industry, the primary focus of this research.

1.2 Federal Initiatives in Nutrient Management

In 1972, the Federal Clean Water Act was the first major legislation to deal with water pollution in the United States. This law has led to important reductions in point-source pollution. Various States are now under court-ordered sanctions to implement section 303 (d) (i.e. non-point source) provisions of the Clean Water Act, by ensuring that all states implement a Total Maximum Daily Load (TMDL) program for all watersheds (US-EPA Office of Water, 2004). A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards set by states, territories, and tribes. Each waterbody has an identified use (e.g. drinking water, recreation, fishing, etc.) with scientific criteria needed to support the use. The TMDL is the allowable load of a single pollutant to a body of water, from all contributing point and non-point sources, which will support the designated use. This TMDL approach broadens the focus of the Clean Water Act from monitoring specific discharges of pollutants from point-sources, to focusing on the *overall quality* of a body of water. The TMDL approach takes into account the ability of the body of water to handle contaminants from all (point- and non-point) sources of pollution that impact it. A TMDL is therefore a written, quantitative assessment of water quality impacts from all potential point and non-point pollutant sources. Each water body will be rated to handle a certain amount of pollutants daily or TMDL while still maintaining water quality.

1.3 Maryland Initiatives in Nutrient Management

In 1983, Maryland, Virginia, Pennsylvania, the District of Columbia, and the Federal Government signed the Chesapeake Bay Agreement. Increasing its scope in 1987, the same parties agreed to reduce nutrient loading from the bay's watershed by 40% of 1985 loading rates by the year 2000. Tributary Strategy teams were developed for 10 watersheds within Maryland to focus on point source controls, non-point source controls on developed lands, non-point source controls on agricultural lands, protection of natural resources and watershed planning (Chesapeake Bay Program, 2000). Additionally, Maryland's Water Quality Improvement Act which was passed in 1998

(Maryland Dept. Agric., 2000) mandated the writing and implementation of N and P management plans for all sectors of agriculture by December 31st 2002. This is of great importance to the nursery industry, where nutrients and water are intensively used.

1.4 Past Nutrient Management Strategies – Arguments for N and/or P controls

Early debate concerning the nutrient enrichment of surface waters focused on N and P, and which element should be regulated to improve water quality. It was known that these two nutrients, naturally found in surface waters in only micromolar concentrations, could control and limit rates of productivity in surface water (Ryther and Dustan, 1971). In the late 1970's, P was understood to be the most important nutrient in freshwater systems. Studies on P effects in freshwater systems became convincing enough to enact P control legislation to prevent surface water eutrophication throughout North America and Europe (Hecky and Kilham, 1988; Carpenter and Capone, 1983). Since then, strict controls on point-sources of P, primarily from sewage, detergents and other industrial effluents (Matuszeski, 2000) has lead to significant reductions in surface water eutrophication (Boynton, 2000).

Phosphorus point-source control has removed half of the point-source P loading to the bay since 1985 (Taylor and Pionke, 2000) and has been relatively simple compared to reducing N inputs. However, nearly to three-quarters of the remaining P load to the bay is contributed by non-point sources. Recent attention from both scientific and political sources has been diverted towards N pollution in marine and estuarine systems because it is a major pollutant. However, the effects of P loading remain largely misunderstood in these brackish water systems. This is evident from recent accounts on nutrient pollution in newspaper articles (Thornton and Dewar, 2000) and State and Federal publications (Boward, et al. 1999), which lack definitive information on P dynamics.

1.5 Phosphorus in the Terrestrial Ecosystem

Phosphorus is a rate-limiting nutrient in many terrestrial systems. Coale (2000a) suggests four broad categories of soil phosphorus based on relative reactivity in soils. The first is soluble or orthophosphate, which includes various bound forms that will pass through a 0.45 µm filter. Secondly, an unstable and dynamic form, comprised of mostly organic P, is found in plant and animal tissues, and microbial biomass. The third form, stable organic phosphorus, is considered a sink for P with limited reactivity. Lastly, an occluded inorganic form of P exists adsorbed on soil clays. Each form is in equilibrium with the others in varying concentrations, depending on the properties of the soil. The availability of P in soils depends primary on soil type. In clay-based mineral soils, P is bound to positively charged surfaces. In soils of low P concentration, movement of P to the root or mycorhizal surface is via diffusion (Marschner, 1995). With an increase in organic matter and microbial activity, P is more readily mobilized (Seeling and Zasoski, 1993; Marschner, 1995) and bulk flow may become a more important factor in P movement. There is little anion-exchange capacity (AEC) in highly organic soils and the soilless substrates used in the nursery and greenhouse industries; consequently, soluble forms of P are readily leached from the root zone (Handreck and Black, 1999).

After transportation on soil particles or from leaching into aquatic systems, P occurs only in the pentavalent form (Correll, 1999), with the most biologically important form being water-soluble orthophosphate (PO_4^{3-}) (Correll, 1998). Apart from anthropogenic inputs, between 5 and 10 percent of P is naturally eroded and mineralized from rock, the rest is presumably organic in origin and carried by fluvial detritus. Unlike N, which can return to the atmosphere as N_2 and other forms via microbially-mediated denitrification, P is retained by deposition in sediments and through biological assimilation. This conservation of P in the environment makes surface water bodies sensitive to additional P inputs if P is limiting (Correl, 1998).

1.6 Nutrients in the Watershed

Many studies on fresh and saltwater systems have been performed to estimate nutrient limitation in fresh, estuarine, and coastal water systems. A review by Hecky and Kilham, (1988), examined research of nutrient limitations in marine and freshwater environments. Historically, differences in nutrient limitations on fresh and saline waters were not expected, because of the similarities in nutrient requirements of phytoplankton within the two environments. Current aquatic research agrees that freshwater ecosystems are P limited, but more research is needed to establish the generality of N limitation in marine ecosystems (Correl, 1999).

A fundamental question that needs to be addressed is -- at what concentrations do N and P become limiting the limiting factor for algal growth? One answer to this question is provided by the Redfield Ratio. Redfield (1958) suggested that under optimal growth conditions, the average N to P atomic ratio was 16 to 1 in algal cells. In systems in which this ratio is greater than 16, it may be assumed that P is the limiting nutrient (Correll, 1999). Before using this concept however, one must take into consideration other factors such as light limitations (Correll, 1999; Wynne and Rhee, 1986; Tett et al., 1985), temperature variations (Correll, 1999; Jahnke et al., 1986), other limiting nutrients such as silicon (Hecky and Kilham, 1988; Ryther and Officer, 1981), and temporal and/or spatial variations in nutrient concentrations that may change internal N:P ratios in algal cells (Hecky and Kilham, 1988). Even though internal N:P ratios in algae differ from species to species (similarly to plant species, Marschner, 1995) the Redfield ratio can be a useful tool for identifying limiting nutrient situations, if concentrations of the nutrients are static for at least a few days and light limitations are at a minimum (Hecky and Kilham, 1988).

What factors could control N/P ratios in the water column? Of several factors, one is of particular interest. In bottom sediments of water bodies, P can be adsorbed onto oxidized iron and aluminum particles, which form a barrier against P returning to the water column (Correl, 1999; Fisher et al. 1992). This is common in oligotrophic lakes and reservoirs with high dissolved oxygen within the water column. In anoxic waters, anaerobic conditions reduce sulfate to sulfide, which in turn, binds to iron particles. This binding of sulfide then releases previously bound P, which allows soluble P to reenter the water column (Fisher et al., 1992).

Additionally, these non-dissolved P builds up in estuarine sediments, which, in time, may be hydrolyzed as orthophosphate (dissolved P) from biological activity (Correl, 1999). This mechanism probably affects P capture and release from bottom sediments (Correll, 1999; Caraco et al., 1989). A phosphate buffer mechanism also acts to equilibrate the desorption and adsorption of P from positively-charged particles in the water column (Froelich, 1988).

Several recent studies have shown seasonal variations of nutrient limitations in the Chesapeake Bay. Phosphorus limitations are noticeable in the spring and N limitations in the warmer months of summer and fall (Boynton, 2000). Several microbiological, hydrological, geochemical, and anthropogenic factors are attributed to this seasonal change. As an estuary, the Chesapeake Bay has retention characteristics unlike water bodies that are solely fresh or marine in nature. Freshwater inputs heading toward the mouth of the bay ride overtop inflowing, dense saline waters that act counter to the freshwater flow. Differences in density create stratification that moderates mixing. In deeper areas of the bay, this stratification prohibits fresh/saline water mixing, especially during the warmer months of the year. This adds to an oxygen deficit in deeper locations in the bay.

Fisher et al. (1992) cited several seasonal changes that lead to a shift in limitation between N and P based on season. In spring, river discharges transport excess N into the Bay increasing the N/P ratio. Dissolved oxygen is relatively high, so P is largely bound to sediments. Spring algal blooms, which are mainly limited by P, consist of diatomaceous species which fall out of the water column into the sediment layer and effectively contribute to the summer anoxia (Fisher et al. 1992). A large amount of bound-P is available for release into solution when conditions favor desorption (Froelich, 1988). During warm summer months, anoxic waters favor desorption, which increases P concentration in the water column, whereby making N the limiting nutrient.

Thus, the role of N and P in the Chesapeake Bay aquatic system is complex. We do not as yet understand the consequences of our management of terrestrial ecosystems, which are providing historically large and continuous inputs of both N and P into the bay.

There is no doubt that N and P loading rates need to be reduced from all sources to the Chesapeake Bay. This is the intent of both Federal regulations (US-EPA Office of Water, 2004) and the Maryland Water Quality Act of 1998 (MDA, 2000). Maryland is the first state in the US to require nutrient management plans for almost all sectors of agriculture (Lea-Cox and Ross, 2001). For the nursery and greenhouse industries, this is the first such mandate in the United States. The development of a nutrient management process for these agricultural industries (Lea-Cox et al., 2001a) has highlighted the lack of knowledge of nutrient dynamics for the many herbaceous and perennial plant species grown by the nursery and greenhouse industry.

1.7 Role of Agriculture in Terrestrial Nutrient Loading

In the terrestrial biosphere, often P is a rate-limiting nutrient and this is especially true for many tropical soils (Ragothama, 1999). Phosphorus has been added to farmland soils around the Chesapeake Bay region to increase soil fertility and dispose of animal wastes for much of the past three hundred years. In the past 40 years a steady increase in the percentage of farms from which soils are at optimal or excessive P concentrations has been identified, especially in areas where there is intensive agricultural animal production (Coale, 2000b). Until very recently, animal wastes were usually applied to soils as fertilizer in these areas, and application rates were based on the N content of the manure. An example may be broiler litter, where N:P ratios are typically much lower than 1:1. Thus, the addition of broiler litter based on crop N needs far exceeds the crop requirement for P. Over time, the resulting soil P content can then exceed the amount required for optimum crop yields (Coale, 2000a).

The 'Green' industry, which includes the floricultural, ornamental and turf and landscape maintenance, is among the fastest growing segments of agriculture in the United States. In 1997, nursery and floriculture industry receipts totaled \$10.6B and accounted for 70% of all horticultural farm gate receipts (U.S. Dept. of Agriculture. 1998). In 2002, greenhouse and nursery products were the second largest wholesale agricultural commodity in Maryland, bringing the total green industry value to \$1.24B (Klapproth et al., 2001**)**. Many greenhouse and container-nursery production operations can be classified as intensive agriculture because they typically use a combination of fertilizers, growth regulators, insecticides, and fungicides to mass-produce ornamental plants in high numbers. Retail greenhouse and nursery operations also tend to be concentrated in and around urban population centers, are very visible to the public, and have the potential to disproportionately impact both urban environments and the public perception of agricultural chemical use (Berghage *et. al.*, 1999**)**.

Container nursery and greenhouse fertility programs commonly utilize high levels of nutrients applied in soluble form via irrigation, and total applications of N can reach several thousand kilograms hectare^{-1} year^{-1} (Nelson, 1991). Over half of the irrigation water used by both open and protected horticulture is applied by sprinkler systems (U.S. Dept. of Agriculture, 1998). Based on irrigation system design recommendations (Aldrich and Bartok, 1994), water-use using overhead sprinkler irrigation can exceed 180,000 liters (l) hectare^{-1} day^{-1}, which can generate from 18 to 90 kiloliters of wastewater hectare^{-1} day^{-1} (Berghage *et. al.*, 1999). Many growers have ignored the negative effects of over-application of water and nutrients because the cost of these inputs is only a small fraction of the total cost of production. However, the increasing scrutiny on the declining quality, and the increased use of surface and groundwater resources, is dictating that we reevaluate many common nursery and greenhouse production practices. Several factors must be considered developing management strategies for efficient nutrient use in the nursery industry, including growing methods (substrates), irrigation methods, fertilization practices, and surface water management methods (Lea-Cox et al., 2001a).

1.7.1 Soilless Substrates

Compared to soil, nutrient retention by soilless substrates is limited (Handreck and Black, 1999). Most container-production operations use soilless substrates of one form or another. Unlike mineral based soils, soilless substrates are usually a mixture of sphagnum peat, wood products for water retention, and amendments for aeration such as polystyrene, vermiculite or perlite. Soilless substrates have little cation exchange capacity and even less anion-retention qualities (Handreck and Black, 1999). Cation exchange capacity (CEC) is the total amount of cations held by a substrate material, and is greatly increased by the content of colloids, (humified organic material or clay particles) (Brady and Weil, 1999). The most important aspect of soil colloids is ionic surface charges. Negative charges predominate but positive charges exist and increase depending on soil pH or mineral constituents (Brady and Weil, 1999). Several intricate factors regulate how ions are held and exchanged via colloids in the soil matrix. Colloid quantity and sometimes specific charge density (amount of electrostatic charges per unit area), if high enough, can increase exchange capacity (Hillel, 1998).

Organic substrates would primarily contain humus, which consists of particulates formed from the decomposition of organic matter. Humus owes its negative charge to the deprotonation of enolic hydroxyl and carboxyl, and phenolic hydroxyl groups attached to complex organic bodies (Brady and Weil, 1999). The electronegative charge forms along the humus colloid structure by the dissociation of protons from the hydroxyl and carboxyl groups. Humus tends to have greater cation exchange capacities than clay colloids, especially at higher soil pH. The regulation of this exchange capacity is due not only to the quantity and quality of colloids, but also ionic species. The concentration of ion species in solution will positively affect the attraction to colloids (Brady and Weil, 1999). Given all concentrations being equal, valance charge, and atomic radii also determine adsorption preference. Ions with a higher charge or smaller radii will have stronger attraction to colloid surfaces (Hillel, 1998). A series of cations known as the lyotrophic series grouped in order of their electronegative affinity or preference in exchange reactions is as follows: $Al^{3+} > Ca^{2+} > Mg^{2+} > NH^{+} > K^{+} > H^{+} > Na^{+}$.

Anion exchange capacity also occurs to a lesser extent from colloids and can be ion selective (Hillel, 1998). Although the net charge for most colloids is negative, ionic substitution of greater positive charge, i.e. Al^{3+} for Mg^{2+}, creates colloids with net positive charges. Often pH plays an important role in determining colloid charge. Surface charges on colloids that are formed from hydroxyl or carboxyl groups will be dependent on the concentration of protons in the soil solution. As concentrations of protons rise, and pH falls, colloids may loose some cation exchange activity and possibly gain anion exchange capacity from the change in surface charge (Hillel, 1998).

1.7.2 Irrigation Management

Complicating the nutrient loss issue, soilless substrates also have varying abilities to retain water, based on physical properties of the components making up the substrate. Irrigation management plays a very important role in the management of nutrient loss. Most soilless substrates require a relatively constant supply of N and P to replace anions that are leached by successive irrigations (Tyler et al. 1996b). Since soluble nutrients that are not held by the substrate move easily through the container with the wetting front (Tyler et al., 1996b), optimizing water use by reducing the leaching fraction has the potential to reduce nutrient leaching from the roots zone (Tyler et al. 1996a). Theoretically, this should increase nutrient uptake efficiency (i.e. the proportion of nutrient applied that is taken up by the plant) of any plant species with a limited rooting volume. One can consider leaching fraction (LF) as the amount of water leaching out of a container, divided by the amount applied, expressed as a percentage. For example, if 1000 ml of water were applied to a container and 250 ml leach, the LF = 25%. Best management practice (BMP) guidelines usually suggest a 25% leaching fraction or less to reduce nutrient leaching (Ku and Hershey, 1991; 1992; Tyler et al., 1996b).

Another consideration, interception efficiency, is the portion of water applied that is intercepted by the plant and/or the container (Lea-Cox et al., 2001a). Compared to drip irrigation, which applies water directly to the substrate, interception efficiency of overhead irrigation can be comparatively low and will vary depending on several factors including container spacing. However, the structure of plant leaves or plant canopy may also have an important effect on interception efficiency. Beeson and Knox, (1991) noted that the structure of plant leaves or plant canopy affects irrigation application efficiency (the fraction of applied water retained within the root volume of the plant) by shedding water away from or directing water into the container. Note that irrigation application efficiency is different from interception efficiency (used in our study) in that interception efficiency takes into account all irrigation water captured by the plant (including canopy), where as irrigation application efficiency measures only what was retained within the root volume of the plant. In a study by Beeson and Yeager (2003), several woody plants species were examined to determine the effects of canopy characteristics and container spacing on irrigation application efficiency. Leaf and canopy characteristics affected the amount of water reaching the substrate and differed between species. More importantly, irrigation application efficiency was highest when containers were placed side-by-side, and decreased with increasing container spacing. In general, nursery plants, especially woody ornamentals, which take several years to grow to market size, must be spaced apart to accommodate canopy growth. Therefore, Beeson and Yeager (2003) suggest that nursery managers utilize the minimum necessary spacing to optimize irrigation application efficiency.

Because overhead irrigation is the most commonly used (and most practical) irrigation method for container plant production of woody ornamentals (Beeson and Knox, 1991), increasing the efficiency of overhead irrigation to reduce over application would greatly benefit efforts to conserve water and reduce runoff. Murray (2001) showed that normal “timed” irrigation scheduling could be improved by using time domain reflectometry (TDR), where soil moisture is monitored by sensors and irrigation schedules are based on actual plant water use. Tensiometers and gypsum block sensors have been shown to have high variability when sensing water content in heterogeneous horticultural substrates (Murray, 2001). Most soilless substrates have plant-available water between matric potentials of -1 and -10 KPa (Murray, 2001, Murray et al., 2004), which is much lower than the resolution of low-tension tensiometers. Time domain reflectometry is a wave propagation system, which measures the velocity of a propagated electrical signal and this signal velocity can be related to substrate (Murray, 2001) or soil water content (Topp, 1985; Ansoult et al., 1985; Topp et al., 1984; Topp et al., 1980). Murray (2001) showed that TDR can accurately sense plant-available water in a range of soilless substrates, and, if accurately calibrated, that TDR can be used to start and stop an automated irrigation system with pre-determined set-points. Time-domain Reflectometry therefore accurately senses substrate water content, by measuring the time taken for a propagated signal to reflect through the column of substrate, bounded by a TDR sensor placed in the root zone (Topp et al., 1980). This relationship is described in detail by Murray (2001). The sensors operate with a TDR unit and a datalogger, which can then be programmed to control irrigation scheduling (Murray, 2001).

1.7.3 Fertilization Management

A primary question that has not received adequate research is what are the nutrient requirements for woody ornamentals for growth to market size? The agronomic industry has recommendations for nutrient application based on expected yields. For instance the Maryland Department of Agriculture (MDA, 2004) recommends applying approximately 150 kg N ha^{-1} for an expected yield of 8.8 metric tons ha^{-1} for corn grain production. These types of "yield" recommendations are not pertinent to the nursery industry, where minimizing the time taken to produce a crop is the most important variable. Chen et al. (2001) cited a list of suggested N application rates for a number of species grown in containers in the greenhouse, and in several cases these rates were as much as 15 times higher than fertilization rates for agronomic field crops. The suggested rate for an azalea variety was 2,237 kg ha^{-1} yr^{-1} (Dole and Wilkins, 1999, cited by Chen et al, 2001).

Fertigation, or the application of soluble fertilizers applied with irrigation, is still a common method for supplying nutrients to plants in many container nursery and greenhouse operations (Berghage *et al.*, 1999). Controlled-release fertilizer (CRF) application, either incorporated into the substrate or topdressed on the surface of the substrate however, has become more of a standard practice to fertilize ornamental species in recent years; however, it is more costly and there are still many problems with matching the nutrient release rate of CRF formulations to actual plant growth requirements. In recent studies, preliminary calculations show that N can be applied in excess of 3000 kg N ha^{-1} $year^{-1}$ when fertigation is used with overhead irrigation over an eight-month growing season (Lea-Cox et al., 1999; John Ruter, University of Georgia, *pers. comm.*). Recent standards for Maryland indicate that for container nurseries, an average density of 10 plants m^{-2} (1 plant ft^{-2}) for container nurseries and a low plant N requirement of 3.5 g N $plant^{-1}$ $year^{-1}$, a "low-risk" fertilization rate equates to a N application of 350 kg N ha^{-1} $cycle^{-1}$ (770 lbs N $acre^{-1}$ $year^{-1}$; Lea-Cox et al, 2001a). It is important to note that these data are conservative, as 3.5 g N $plant^{-1}$ $year^{-1}$ is a very *low rate* and they imply that most nurseries using these fertilization methods can apply well in excess of 3 times more N per acre than average agrarian system. With the abundance of irrigation water application in container-nursery production, the assumption is that nutrients have a high potential for runoff, if no mitigating structures are used (Ross et al., 2001).

1.8 Nutrient Management Options

Traditional soil-based agronomic nutrient management plans take into account several factors. The soil is analyzed for presence and availability of nutrients. The total nutrient removal over the season by the crop is then estimated as well as efficiency factors, based on nutrient removal by other mechanisms (e.g., microbial use, soil fixation etc.). Subsequently, fertilizer application rates for each crop and soil type can be calculated. This nutrient management process can become more complex, i.e. when soil-P values are found to be excessive. For nursery and greenhouse operations, the nutrient management planning process becomes more complicated because the nutrient use of many ornamental species has not been adequately studied, plant nutrient uptake rates over time are not known, and production times vary from a few weeks for bedding plants to many years for perennial species. Production methods differ greatly between field, container, and greenhouse operations and in addition the variety of fertilization methods like soluble, controlled release or slow release fertilizers further complicate the planning process (Lea-Cox et al., 2001a).

Soil compaction, which is typical for many container-production and greenhouse sites, usually means that surface-water control measures are necessary to regulate and contain water and nutrient runoff. Water management becomes an integral component of the nutrient management process in nursery and greenhouse operations, especially where irrigation or rainfall has the ability to leach soluble nutrients through soilless substrates (Lea-Cox et al., 2001a).

1.9 Nutrient budgeting

Budgeting strategies are multidisciplinary, being utilized in economics, nutrition, agriculture and ecology. Nutrient budgets are developed to assess inputs, redistribution and losses relative to environmental factors. Ecologists employ nutrient budgets to understand nutrient cycling (Chapin and Cleve, 1991). In agriculture, nutrient budgeting is a useful tool for understanding crop nutrient requirements and investigating efficiencies in plant nutrient use (Jokela and Randall, 1997; Li et al. 1992; Sharpe et al, 1988) or evaluating effects of fertilizer use on the environment (Zebarth et al, 1999; Watson and Atkinson, 1999; Aulakh and Bijay-Singh 1996). This study utilizes nutrient budgets for both purposes described above.

1.9.1 Nitrogen Dynamics in Container Nursery Operations

Nitrogen dynamics are far less understood in nursery production systems than in agronomic systems, where nutrient applications are traditionally based on expected yield and specific field conditions. Many agronomic and horticultural studies on nutrient uptake and use-efficiency have indicated, in general, that agricultural crops are poor competitors for N and P in soil production systems. Several published studies on agronomic crops have shown whole plant ^{15}N recoveries ranging from 25 to 80% (cited by Jokela and Randall, 1997) to first year plant N recoveries between 30 and 70% with agronomic ^{15}N studies (Sharpe et al., 1988; Kundler, 1970). A recent review by Baligar et al. (2001) stated that estimates of overall N uptake efficiency in agricultural systems are usually less than 50%. Little is known about the efficiency of nutrient applications when plants are grown in intensive, out-of-ground container-nursery and greenhouse operations but similar or lower efficiencies have been shown in ornamental perennial species. Yeager (1996) reported N recovery rates between 33 and 55 % in *Ilex vomitoria*, but Tyler et al. (1996b) reported higher uptake efficiencies of 56 - 69% for N by *Cotoneaster dammeri* Schneid. 'Skogholm' in a controlled-release fertilizer (CRF) study. Ivey et al. (2002) reported much lower uptake efficiencies between 8 - 19% for N and 10 - 24% P for *Viburnum awabuki* 'Chindo', and Struve (1995) reported N recovery rates by *Quercus rubra* of 4 - 9%. Typically, many studies report that the greater the N rate applied, the lower the proportion of N is recovered. A variety of factors affect availability and loss of mineral N including soil fixation, gaseous emission, microbial competition and denitrification, and runoff and leaching, all of which significantly reduce uptake efficiency by various species. This research therefore seeks to improve our understanding of N dynamics in container-nursery production systems, by integrating N application, leaching, and uptake data over the long-term.

1.9.2 Phosphorus Dynamics in Container Nursery Operations

Baligar et al. (2001) also stated that estimates of overall P uptake efficiency in agricultural systems are less than 10%. Presently, P fertilization in many nursery and greenhouse operations is likely in excess of plant requirements, which results in low uptake efficiencies and increases potential P runoff. Tyler et al. (1996b) recovered 50 to 80% of applied P in the leachate, substrate and plant, and found P uptake efficiencies to only be between 17 and 25% in a field study examining leaching fractions and CRF rates on growth in containerized cotoneaster plants. Other research on woody perennial species has focused on the effect of P on plant growth (especially roots), and the appropriate levels of P fertilization to reduce P loss into the environment (Zhang et al. 2002; Borch et al. 1998; Hanson and Lynch, 1998; Lynch et al., 1991). However, until now there have been no integrated studies of P fertilization in container nursery systems. Consequently, no definitive knowledge base has been developed that follows the dynamics of P fertilization, from application to uptake efficiency and potential runoff. This lack of data illustrates the need for increased research on P dynamics in container nurseries.

1.10 Nutrient Use Efficiency

Nitrogen/phosphorus ratios differ in plants species and can differ within the same species depending on nutrient availability, growth conditions, and the morphological stage of growth. Nitrogen requirements needed for optimal growth in terrestrial plants can range between 2 and 5% of plant dry mass and P requirements during the vegetative growth stage are between 0.3 and 0.5 % of plant dry mass (Marschner, 1995), although Koerselman and Mueleman (1996) found N/P limitation ratios in several plant communities to be similar to the Redfield ratio. Given this and the fact that plant roots have a high affinity (low K_m) for P (Ragothama, 1999), theoretically, fertilization should be based on N:P ratios greater than 10:1 by weight. Despite this, several ready-made soluble fertilizers and controlled release formulations have N:P ratios of 2:1, which are far in excess of plant P requirements.

Plant P requirements remain largely misunderstood by growers in the industry, due to several misnomers. In plants, P is associated with growth of meristematic tissue and in particular, root growth (Tisdale et al., 1985; Wittwer, 1969). There is a widespread belief in the horticultural industry that P fertilization stimulates root growth over shoot growth. References to P fertilization and increased root/shoot ratios have promoted the use of fertilizers with extremely high P concentrations for the establishment of plants. In a review on root:shoot ratios in trees, Harris (1992) cites seven examples of books or manuals on plant care that either stated or implied that P and N primarily promotes root and shoot growth respectively. This "belief" that P fertilization preferentially stimulates root growth over shoot growth has led to the practice of providing high P content fertilizers to promote rapid transplant establishment of horticultural plants (Wittwer, 1969). However, there are few definitive experimental data to support this dogma. Studies have shown high P fertilizers were found not to increase root/shoot ratios in several varieties of containerized plants (Yeager and Wright, 1982: Broschat and Kloch-Moore, 2000). In contrast, P-deficient plants tend to have increased root/shoot ratios.

Lea-Cox and Syvertsen (1996) showed that the concentration of soil ^{15}N susceptible to leaching was affected by the efficiency with which citrus seedlings took up and assimilated ^{15}N. In a study that quantified ^{15}N uptake in citrus trees with varying N availability, Lea-Cox et al. (2001b) found that N-NUE increased with decreased N availability. Nitrogen leaching was highly correlated to the N not used by trees and which remained in the soil (i.e. the ^{15}N in excess of immediate plant growth requirement). Rose et al. (1994) also demonstrated that nutrient-use efficiency decreased at a high rate of N supply. Poinsettias fertilized with incremental concentrations of N that mirrored the plant's growth requirements were not different in shoot N content, N concentration, dry weight, and leaf area and quantity from plants fertilized with a constant rate of N. Poinsettia N uptake efficiency decreased for the constant treatment in comparison to the incremental treatment. Most importantly, the incremental treatment had less N in the substrate that was potentially available for leaching.

Nutrient use efficiency is an effective tool for examining nutrient availability and limitations in natural environments and explaining physiological adaptation to nutrient availability. However, since NUE does not adequately describe situations where attempts are made to maximize yield or growth, which is the stated goal of agriculture at present, its use is somewhat limited in agricultural studies.

1.11 Scope of Study: Investigating Nutrient Uptake Efficiency

Little is known about the efficiency of water and nutrient applications when plants are grown in intensive, out-of-ground container-nursery and greenhouse operations. Apart from the following research hypotheses, the goals of this study were to improve our understanding of N and P dynamics in a containerized nursery by integrating N and P application, leaching, and uptake data.

Several primary research hypotheses for the production of containerized ornamental species were tested in a long-term (40-month) field study. Firstly, that method of irrigation has no effect on the growth (i.e. increase in dry mass) of azalea (*Rhododendron* var 'Karen') or holly (*Ilex cornuta* var 'China Girl), being representative of two different woody perennial model species. Secondly, the use of drip irrigation increases nutrient uptake efficiency of both azalea and holly compared to overhead irrigation, due to direct placement and minimal leaching, by increasing nutrient residence time in the root zone. Thirdly, plant dry mass will not be different between Time Domain Reflectometry (TDR) and cyclically scheduled irrigation treatments for both irrigation methods. In addition, since TDR applications were based on actual plant water use, I hypothesize that TDR scheduling would increase nutrient uptake efficiency for both drip and overhead irrigation systems, compared to normal timed irrigation scheduling..

In addition, a set of greenhouse studies examined nutrient uptake efficiencies under controlled greenhouse conditions, specifically, to research the absolute N and P requirements and interactions of these nutrients on the growth of azalea. For these greenhouse experiments I hypothesized that current N and P application rates to most ornamental plants in container nurseries exceed normal plant N and P requirements, resulting in low uptake efficiencies and excessive nutrient loss via leaching. I also hypothesized that uptake efficiency would increase at lower application rates, and that there is a point at which growth is not limited, but nutrient uptake efficiency is maximized and leaching is minimized. Lastly, I hypothesized that root growth is in fact improved by reducing P availability to a minimum with azalea.

Chapter Two

Methods and Materials

2.1 Field Study – Long-term Water, N and P Dynamics

2.1.1 Treatments

A long-term container-nursery system "field" study was initiated in July, 1999 to quantify water use and nitrogen (N) and phosphorus (P) uptake, efficiency, partitioning and loss over three consecutive growing seasons until November 2002 (40 - months). Two ornamental species that are widely-grown in the Eastern United States (US), namely, azalea (*Rhododendron* cv. 'Karen'), an ericaceous 'low nutrient use' cultivar and holly, (*Ilex cornuta x regosa* cv. 'China Girl'), an evergreen 'high nutrient use' cultivar were used in this study. Growth (change in dry mass) and nutrient uptake dynamics were investigated with these species. In addition, the effects of two irrigation methods (drip vs. overhead sprinkler) on water application volumes and runoff volumes were examined, along with the effects of these irrigation methods on N and P uptake and leaching from azalea and holly. Also investigated were the effects of reducing water applications on nutrient uptake, leaching and loss by comparing scheduled 'cyclic' water applications with a plant-driven irrigation scheduling methodology (i.e. Time Domain Reflectometry).

Each 'growing season' was examined as three discrete data sets (Table 1), comparing the fertilization and irrigation efficiencies of different management practices utilized by most container nurseries in the U.S.. These management practices included container size and spacing, fertilization strategies, and irrigation methods and timing. Water and nutrient budgetary information was gathered from water and fertilizer

Table 2.1. Field Study Data sets (Management Practice timeline).

	Data Set 1 (July 1999 – Sept. 2000)	**Data Set 2 (Sept. 2000 – Sept. 2001)**	**Data Set 3 (Sept. 2001 – Nov. 2002)**
Container size	11.6 Liter (3 Gallon)	11.6 Liter (3 Gallon)	19.4 Liter (5 Gallon)
Container spacing No. of Plots Plants / Plot	Unspaced (16.7 pots/m^2) 8 plots 448 plants per plot	Spaced (8.4 pots/m^2) 16 plots 224 plants per plot	Spaced (5.2 pots/m^2) 16 plots 140 plants per plot
Fertilization Timing of Application	Controlled Release and Soluble Fertilizer CRF incorporated at planting and topdressed in January 2000 Biweekly soluble applications thereafter	Controlled Release and Soluble Fertilizer CRF topdressed in January 2001 Biweekly soluble applications thereafter	Soluble Constant Fertilization (i.e. at every irrigation)
Irrigation Type **Irrigation Scheduling**	Drip vs. Overhead, Cyclic Irrigation	Drip vs. Overhead, Cyclic Irrigation	Drip vs. Overhead, Cyclic vs. TDR
Plant Harvest Times No. of plants, samples	July, October, June, September 32 plants x 5 tissues = 160 samples per harvest	June, August, November 32 plants x 5 tissues = 160 samples per harvest	July, November 32 plants x 5 tissues = 160 samples per harvest

application totals, runoff volumes and leachate concentrations, plant tissue dry mass data and nutrient content.

2.1.2 Wye Research Station Experimental Site

The Wye research site consisted of replicated 68 m long cold frame structures (houses) in a north-south alignment with eight, 9m wide x 8m long plots per house (Fig. 2.1). Two continuous layers of 6-mil polyethylene plastic were sandwiched between two continuous layers of fabric ground cloth (groundpac) forming the floor of each plant house. This created a completely impervious surface for collection of irrigation water runoff and leachate from each plot. Each house sloped at 1% from north to south. The east and west sides of each plot sloped at 6% and drained into a 0.3m-wide central furrow which ran down the length of each plot (Fig. 2.1). All runoff was diverted into this furrow and towards the end of each plot, where it was collected by a below-ground 170 l polyethylene barrel that was sealed into the plastic liner and groundpac fabric. Irrigation and rainfall runoff on each plot was pumped from the sub-surface barrel by a Rule 1800 submersible sump pump (ITT Industries, White Plains, N.Y.) equipped with an automatic sensor that cycled the pump every 2 minutes and pumped water through a digital flow-meter (Great Plains Industries, Wichita, KS) into above-ground collection barrels (Fig. 2.1). A fraction of the runoff was collected for N and P analysis; the rest was automatically diverted to through a 3.8-cm (1.5 inch) polyvinylchloride (PVC) schedule 40 underground waste pipe. This runoff water then drained into a concrete sump box at the south (lower) end of each cold frame, and was diverted via a 10 cm (4 inch) PVC class 160 drain pipe, into a lined 100 kl containment pond located 25 meters from the cold-frames.

Figure 2-1. Overview of one half of one of two replicated cold-frame houses at the container-production research site at the Wye Research and Education Center, Queenstown, Maryland. Azalea (foreground) are shown here under overhead irrigation and holly are shown are shown with drip irrigation in separate blocks. Above-ground runoff collection barrels are visible.

2.1.3 Field Study – Irrigation

Water was delivered to the experimental site via a nominal 5 cm (2 inch) schedule (sch.) 40 PVC main, routed into a head house and split into two 3.8 cm (1.5 inch) sch. 40 PVC water lines. In the head house, two Dosatron (Dosatron International, Terres, France) injectors were placed in-line on each of the parallel 3.8 cm water lines. From the head house, two parallel 3.8 cm Class 160 PVC main water lines were then routed down each side of each cold frame, a separate line supplying each species. Irrigation was delivered to the east and west side of each plot by tapping into the main water lines at the lower end of each plot. Drip or overhead irrigation (Fig. 2.1) was delivered to plant containers by laying a 1.9cm (¾ inch) sch. 40 PVC sub-main across each half - plot (east and west side). Sub-mains on each half-plot were further split into two separate lateral lines, and laid between the plant containers (Fig. 2.1). Overhead irrigation water was applied to each plot using two sets of 12 Netafim (Tel Aviv, Israel) overhead sprayer assemblies. Each sprayer had a maximum output of 1 liter per minute at 350 KPa, but output was adjusted to approximately 500 ml per minute to minimize over-spray outside of the growing plots. Each overhead sprayer was mounted on a 1.9cm (¾ inch) sch. 40 PVC riser, 75 cm in height, spaced equally apart at 92 cm down the row and approximately 90 cm between rows on each half-plot. Drip irrigation was delivered to each plant container via 1.9 cm (¾ inch) black polyethylene (PE) hose in the same sub-main and lateral configuration as described for the overhead sprinklers. Twenty-eight Netafim multiple outlet drippers (MOD's) per half-plot were plugged into the two PE hose-lines running between the containers. Each MOD supported eight drip lines, each with one drip stake. Each drip stake delivered approximately 20 ml per minute at 100

KPa. In the first season (data set 1), one drip stake was placed in each container. To accommodate for increased plant size in data set 2 and increased container size in data set 3, an additional drip stake was placed in each container to give a total of 40 ml per minute at 100 KPa. Irrigation volume/timing was managed by a datalogger (Campbell 23X, Campbell Scientific, Logan, UT) that controlled solenoids on each submain lateral. Seninger (Orlando, FL) pressure regulators controlled irrigation pressure at 100 KPa for drip emitters and 172 KPa for overhead sprinklers on each side of each pot. All irrigation application volumes to each side of each plot were monitored by digital flow-meters that measured flow rate and total flow accumulations.

2.1.4 Time Domain Reflectometry

Time domain reflectometry (TDR) was utilized in data set 3 for comparison with cyclic irrigation scheduling. Sensors were manufactured according to Murray (2001). Four sensors, each with 18 cm wave-guides were randomly placed in plant containers on each plot designated for the TDR treatment. Sensors were placed diagonally (45°) through the root ball of overhead irrigated plants and directly underneath the dripper in the case of drip irrigated plants to improve substrate contact as suggested by Murray (2001). Each of four sensors per plot was attached to a 10m RG8 (Alpha Wire Co., Elizabeth, NJ) coaxial cable, which was connected to a secondary multiplexer (Campbell Scientific, Inc. Logan, Utah). Each secondary multiplexer was connected to a primary multiplexer with a 22.9 m RG8 coaxial cable. The primary multiplexer was connected to the TDR and a Campbell 10X datalogger (Campbell Scientific, Inc. Logan, Utah). At the start of the cycle, the TDR would propagate a signal to the primary multiplexer and on to the first secondary multiplexer at the first TDR plot, which in turn would send that electric wave to each of the four sensors, one at a time. The time for the wave to return to the TDR was converted to dielectric readings and averaged. Dielectric set points were programmed into the Campbell 10X datalogger for each substrate, according to the standard curve determined for that substrate (Murray, 2001). For the azalea substrate, the dielectric set points were 3.80 and 4.45 for turning on and turning off irrigation, respectively. For the holly substrate, the dielectric set points were 4.20 and 4.80 for turning on and turning off irrigation, respectively. A larger dielectric value signifies greater moisture content. Irrigation is turned on when the average dielectric value of the four sensors is below the 'on' set point, indicating the substrate moisture content is below plant available water. Alternatively, irrigation is turned off when the average dielectric value of the four sensors is above the 'off' set point, indicating the moisture content is at container capacity. After irrigating a plot, the TDR would move onto the next TDR plot. If the average dielectric reading from a plot was not lower than the "on" set point, the TDR would move onto the next plot, until all TDR plots were tested. This cycle was repeated throughout the day in a continuous monitoring and control fashion.

2.1.5 Field Study –Interception Efficiency

Interception efficiency (IE) is defined as the percentage of water applied that is captured by the plant container. Interception efficiency can be influenced by many physical, environmental and developmental factors such as container spacing, leaf area and canopy size, as well as wind (Beeson and Knox, 1991). In the first and second field study data sets, interception efficiency within each plot was calculated by dividing the pot surface area within each plot by the area under double irrigation coverage and half of the single irrigation coverage within the plot, i.e.,

$$\text{Interception Efficiency (IE)} = \frac{\text{total container surface area}}{\text{Irrigated area with double coverage} + \left(\frac{\text{area with single coverage}}{2}\right)}$$

This is a theoretical value and does not take into account effects of plant canopy architecture, which affects the amount of water that is shed, held or evaporated. Since the size and shape of the plant canopy changes over time, interception efficiency can also change. Thus, it is important to recognize that the measurement of IE is specific to one set of variables, by and large dictated by container size, spacing and plant architecture. Using the above concept, for TDR you would take the water retained by canopy and container and divide by the water applied. The water retained (water applied (V) less water that runs off V_{RO}) is V_R, volume of water retained = $V - V_{RO}$.

In the third data set, IE was calculated empirically utilizing the TDR data from the overhead plots, i.e.,

$$IE = \frac{V_R}{V} = \frac{V - V_{RO}}{V}$$

where, (V_{RO}) = Volume of runoff from Time Domain Reflectometry (TDR) irrigated plots, (V) = Total Volume of water applied to TDR-irrigated plots, , and (V_R) = Volume of water retained by the canopy and the container in overhead irrigated plots scheduled by TDR

These IE calculations were used to normalize the water and soluble nutrient application data for overhead irrigation in these data sets, so that direct comparisons could be made for drip versus overhead irrigation applications.

2.1.6 Field Study –N and P Fertilization

Fertilization management and methods differed for each data set (Table 1), as per normal industry management techniques. Control release fertilizer was either incorporated into the substrate or top-dressed (data set 1) or was top-dressed only (data set 2). Soluble fertilizer was injected directly into the irrigation lines via Dosatron injectors at different rates and times during the season (Table 1), according to a local nursery practice. Fertilizer concentrations and Dosatron injection rates were adjusted to suit seasonal fertigation regimes. The fertilizer concentrate was made using ammonium nitrate, potassium nitrate, ammonium polyphosphate, iron chelate (Sprint® 330) and STEM® (soluble trace elements). Fertilizer concentrates were made in 72 l quantities in plastic containers, from which each injector metered out the concentrate. A complete recipe for each seasonal rate is given in Appendix A, Tables A2-2, 3 and 4.

2.1.7 Field Study -Pest Management

Control of pest species was performed using an integrated pest management approach, whereby monitoring of common pest species was performed twice-weekly, and targeted control measures where taken when pest populations reached a threshold number. Major insect pests included Japanese beetle (*Popillia japonica* Newman) which fed on azalea leaves, southern red spider mite *Oligonychus ununguis* (Jacobi),) and two-spotted spider mite *Tetranychus urticae* (Koch). Japanese beetle was controlled by Turcam® (bendiocarb) when counts exceeded 100 beetles per plot. Spraying occurred once every data set in mid-July. Spider mites were controlled by Avid® (abamectin), Neem oil, and horticultural oil when leaf damage or colonies became visible on leaves.

Spraying for mites was typically carried out twice in April and once in May. In addition, one application of fungicide (Fungiflo® and Truban®) was applied to holly and Subdue® on azalea during the fall season of data sets 1 and 2 on the advice of the manager of a large commercial nursery in the area. No further fungicide was applied to plants throughout study. One application of pre-emergent herbicide (Ronstar® and Rout®) was applied during the first data set for the control of *Taraxacum*, *Euphorbia* and *Secnecio* weed species.

2.1.8 Field Study - Substrates

Holly plants were grown in a commercial hardwood-based substrate that had been initially amended with 1.39 kg Osmocote 19-5-9, 0.38 kg dolomitic lime, 0.7 kg gypsum, 1.15 kg iron sulfate and 0.50 kg micromax m^{-3}, respectively. Azalea plants were grown in a commercial pine-bark substrate, similarly amended, but with only 1.04 kg m^{-3} Osmocote 19-5-9 and without dolomitic lime. Since each plant species was grown in a separate substrate, comparisons between azalea and holly were confounded and were not made between species.

2.1.9 Field Study - Nutrient Budgets

2.1.9.1 Leachate / Runoff Analysis

As previously noted, the runoff from each block was pumped from the sub-surface barrel through a digital flow-meter into above-ground collection barrels on each plot, where a fraction was collected for N and P analysis; the rest was diverted to a lined 100 kl containment pond off-site, which was periodically pumped out onto a grassed field. Specifically, water samples were taken on average 3 times a week during the period from April to November each year. Water samples were contained in 25ml scintillation vials and preserved with 50 µl concentrated sulfuric acid (32 N). The samples were kept frozen until analyzed for NO_3-N, NH_4-N and PO_4-P concentration on a Flow 3000 System NP analyzer (O.I. Analytical, College Station, TX). Nitrate-N was analyzed using the cadmium reduction method, NH_4-N by the phenolic method and Total and PO_4-P by the ascorbic acid method (Cleseri et al, 1989). Nitrogen and ortho-P runoff/leachate contents were calculated by multiplying the concentration of each ion by the volume of the water collected at each collection time.

2.1.9.2 Plant Harvests

A total of ten harvests were performed for this study, which ran from July 1999 to Nov. 2003. Thirty-two plants from each plot were randomly selected and tagged for each of the ten harvests at the beginning of the study in July, 1999. The last harvest of data sets 1 and 2 (harvests 4 and 8 respectively) were considered the initial harvest of data set 2 and 3 respectively. During each harvest, the plants were divided into five plant tissues, namely root, stem, primary branches and secondary branches and leaf tissue. Root tissue was separated from stem tissue and cleaned of all substrate by physical shaking and then washing with three successive rinses of water. Care was taken in recovering all root tissue by sieving (#30) at all steps. Stem tissue comprised of the main trunk of the plant. Stem diameter measurements were taken at 5cm above the base of the stem. Primary branches included all woody tissue branching directly from stem. Secondary branch tissue was all branch tissue other than primary branch. Tissues were separated at each harvest and fresh weights taken. A 10 to 15g sub-sample of each tissue from each replicate plant was freeze-dried using a Labconco lyophilizer (Kansas City, MO). Dry weights were measured after lyophilization (freeze-drying) or drying in a force-air ventilated oven at 40 C for 72-96 hr. Each tissue sub-sample was milled through a 100 µm screen (Foss/Tecator Mill, model 1093). All tissues were analyzed for total carbon and total N content using a Carlo-Elba CE 2000 CN analyzer. Exact analytical sample dry weights were noted for each sample, to calculate total N and P contents (see below). Tissues from the initial and final harvests of each data set were analyzed for total P using an open vessel microwave system (Star System 6, CEM, Raleigh, NC). Approximately 0.5g of each tissue type (0.2 - 0.3 grams for leaf tissue) was placed in each microwave vessel containing 0.5g of potassium persulfate. Tissues were digested at 250 C^{o} for 30 minutes with concentrated sulfuric acid (32N) and nitric acid (12N). Sample digestion continued at 200 C^{o} for a further 20 minutes. After digestion, each sample was treated with 2 ml of 10N sodium hydroxide and reconstituted to 100 ml using a volumetric flask. The samples were analyzed with the Alpkem FS 3000 for total phosphorus using the ascorbic acid method (Cleseri et al, 1989). During the 40-month study, all plants were pruned according to standard industry practice. The leaf and secondary branch tissues that were pruned from each plant marked for harvest were dried, weighed and analyzed as noted above, so that total N and P budgets could be obtained from these plants. Leaf loss from the azalea plants during the winter months was calculated from the difference between the November and March/April harvests from each year. This estimate of leaf N and P loss was also added into the total nutrient budgets (as a loss).

2.1.9.3 Substrate analysis

Residual nutrients in each substrate were quantified at the end of each data set. Substrate analysis for the first data set was performed by Scotts Laboratory (Allentown, PA) using the saturated media extract method (SME) (Warncke, 1998). However, it was subsequently learned that this analysis was not quantitative. Thus substrate analysis for data sets 2 and 3 were quantitatively analyzed using the 1:1.5 volume extract method detailed in Handreck and Black, 1994). Each substrate extract was then colorimetrically analyzed using the Alpkem FS 3000 for NH_4-N, NO_3-N and PO_4-P (ortho-P), as outlined above.

2.1.10 Data Set 1 – July 1999 to September 2000

One-year-old (quart) liner plants were transplanted into 11.7 l (3-gallon) containers in July, 1999. The experiment was laid out as a completely randomized design utilizing the four north plots of each cold frame. Four treatment combinations (species x irrigation method) were randomly allocated to one of eight plots and replicated twice. Each plot became an experimental unit. The randomization of treatments placed both replicates of each irrigation/species combination within a house. For instance, all holly drip replicates were located in one house. This may have confounded the effects of irrigation treatments on our response variables since treatment combinations were not evenly distributed within the cold frames, possibly adversely affecting the independence of my experimental units (plots). On each plot, 448 plants of each species were placed side by side in an offset, packed formation (side by side) in four sub-plots, with the central furrow and a 50cm walkway dividing each sub-plot (Fig. 2.1). The total area occupied by the containers was approximately 38% of the total irrigated area on each plot at a density of 16.7 plants m^{-2}.

2.1.10.1 Management Practices

Irrigation durations during data set one were scheduled by time (20 minutes for drip and 20 minutes for overhead in 1999 and 15 minutes for drip and 30 minutes for overhead in 2000) and delivered in two cyclical irrigation events three hours apart (08h00 and 11h00). The irrigation sequence was performed by programming a Campbell Scientific Model 23X datalogger to electronically switch the Senninger solenoid valves controlling the irrigation water supply to each plot every day.

2.1.10.2 N and P Fertilization

Controlled release fertilizer (CRF) was incorporated in the substrates at the onset of the study at a rate of 1.39 kg m^{-3} (Osmocote 19-5-9) in the Holly substrate and 1.04 kg m^{-3} (Osmocote 19-5-9) in the Azalea substrate. This equated to approximately 4.94 g N and 0.57 g P per plant for Holly substrate and approximately 3.70 g N and 0.42 g P per plant in the azalea substrate. An additional 6.12 g N and between 0.59 and 1.04 g P was top-dressed with CRF on all plants during the over-wintering period. In addition, supplemental soluble fertilizer applications were made, on average, twice a week during the growing season, with applications as noted in Appendix A Table A2-1. The calculations for the N and P applied are detailed in Appendix A Table A2-3. Applications of 150 mg N l^{-1} were applied from August 1999 to September 1999, 75 mg N l^{-1} were applied from September 1999 to November 1999. May 2000 through July

2000 rates of 150 mg N l^{-1} were applied. Applications of 75 mg N l^{-1} were applied from August 2000 to September 2000. Soluble P applications were applied at a concentration of 1.5 mg N l^{-1} throughout the year. All applications were on a biweekly basis, reflecting the standard practice of the advising nursery operation at that time.

2.1.11 Data Set 2 –September 2000 to September 2001

For the second data set, (Sept 2000 – Sept, 2001), plants were spaced to half the density to accommodate canopy growth. The south half of the cold frames were now utilized, adding eight additional plots to the experimental site. Half the plants from each plot of data set 1 were randomly assigned to one of 4 south plots of the opposite house. The plants were assigned to the same irrigation method, as previously noted. Each cold frame thus became a block and a total of sixteen plots were now utilized in a randomized complete block design i.e., two blocks and four treatment combinations with two replications per block. The 224 plants on each plot were divided into four equal sub-plots as previously noted.

2.1.11.1 Management Practices

Plants for the second data set were placed in an offset, spaced formation at a density of 8.4 m^{-2}, and remained in 11.7l (3 gallon) containers. Cyclic irrigations were automatically scheduled as previously described, twice a day (08h00 and11h00) in 2000, and three times a day (05h00, 08h00 and 11h00) in 2001, set for 15-min durations for drip and 30-min durations for overhead plots. The increase in irrigation during 2001 was to accommodate increased plant size.

2.1.11.2 N and P Fertilization

Again, controlled release fertilizer was applied as a top-dress application in Jan 2001 at a rate of 6.12 g N and between 0.77 and 1.00 g P to all plants, with supplemental soluble fertilizer application applied twice a week on average during the April – November 2001 period. Biweekly applications of 100 mg N l^{-1} were applied from September 2000 to November 2000, 250 mg N l^{-1} from May 2001 to June 2001, and 200 mg N l^{-1} from May 2001 to June 2001. Nutrient applications were constant at a concentration of 75 mg N l^{-1} and 2 mg P l^{-1} from July 2001 to September 2001. Soluble P applications were applied at a concentration of 2.0 mg N l^{-1} throughout the year.

2.1.12 Data Set 3 –September 2001 to September 2002

At the beginning of the third data set starting in September 2001, plants were transplanted into 19.7 l (5 gallon) containers to avoid root restrictions on plant growth, and spread out to accommodate larger canopy growth. Time Domain Reflectometry (TDR) irrigation scheduling was incorporated into the study at this time. One of the two treatment replicates for each block from data set 2 was randomly selected and irrigated by TDR- controlled irrigation (Murray et al., 2004). Now, with the addition of the TDR treatment, a simple randomized complete block design was maintained with each treatment combination represented once in each block. One hundred and forty plants were now spaced apart at a density of 5.7 plants m^{-2}. The 140 plants on each plot were divided into four equal subplots, as previously described.

2.1.12.1 Management Practices

The 19.7 l containers were placed in an offset, spaced formation. Irrigation was either controlled by time-clock (datalogger controlled cyclic irrigation) three times a day at 05h00, 08h00 and 13h00, set at 15 minutes for drip and 30 minutes for overhead, or was controlled by TDR, which was controlled by the substrate moisture status of four replicate plants per plot. Briefly, TDR probes were inserted vertically into each container, either beneath the drip emitter or at a similar position in the container under overhead irrigation. The 20 cm probe was designed to explore the majority of the root volume in the container. Probes were calibrated to each substrate according to the data of Murray (2001). TDR measurements were taken using a Tektronix (Beaverton, OR) 1502C metallic cable tester connected to a multiplexed Campbell Scientific CRX-10 data logger (Logan, UT). Each block assigned a TDR treatment had four probes that were placed in random plant containers within that block. The datalogger program cycled through each TDR block, averaging the readings of the four probes, as previously described. Each substrate had a calibrated TDR set point for minimum (-10 KPa) and maximum (-1 KPa) plant available water content. When the average readings of the four probes reached those set points, the datalogger would switch the irrigation system on or off, respectively, to that block.

2.1.12.2 N and P Fertilization

All fertilization during data set 3 was applied as a constant feed of soluble N and P in the irrigation water. Complete fertilizer schedules are noted in Appendix A Table 2-1. In summary, N was applied at 75 mg N l^{-1} and P was applied at 1.5 mg P l^{-1} from Sept.

2001 to Nov. 2001. No CRF was applied to the plants in winter (Jan. 2002). In May 2002, the constant fertigation was continued at a concentration of 100 mg N l^{-1} and 4.5 mg N l^{-1} until June 2002. At that point the N concentration was dropped to 50 mg N l^{-1}. The P concentration remaining constant at 4.5 mg l^{-1} until the study was terminated in Nov. 2002.

2.1.13. Field Study - Weather Measurements

Weather data was recorded at a Campbell weather station (Campbell Scientific, Logan, UT) set approximately 50 m from the western cold frame. The station included instruments for measuring air temperature, relative humidity, wind speed and direction, and a tipping rain gauge for measuring rainfall. Weather data for these variables were logged every 15 minutes by the Campbell CRX-23 datalogger on site, and downloaded every 60 days on average.

2.1.14 Field Study - Statistical Analysis

All sample data from data sets 1 and 2 were analyzed with ANOVA using the MIXED procedure (SAS Institute, Cary, NC). In data set 3, a two-way ANOVA was used. If treatment interaction was not significant, main effects would be reported and discussed. However, if treatment interaction was significant, treatment interaction was not significant, simple effects were reported and discussed. Pairwise comparisons were done under LSD criterion at $p<0.05$. I used LSD (a liberal test) because this criterion is commonly found horticultural literature. Variance of homogeneity was tested by the Corr Spearman procedure of the SAS system (SAS Institute, Cary, NC).

In analyzing differences between pre and post data (e.g.change in dry mass and N and P uptake) with ANOVA, an assumption, in addition to the usual ANOVA assumptions was made. When analyzing the difference between pre and post, the assumption is that the relationship between pre and post is linear, with a slope of one. An ANCOVA, in which post data would be treated as the response and pre-data would be the covariate would have been the most appropriate method for analysis of such data.

2.2 Nitrogen and Phosphorus Spring Uptake Study

The system field study was complemented by a series of N and P uptake and use efficiency studies that were performed within a controlled greenhouse environment. These two studies (Spring 2001 and Spring 2002) proposed to examine the uptake of N and P uptake by the ornamental species *Rhododendron* var. 'Karen' (Azalea). This species was chosen as a model woody perennial, since it is widely grown in the nursery and landscape industry throughout the United States. There are few data for azalea on nutrient uptake and use-efficiency from a budgetary perspective; a few studies on other species like poinsettia (Rose et al., 1994, Ku and Hershey, 1991) or in woody ornamentals (Tyler et al., 1996b) have examined nutrient use from the perspective of reducing nutrient concentrations in fertilizer applications, to reduce leaching without impacting growth or quality. No studies on azalea have explored the absolute N and P requirements for maintaining growth and maximizing uptake-efficiency, yet minimizing nutrient leaching.

2.2.1 Spring Study 2001

The first greenhouse experiment was conducted over a 12-week period from March to May 2001, to investigate the uptake and partitioning of N and P by azalea. Five replicate plants per treatment were randomly allocated to two N and three P treatments in a completely randomized factorial design, that provided limiting and luxurious rates of N (i.e. 25 and 250 mg N week^{-1}, respectively) combined with limiting, sufficient and luxurious rates of P (0, 5 and 25 mg P week^{-1}, respectively). Eight-month-old *Rhododendron* var. 'Karen' were transplanted in late February, 2001 into 11.7 l (Classic #2) plastic containers filled with a composted pine bark media that had been amended with 0.22 kg iron sulfate and 0.68 kg micromax m^{-3} (micronutrients), respectively. The plants were not fertilized over the winter (dormancy) period prior to onset of this study, so that the plants and substrate were slightly N and P-deficient according to the initial plant harvest. Plants received a weekly application of N and P in an otherwise balanced liquid fertilizer solution (at the rates specified above) for each treatment throughout the experimental period. The fertilizer was applied to each plant in 250 ml aliquots once a week. Fertilizer solution compositions are tabulated in Appendix A, Table A2-6. Between fertilizations, all plants were deficit irrigated, i.e. hand-watered to ensure no leaching, but all plants were watered to excess the day prior to fertilization; the intention was to leach the excess soluble N and P remaining in the substrate from the previous week. The replicate plants that were designated for the final harvest were placed above catchment saucers to retain the leachate. Leachate volumes were recorded two hours after leaching, and samples were taken and frozen for later N and P analysis, as described above. The first plant harvest was performed prior to the onset of the study to provide baseline dry mass and nutrient content data. Five further plant harvests were conducted every two weeks to provide sequential plant N and P uptake, partitioning and use-efficiency data. Harvest methods and tissue analysis are described above.

2.2.2 Spring Study 2002

A second greenhouse experiment was conducted over a 11-week period from March to May 2002 to further investigate the uptake and partitioning of N and P by azalea. All procedures were similar to those described above, except for fertilization treatments. An additional intermediate N treatment of 100 N mg week^{-1} created nine treatment combinations. In addition, fertilizer concentrations were halved and plants were fertilized twice weekly with 300 ml aliquots to supply the N and P allotment for each treatment combination, to reduce the salt load differential between treatments.

2.2.3 Statistical Analysis

All sample data were analyzed using a factorial analysis of variance using the PROC MIXED routine (SAS Institute, Cary, NC). If treatment interaction was not significant, main effects would be reported and discussed. However, if treatment interaction was significant, treatment interaction was not significant, simple effects would be reported and discussed. Pairwise comparisons were done under LSD criterion at $p<0.05$. I used LSD (a liberal test) because this criterion is commonly found horticultural literature and I wanted to increase the power of my test and protect my analysis interpretation from incorrectly accepting the null hypothesis (Type II error). The use of LSD increases the power of the test, and hence, increasing the probability of detecting a real effect. Variance homogeneity was tested by the Corr Spearman procedure of the SAS system (SAS Institute, Cary, NC).

Chapter Three

Field Study – Irrigation Water Management

3.1 Introduction

Growing concerns over the intensive use of groundwater, deterioration of surface waters and various state and Federal nutrient and water management regulations are making us reexamine the efficiency of nutrient and water management strategies in nurseries (Berghage et al., 1999; Lea-Cox and Ross, 2001). Water is an integral component of the nutrient management equation, particularly where irrigation or rainfall has the ability to move soluble nutrients with ease (Ross et al., 2001). Water application methods and efficiencies must be considered in the nutrient management planning process (Lea-Cox et al., 2001a), combined with any unique infrastructure and site characteristics that may contribute to runoff from production areas (Ross et al., 2001). The majority of container nursery and greenhouse operations in the United States are irrigated by overhead irrigation systems (USDA, 1998). Berghage et al., (1999) calculated that nursery water use could exceed 180 kl per hectare per day, generating from 18 to 90 kl of wastewater per hectare per day based on irrigation system design recommendations for overhead irrigation (Aldrich and Bartok, 1994).

Site, environmental and cultural factors can alter the dynamics of water application and nutrient runoff. Among these factors are total area, slope, plant size and container spacing, plant canopy architecture, irrigation type and design, irrigation duration, interception efficiency, soilless substrate characteristics, the effects of diurnal and seasonal temperature changes, light intensity, rainfall, and relative humidity. Other factors affecting irrigation efficiency include application uniformity and application rate

(Beeson and Knox 1991; Beeson and Haydu, 1995; Lamack and Niemera, 1993), total volume applied (Beeson and Knox 1991; Beeson and Haydu, 1995), and sprinkler type (Beeson and Knox, 1991).

By taking these factors into account, efficient (optimum) irrigation management practices can be achieved to maximize plant growth and minimize nutrient runoff. While drip and other microirrigation techniques are excellent for minimizing water use, they are costly and management intensive. Overhead irrigation is the most reliable and economic form of irrigation for container production of woody ornamentals, particularly for plants grown in containers less than 20 l in volume (Beeson and Knox, 1991). The efficiency at which irrigation water is applied to plants is an important consideration for irrigation managers. Reducing water applications and understanding the inadequacies of irrigation system design, together with the water requirements of plant species being grown can effectively increase irrigation efficiency.

Cyclic irrigation is a form of scheduling water applications, which entails dividing the daily water allotment into a series of cycles comprising of both irrigation and rest periods. Smaller volumes applied more frequently have a tendency to increase the percentage of applied water held by the substrate (Tyler et al.,1996a; Fare et al.; 1996; Beeson 1995; Fare et al.,1994; Kerr 1985) and in turn, help maintain adequate moisture levels in the substrate for plant use. Cyclic irrigation was employed throughout the duration of the field studies. Nevertheless, even when cyclic irrigation is used, too long an irrigation period can reduce efficiency (Tyler et al, 1996a).

By accurately managing the durations of water applications and optimizing the efficiency by which water is applied, large reductions in potential runoff can be made

(Ross et al., 2001). Theoretically, water applications should match plant daily water use by replacing water lost through transpiration and evaporation from the substrate (Tyler et al., 1996a). Ku and Hershey (1992) suggested only watering to container capacity, minimizing leaching fractions. Tyler et al. (1996a) noted a decrease in irrigation and runoff volume, a decrease in cumulative nutrient loss and improvements in irrigation use efficiency with only a 10% decrease in growth of *Cotoneaster dammeri* Schneid. 'Skogholm', by reducing leaching fractions to below 20%. Biernbaum (1992) recommended the application of water when plant available water in the substrate is reduced by 60 to 70%.

Plant available water (PAW, Handreck and Black, 1999) is the water held in a substrate, which is readily-available to roots. Roots exert tension (initiated within the leaf by evapotranspiration) on the available water, which enters passively into roots, moving from a high to a low water potential. Soil or substrate particle size determines in part, the availability of water or matric potential expressed in kilopascals (KPa). Smaller particles can hold greater amounts of water because of greater overall surface area of all particles, (de Boodt 1972; Fonteno 1981). The initial water is removed easily (PAW) but after a time the surface tension becomes so great that a point is reached when no water can be taken up by plant roots (Handreck and Black, 1999). In mineral soils, this point is reached at tensions of -1500 KPa (Taiz and Zeiger, 1998). However, in horticultural substrates with large particle sizes, the majority of the water is released between 0 and -10KPa, and water becomes unavailable to plants at -10KPa (Murray, 2001, de Boodt 1972). Until recently, no precision technology for sensing plant available water in soilless substrates has been available. Tensiometers and gypsum blocks are unreliable in substrates with larger particle sizes and hence higher porosity, as these substrates have a high percentage of air between particles. Murray (2001) determined the precision of Time Domain Reflectometry (TDR) in a range of soilless substrates, both in laboratory and greenhouse studies. Time Domain Reflectometry is a more precise technology, as it is not affected by the percentage of air contained in a substrate, and it calculates the relative change in the dielectric constant of the water within the rootzone, which varies between infinity (in air) and the value 81 (in pure water). By calibrating the TDR probe in each substrate (Murray 2001), a mathematical formula was derived to monitor and control the application of irrigation water to the plant in each substrate. In this way, TDR can be calibrated to turn the irrigation on when PAW is nearly unavailable (-10 KPa) to the plant and to turn the irrigation off when moisture levels are near container capacity (-1 KPa). The plant canopy therefore integrates all the aforementioned environmental variables, which is related to the reduction in substrate water content, which then controls the time and duration of irrigation water application (Murray 2001, 2002).

In this study, interception efficiency is defined as the fraction of water applied that is retained by the plant and which does not become runoff. Compared to drip irrigation which applies water directly to the substrate, the interception efficiency of overhead irrigation can be comparatively low and will vary depending on several factors most important of which are container spacing, and size and leaf/canopy characteristics of a given species. In a study by Beeson and Yeager (2003), several woody plants species were examined to determine the effects of canopy characteristics and container spacing on the fraction of applied water retained within the root volume of the plant (irrigation application efficiency). Leaf and canopy characteristics affected the amount of water reaching the substrate and differed between species. More importantly, irrigation application efficiency was highest when containers were placed side-by-side and decreased with increasing container spacing. In general, nursery plants, especially woody ornamentals, which take several years to grow to market size, must be spaced apart to accommodate canopy growth. Therefore, Beeson and Yeager (2003) suggest that nursery managers utilize the minimum necessary spacing to optimize irrigation application efficiency.

Although past research provides insights into water management (Tyler et al., 1996a; Fare et al., 1996; Beeson 1995; Fare 1994; Kerr 1985), there is a lack of data on the effect of water application methods used in the container-production of ornamentals, and how this may affect N and P runoff. The primary objective of this long-term (40-month) field study was to examine the efficiencies of water application and the potential for runoff and leaching from drip and overhead irrigation. In the third year of this study, I field-tested the ability of TDR to monitor container moisture and control irrigation durations in an "open" production environment. The effects of the two irrigation scheduling systems on applied irrigation volume and runoff could then be compared. My research hypothesis was that drip irrigation would be more efficient at delivering water to the plant and in turn, more efficient in reducing potential runoff volumes. I hypothesized that since TDR has the capability of sensing water availability in substrates similar to the quantities used by plants, that TDR-controlled irrigation would result in more efficient applications of irrigation water, and would reduce the total applied volume and runoff of N and P.

3.2 Materials and Methods

The general details of the variables used in the collection of each field experiment data set are presented in the general materials and methods (Chapter 2.1). Additional, specific experimental and analytical details are provided here. Applied irrigation was a measured response of the irrigation method and scheduling treatments. Applied irrigation was calculated on a per plant basis from the total irrigation water applied to each plot (logged by each sub-plot flow meter), averaged and divided by the number of plants on each plot for each data set (Tables 3-1, 3-2 and 3-3, respectively).

The rainfall for each data set was calculated from data collected by the Campbell Scientific (Logan, Utah) tipping rain gauge, situated 50 m from the westernmost plots (Chapter 2). This rainfall (total mm over the period) was converted to liters per plot (see Appendix A), and then divided by the number of containers on the plot for each data set similar to applied irrigation. I could not discriminate runoff from rainfall and irrigation, but can assume that all plots received similar amounts of rain with high probability, since all plots were located within 65 m of each other.

Theoretical interception efficiency for data set 1 and 2 was calculated based on the area plant containers (top surface area of container) occupy on the growing plots (production area). In order to calculate theoretical interception efficiency based on container density, the production area occupied by containers receiving double irrigation coverage (where irrigation spray overlaps) and single irrigation coverage must be calculated (see Figure 3-1). This calculation will better estimate the volume of water being applied within any specific area of production.

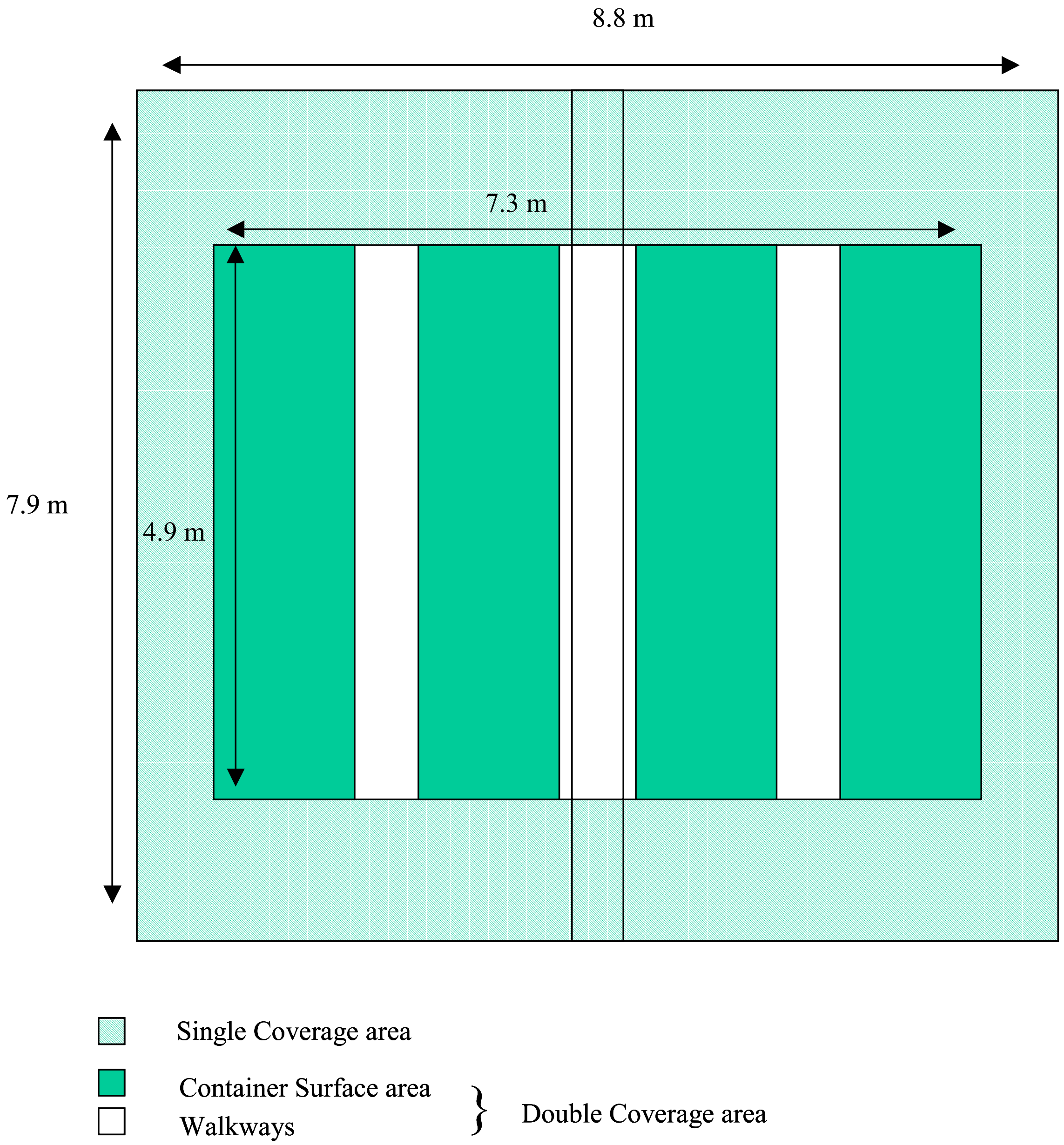


Figure 3-1. Schematic view of growing plot. Interception efficiency was calculated based on the fraction of the growing plot area occupied by containers (container surface area), divided by the sum of double coverage area and half of single coverage area.

The following formula calculates the theoretical interception efficiency for data sets 1 and 2.

Production area = 7.9 x 8.8 = 69.5 m^2
Double irrigation coverage area = 4.9 x 7.3 = 35.8 m^2
Single irrigation coverage area = 69.5 – 35.8 = 33.7 m^2

Data set 1
Container surface area = 20.5 m^2

Data set 2
Container surface area = 10.3 m^2

Interception Efficiency (IE):

$$\frac{\text{Container surface area}}{\text{Double coverage area} + \left(\frac{\text{single coverage area}}{2}\right)}$$

Interception efficiency is calculated to be 38.8% for data set 1 and 19.4% for data set 2. In data set 3, IE could be calculated empirically via TDR, assuming that TDR minimizes leaching from containers, according to the following formula.

$$IE = \frac{V_R}{V_{TOT}} = \frac{V_{TOT} - V_{RO}}{V_{TOT}}$$

where (V_{RO}) = Volume of runoff from Time Domain Reflectometry (TDR) irrigated plots, (V_{TOT}) = Total Volume of water applied to TDR-irrigated plots, , and (V_R) = Volume of water retained by the canopy and the container in overhead irrigated plots scheduled by TDR Calculations were made from several sample sets within data set 3 that were not confounded by rainfall. Cyclic fertilization schedules are described in

Appendix A, Table A2-1. Between August and September 1999, plants were irrigated three times weekly and fertilized at the same time. Between September and November 1999, plants were irrigated three times weekly and fertilized twice weekly. This accounts for the low irrigation volumes calculated for the first data set. Note that in data sets 2 and 3 two drip stakes were placed in each container. This doubled the rate of application each container received compared to data set 1.

Statistical analysis for data set 1 was performed using a one-way ANOVA. Irrigation method was the treatment with two levels: drip and overhead. Response variables included applied irrigation and total runoff. Data set 2 was analyzed similarly, but block was added as a random variable. In data set 3, a two-way ANOVA was performed adding scheduling treatment with two levels, cyclic and TDR, making this a factorial design. Blocks remained as a random variable. Response variables were same as data set 1 and 2. If treatment interaction was not significant, main effects are reported and discussed. However, if treatment interaction was significant, simple effects are reported and discussed. Pairwise comparisons were done under LSD criterion at $p<0.05$. Assumption of variance homogeneity was carried out by Proc Corr Spearman (SAS Institute, Cary, NC).

3.3 Results

3.3.1 Applied Irrigation and Rainfall

Applied irrigation was significantly higher from overhead than from drip irrigation treatments for both azalea ($P<0.01$) and holly ($P<0.01$) in data set 1 and for azalea ($P<0.001$) and holly ($P<0.001$) in data set 2, applying more than three times the water during the first two data sets (Tables 3-1 and 3-2). In data set 3, significant interactive effects were detected with total applied water between irrigation and scheduling treatments in azalea (P<0.01) (Table 3-3). Therefore, simple effects will be reported and discussed. Simple effects showed that irrigation application was significantly different between all treatments, except between cyclic and TDR drip irrigation.

In holly, the interaction between method and scheduling treatments on irrigation application was not significant (P>0.11). Applied irrigation volumes were significantly different between drip and overhead irrigation (P<0.01). TDR-controlled overhead irrigation applied, on average, 52.4% less water than that applied by cyclic (timed) overhead irrigation (P<0.08) (Table 3-3).

3.3.2 Runoff/Leachate

In data sets one and two, runoff volumes from overhead irrigation were two to three times greater than from drip irrigation (Table 3-1). In the first data set, differences were significant for holly (P<0.05) but not for azalea (P>0.12). However, runoff volumes were significantly higher from overhead irrigation for both azalea (P<0.0001) and holly (P<0.01) in the second data set (Table 3-2). In the third data set, runoff again averaged two to three times more from overhead irrigation treatment combinations (Table 3-3).

Treatment interactions between irrigation method and scheduling were significant in azalea (P<0.03). Simple effects showed that runoff from drip irrigation under cyclic scheduling was lower than from cyclic (P<0.001) or TDR scheduled overhead (P<0.01). Runoff from drip irrigation under TDR scheduling was lower than from cyclic overhead

Table 3-1. Applied irrigation, rainfall, and runoff /leaching totals (liters per plant) for close-spaced, containerized (11.7 l volume) azalea and holly plants, grown under drip and overhead irrigation from August 1999 to September 2000 (data set 1). Standard errors are in parenthesis, n=2. P values show significance level.

Treatment	Applied Irrigation (l per plant)	Total Rainfall (l per plant)	Total Runoff / Leaching (l per plant)
Azalea Drip	50.9 (± 0.54)	189.4	57.9 (± 5.6)
Azalea Overhead	153.8 (± 8.80)	189.4	127.0 (± 26.1)
P	< 0.01	-	> 0.12
Holly Drip	47.5 (± 2.89)	189.4	77.3 (± 10.9)
Holly Overhead	150.1 (± 4.01)	189.4	131.6 (± 4.8)
P	< 0.01	-	< 0.05

Table 3-2. Applied irrigation, rainfall, and runoff / leaching totals (liters per plant) and for close-spaced, containerized (11.7 l volume) azalea and holly plants, grown under drip and overhead irrigation from September 2000 to September 2001 (data set 2). Drip output per plant twice that for each irrigation event compared to data set one. Standard error values in parenthesis, n=4. P values show significance level.

Treatment	Applied Irrigation (l per plant)	Total Rainfall (l per plant)	Total Runoff / Leaching (l per plant)
Azalea Drip	141.6 (±10.96)	310.1	127.5 (±21.94)
Azalea Overhead	478.2 (±40.89)	310.1	367.9 (±45.58)
P	< 0.01	-	< 0.01
Holly Drip	119.2 (±15.51)	310.1	147.9 (±34.92)
Holly Overhead	471.5 (±87.07)	310.1	375.1 (±100.86)
P	< 0.01	-	< 0.01

Table 3-3. Applied irrigation, rainfall and runoff/leaching totals (liters water per plant) for close-spaced, (18.9 l), grown under drip and sprinkler irrigation and TDR and cyclic scheduling from September 2001 – November 2002 (data set 3). Drip output per plant twice that for each irrigation event compared to data set one. Standard error values in parenthesis, n=2. P values show main effects and interactive effects

Treatment	Applied Irrigation (l per plant)	Total Rainfall (l per plant)	Total Runoff and Leaching (l per plant)
Azalea – Cyclic Drip	397.6 (± 38.3)	2814	400.6 (± 49.7)
Azalea – TDR /Drip	303.3 (± 29.2)	281.4	362.5 (± 34.1)
Azalea – Cyclic Overhead	1811.1 (± 39.2)	281.4	1313.3 (± 10.0)
Azalea – TDR/ Overhead	881.9 (± 131.2)	281.4	871.3 (± 112.8)
P: irrig.	< 0.01	-	< 0.01
P: schedule	< 0.01	-	< 0.02
P: irrig. x schedule	< 0.01	-	< 0.03
Holly –Cyclic Drip	458.1 (± 21.0)	281.4	529.3 (± 53.3)
Holly – TDR/Drip	388.1 (± 13.6)	281.4	465.9 (± 103.4)
Holly – Cyclic Overhead	2053.8 (± 308.3)	281.4	1718.8 (± 70.1)
Holly – TDR/Overhead	1075.9 (± 52.4)	281.4	682.2 (± 130.5)
P: irrig.	< 0.02	-	< 0.02
P: schedule	< 0.08	-	< 0.04
P: irrig. x schedule	> 0.10	-	< 0.06

($P<0.001$) or TDR scheduled overhead ($P<0.01$). Also, TDR reduced runoff in overhead irrigation compared to cyclic scheduling ($P<0.01$), but there were no differences in runoff between cyclic and TDR drip ($P>0.63$).

In holly, there was treatment interaction on runoff/leachate ($P<0.05$). Main effects were significant for both irrigation method ($P<0.02$) and scheduling ($P<0.04$) treatments as drip and TDR irrigation generated significantly less runoff than overhead and cyclic methods. The interaction of treatments in azalea and possibly holly show that time domain reflectometry was more effective in reducing runoff from overhead irrigation than from drip irrigation.

3.4 Discussion

The irrigation management data presented shows applied irrigation for treatment plots on a per plant basis. This estimation of water application is valid for treatment plots under drip irrigation where all water applied is intercepted by the container and is potentially available to the plant. For overhead irrigation treatments and total rain estimates however, this value overestimates what each plant actually received, since a fraction of the applied water and rainfall is not intercepted and falls between the containers onto the ground or intercepted by the canopy and directed away from the container.

In the first two data sets, leaching volumes from overhead irrigation could not be separated from the proportion that was not intercepted. As such, leaching volumes added an unknown fraction to runoff volume and I could not use runoff data to calculate interception efficiency. In data sets one and two, interception efficiency was calculated based on the formula given above which takes into account the total area occupied by containers (top container surface area) and total area under irrigation, for both single and double coverage. In data set one, the calculated interception efficiency was 38.8%. That is to say that 38.8% of water applied by irrigation was theoretically captured by the plant up until the substrate was saturated. In data set two, this theoretical interception efficiency dropped to 19.4%, as plants were spaced at half the density in data set one. However, it is important to note here that true interception efficiency will likely change over time with canopy size and architecture, regardless of plant density.

In the third data set, TDR was used to calculate the interception efficiency since leaching volumes were theoretically eliminated or minimized. In this treatment, the runoff was therefore equivalent to the proportion of non-intercepted water. The resulting 'empirical' interception efficiencies for azalea plots averaged 49.5% (± 3.5) and 63.5% (± 0.5) for holly plots. Interestingly, the theoretical interception efficiency for data set 3 was 27% based on container surface area alone. From these calculations plant canopy size or architecture may have decreased the volume of water lost to runoff by increasing interception efficiency between 1.8 (azalea) and 2.4 (holly) times the theoretical value. This data suggest that interception efficiency for data set 2 was much higher than the theoretically calculated 19.4%.

The results of these experiments indicate that cyclic drip irrigation utilized two to three times less water than cyclic overhead irrigation, and generated two to three times less runoff. While microirrigation such as drip is the most efficient method for increasing irrigation efficiency, it can be the most costly and certainly management intensive. During the 40 months of this study, management of the drip system treatment was time consuming and difficult for several reasons. The most serious problem encountered was damage to the drip line by eastern cottontail rabbit, *Sylvilagus floridanus*. This was a chronic problem throughout the research site. Additionally, I spent twice the time in resetting containers on drip plots than overhead plots when cleaning and pruning. This has important cost implications for commercial nurseries, since labor costs are high. Additionally, with drip irrigation, if the substrate was allowed to dry to any appreciable extent, channelization of applied water through the substrate could occur, increasing the leaching fraction, and thus reducing the efficiency of the irrigation event. Due to these drawbacks, it is understandable as to why drip irrigation is not utilized more in commercial nurseries despite its' obvious efficiency. The impracticality of drip irrigation in nursery operations that grow a large proportion of small volume container plants forces us to focus on making overhead irrigation systems more efficient.

I use the term interception efficiency as the fraction of applied water and rain that is potentially available to the plant, plus the water captured by the canopy that may not enter the substrate but is not directed to the ground (i.e. which is eventually lost to evaporation). Data set 1 illustrates the efficiency of overhead irrigation compared to the other two data sets when plants are small and are compactly grown (i.e. containers not spaced apart). Plant canopies did not extend beyond container edges and at this time, interception efficiency should have been close to the theoretical irrigation interception efficiency of 38.8%.

In data set 2, the calculated interception efficiency was at 19.4%, but due to leaf and canopy interactions with overhead irrigation, the actual interception efficiency was probably much higher (Beeson and Yeager, 2003). Plants were spaced to allow for canopy development and to maximize light interception, thereby decreasing theoretical interception efficiency for overhead irrigation. Water application volumes in data set 2 were three times that applied to plants in data set 1. This was due in part to half the number of containers on the plot and increased irrigation volume to accommodate plant growth in this data set.

In the third data set, the use of TDR technology significantly reduced the water application and runoff volumes from overhead irrigation in azalea. Time domain reflectometry had reduced overhead irrigation application on holly by 52.4% compared to cyclic scheduled overhead (P=.077). It is possible that the actual interception efficiency was so high with overhead systems that by comparison, holly received adequate volumes of water with both TDR and cyclic treatments. In data set 3, leaf and canopy interaction may have positively influenced percent capture and the theoretical interception efficiency of 27.0% was low considering the comparatively high irrigation efficiencies calculated from TDR plots. From this information, canopy influences may have increased interception efficiency from the theoretical value in data set 2, and plants consequently may have been over-watered.

Time domain reflectometry scheduling for drip irrigation did not significantly reduce the applied water volume as compared to the cyclic scheduling of three 15-minute drip cycles for either species. A 5-minute longer drip cycle would presumably have increased this water application by 33% (i.e. 60 vs. 45 minutes per day), and perhaps increased runoff volume by at least this amount. This suggests that the cyclic irrigation durations were closely matched the actual plant water requirements.

3.5 Conclusions

Some may equate current irrigation management scheduling as more of an art than a science. Methods for delivering the correct amount of water based on plant needs have yet to be fully utilized in nursery settings. Ideally, water should not be applied to containers past their holding capacity to prevent excessive water loss and nutrient leaching, both of which have potentially high environmental costs.

Drip irrigation was shown to be more efficient water application and to have less runoff. Yet, drip irrigation is impractical for most container nursery operations. Improving overhead irrigation management by increasing interception efficiency and reducing leaching fraction will have a positive effect on reducing potential runoff. Further research on interception efficiency is required, looking primarily at the affects of container spacing and plant canopies.

I have effectively shown that the use of plant-driven irrigation scheduling technology such as TDR can be effective in reducing irrigation water applications and particularly in reducing runoff volumes from overhead irrigation systems. Once these systems are mature and can be economically implemented by the nursery industry, they should provide a tremendous opportunity to conserve water and reduce nutrient runoff potential from container-nursery production systems.

Chapter Four

Field Study – Long Term Dry Mass and Nitrogen Dynamics

4.1 Introduction

Nitrogen dynamics are far less understood in nursery production systems than in agronomic systems, where nutrient applications are traditionally based on expected yield and specific field conditions. Armed with specific information about soil chemistry, residual fertility, crop nutrient requirements and production goals for each field, a farm operator can therefore make informed decisions on nutrient application rates from year to year. Exact nutrient application recommendations for woody and herbaceous perennials are sparse in the peer-reviewed literature. Chen et al., (2001) extrapolating from a horticultural text by Dole and Wilkins (1999), noted a greenhouse production N fertilization rate of 2200 kg per hectare per year for azalea. This rate is ten to fifteen times higher than typical recommended agronomic rates for corn. For container nurseries and greenhouses, N application rates in excess of 700 kg N per hectare per year are considered high risk for leaching to the environment, especially if applied as soluble fertilizer through overhead irrigation systems (Lea-Cox et al., 2001a).

Many agronomic and horticultural studies on nutrient uptake and use-efficiency have indicated, in general, that agricultural crops are poor competitors for N and P in soil production systems. Many N fate studies have been published in the past with wide ranging N recoveries for agronomic crops. Jokela and Randall (1997) cite several ^{15}N studies with results ranging from 25 to 80% whole plant N recoveries. Kundler (1970) reported first year plant N recoveries between 30 and 70% with agronomic ^{15}N studies (Sharpe et al., 1988). A recent review by Baligar et al. (2001) stated that estimates of overall N uptake efficiency in agricultural systems are typically less than 50%. A variety of factors affect availability and loss of mineral N including soil fixation, gaseous emission, microbial competition and denitrification, and runoff and leaching, all of which significantly reduce uptake efficiency by various species. A limited number of ornamental studies have indicated similar or lower efficiencies. Yeager (1996) reported N recovery rates between 33 and 55 % in *Ilex vomitoria*, but Tyler et al. (1996b) reported higher uptake efficiencies of 56 - 69% for N by *Cotoneaster dammeri* Schneid. ‘Skogholm’ in a controlled-release fertilizer (CRF) study. Ivey et al. (2002) reported much lower uptake efficiencies between 8 - 19% for N and 10 - 24% P for *Viburnum awabuki* ‘Chindo’, and Struve (1995) reported N recovery rates by *Quercus rubra* of 4 - 9%. Typically, many studies report that the greater the N rate applied, the lower the proportion of N is recovered.

Many studies indicate that N uptake efficiency in influenced by time, rate, and method of fertilization. There is some argument about timing fertilizer applications to field and containerized ornamental plants. Rose (1999) cited two studies (Good and Tukey, 1969; Meyer and Tukey, 1967), which found root growth in woody plants increases at low temperatures when shoots are dormant. Late season fertilization offers many advantages in field-grown plants including increased root activity and uptake at lower soil temperatures, better soil moisture conditions, and a reduction in nursery activities like digging and planting (Rose, 1999). Opponents to late season fertilization suggest that fall acclimation of plant tissue is delayed (Smith, 1989), especially in species with several shoot flushes throughout the growing season (Rose 1999; Davidson et al., 1994). Several recent studies have found evidence contrary to this opinion. A review by

Pellet and Carter (1994) found that moderate rates of fall fertilization did not reduce cold hardiness in woody plants and Dehayes et al. (1989) found that fall N fertilization of red spruce may actually increase cold hardiness (Rose, 1999). It is well known that commercial landscapers suggest tree fertilization in fall. Containerized species could also benefit from fall fertilization. Several studies looking at fertilization timing in plants with alternating root/shoot growth patterns show greatest N uptake when root growth was most active (Rose, 1999; Evens et al., 1992; Hershey and Paul, 1983;Gilliam and Wright, 1978) and the most efficient N uptake was between shoot flushes with Japanese Holly (Yeager et al., 1980). In this case, timing of fertilization certainly becomes an issue when considering the efficiency of N use.

Given published evidence, it is possible to hypothesize that many agronomic crops and most ornamental species have low nutrient uptake efficiencies due to a number of inter-related factors. That first, many agricultural (food) crops and certainly, most intensively grown ornamental species have not been selected or bred for high nutrient uptake or nutrient use-efficiencies (i.e. higher mole nutrient per mole carbon ratios). Secondly, agricultural systems are nutrient-rich environments, which tend to promote shoot growth (increasing light interception), and reducing the need for plants to invest in carbon-intensive root systems to scavenge for water and nutrients. As a result, plants in agricultural or nursery environments with limited or confined root systems, either do not or cannot effectively explore large soil/substrate volumes and consequently, nutrient uptake efficiencies are low. Over-application of nutrients or poorly-timed nutrient applications are not intercepted by these small root zones, which can rapidly leach out of soilless substrates, or are susceptible to microbial use or other loss mechanisms.

In addition to these plant factors, methods of nutrient application and nursery management practices should be scrutinized for inefficiencies. Irrigation water management plays a major role in optimizing nutrient uptake efficiency in container-nursery systems. Optimizing cultural practices such as container spacing, the timing and frequency of soluble fertilization, leaching fraction, and pruning can optimize nutrient uptake efficiency and growth.

Little is known about the efficiency of water and nutrient applications when plants are grown in intensive, out-of-ground container-nursery and greenhouse operations. Several primary research hypotheses were tested in this study. Firstly, the method of irrigation has no effect on the growth (i.e. increase in dry mass) of azalea (*Rhododendron* var 'Karen') or holly (*Ilex cornuta* var 'China Girl), being representative of two different woody perennial model species. Secondly, the use of drip irrigation increases nutrient efficiency of both azalea and holly, compared to overhead irrigation, due to direct placement and minimal leaching, by increasing nutrient residence time in the root zone. Thirdly, we hypothesized that plant dry mass will not be different between Time Domain Reflectometry (TDR) and cyclically scheduled irrigation treatments for both irrigation methods. In addition, since TDR applications were based on actual plant water use, I hypothesize that TDR scheduling would increase nutrient uptake efficiency for both drip and overhead irrigation systems.

4.2 Materials and Methods

The general methods and materials used throughout this study are noted in Chapter 2.1. This three-year study was initiated in 1999 to gather long-term data on N movement in a container-nursery operation. In this study, two ornamental species of contrasting nutrient requirements, *Ilex cornuta* var. 'China Girl' (holly) and *Rododendron* var. 'Karen' (azalea) were used as model woody perennial species commonly grown in the Eastern United States. Two irrigation methods (drip vs. overhead sprinkler) were used to grow these plants for 40 months, based on management techniques utilized by a large local container nursery. This experiment aimed to quantify N application, uptake and partitioning by these two plant species and the cumulative N runoff and loss from each irrigation method over time.

In general, treatment responses were analyzed by species, that is, the response variables between holly and azalea (as different model species) were not compared. This was, in part, due to the fact that the two different substrates used for azalea and holly (e.g. hardwood vs. pine bark) were co-factors, and in addition, comparison of nutrient use between these two species are erroneous, due to growth differences.

Statistical analysis for data set 1 was one-way ANOVA. Irrigation method was the treatment with two levels: drip and overhead. Response variables included change in dry mass, N and P uptake, N pruned, N in runoff/leachate, total N recovery and N uptake efficiency. Data set 2 was analyzed similarly, but block was added as a random variable, as noted previously. In data set 3, a two-way ANOVA was performed adding scheduling treatment with two levels, cyclic and TDR, making this a factorial design. Blocks remained as a random variable. Response variables were same as for data set 1 and 2. If treatment interaction was not significant, main effects would be reported and discussed. However, if treatment interaction was significant, simple effects would be reported and discussed. Pairwise comparisons were done under LSD criterion at $p<0.05$Assumption of variance homogeneity was carried out by Corr Spearman procedure in SAS systems (SAS Institute, Cary, NC).

In analyzing the change in dry mass and N uptake by ANOVA, an assumption, in addition to the usual ANOVA assumptions was made. When analyzing the difference between pre and post, the assumption is that the relationship between pre and post is linear, with a slope of one. An ANCOVA, in which post data would be treated as the response and pre-data would be the covariate would have been the most appropriate method for analysis of such data.

4.3 Results

4.3.1 Plant dry mass

Table 4-1 shows change in dry mass for holly and azalea for all data sets. In data set 1, change in dry mass between irrigation treatments was not significant for either azalea (P>0.78) or holly (P>0.87) (Table 4-1). In the second data set, change in dry mass was greater for azalea under overhead irrigation than under drip irrigation (P<0.01), but irrigation method did not significantly affect the change in dry mass for holly (P>0.09). In data set 3, there was no interaction between irrigation method and scheduling treatments on the change in dry mass for azalea (P>0.20). Main effects showed that azalea grew equally well with each irrigation method (P>0.17) or type of irrigation scheduling (TDR vs. cyclic) (P>0.46). With holly, there was no interactive effect between irrigation method and scheduling on the change in dry mass (P>0.78) and no main effect between irrigation method on change in dry mass (P>0.10). However, main effects were significant for irrigation scheduling (P<0.03) and subsequent pairwise

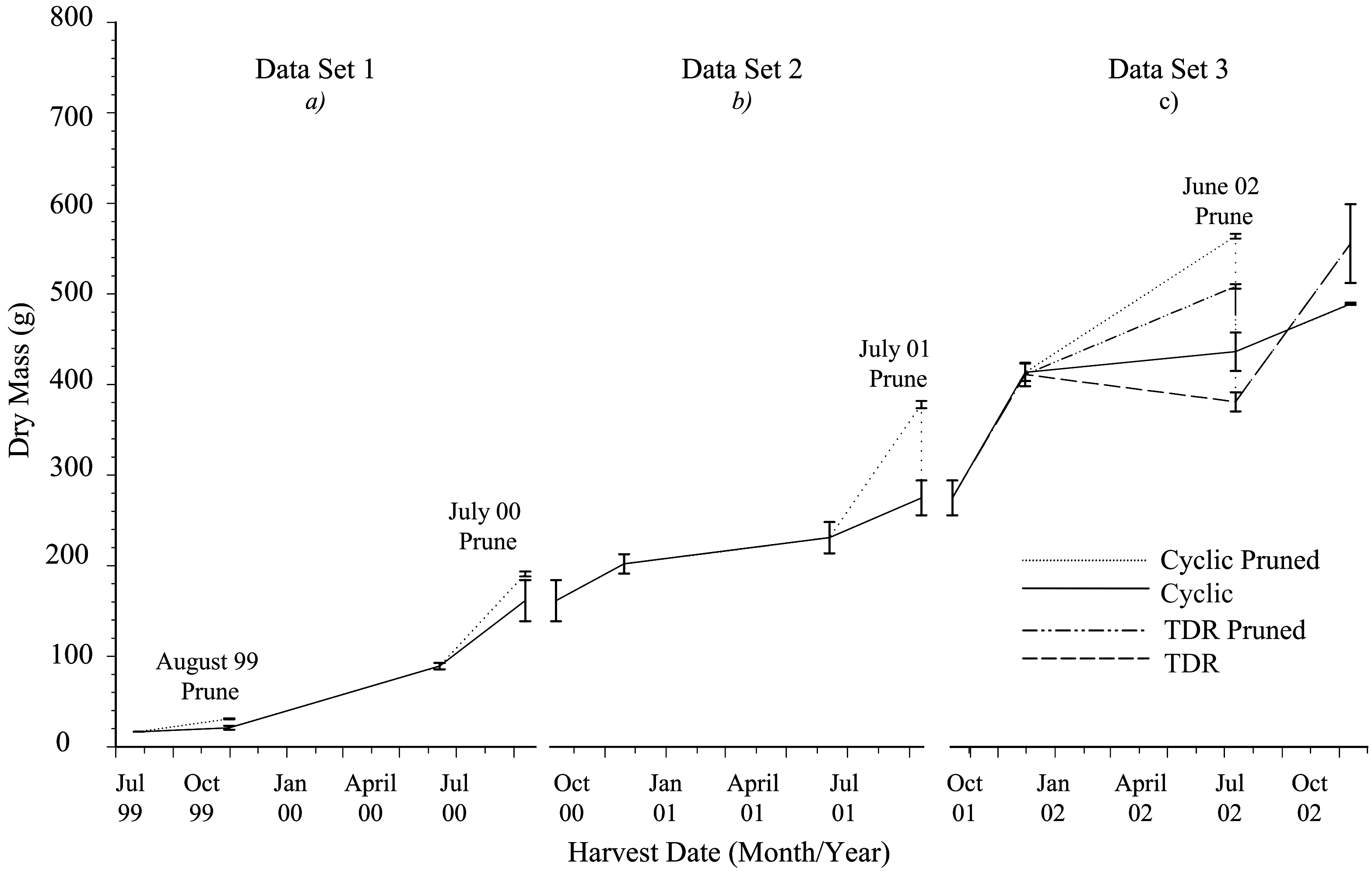
Table 4-1. Average change in dry mass for azalea and holly plants, grown under drip and overhead irrigation from August 1999 to September 2000 (data set 1), September 2000 to September 2001(data set 2), and September 2001 to November 2002 (data set 3). Standard error values in parentheses based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3. P values show level of significance.

Treatment	Data set 1	Data set 2	Data set 3
	Change in Dry Mass (g)	Change in Dry Mass (g)	Change in Dry Mass (g)
Azalea Drip	173.5 (± 27.8)	217.0 (± 25.56)	347.7 (± 41.5)
Azalea Overhead	164.8 (± 2.5)	312.8 (± 14.26)	480.3 (± 66.9)
Azalea –TDR /Drip	-	-	378.3 (± 1.9)
Azalea – TDR/ Overhead	-	-	384.5 (± 7.1)
P: irrig.	> 0.78	< 0.01	> 0.17
P: scheduling	-	-	> 0.46
P: irrig. x scheduling	-	-	> 0.20
Holly Drip	153.7 (± 3.9)	193.8 (± 1.63)	669.5 (± 62.6)
Holly Overhead	156.8 (± 17.0)	135.5 (± 39.54)	759.7 (± 0.4)
Holly – TDR/Drip	-	-	540.5 (± 28.3)
Holly – TDR/Overhead	-	-	609.7 (± 1.5)
P: irrig.	> 0.87	> 0.09	> 0.10
P: scheduling	-	-	< 0.03
P: irrig. x scheduling	-	-	> 0.78

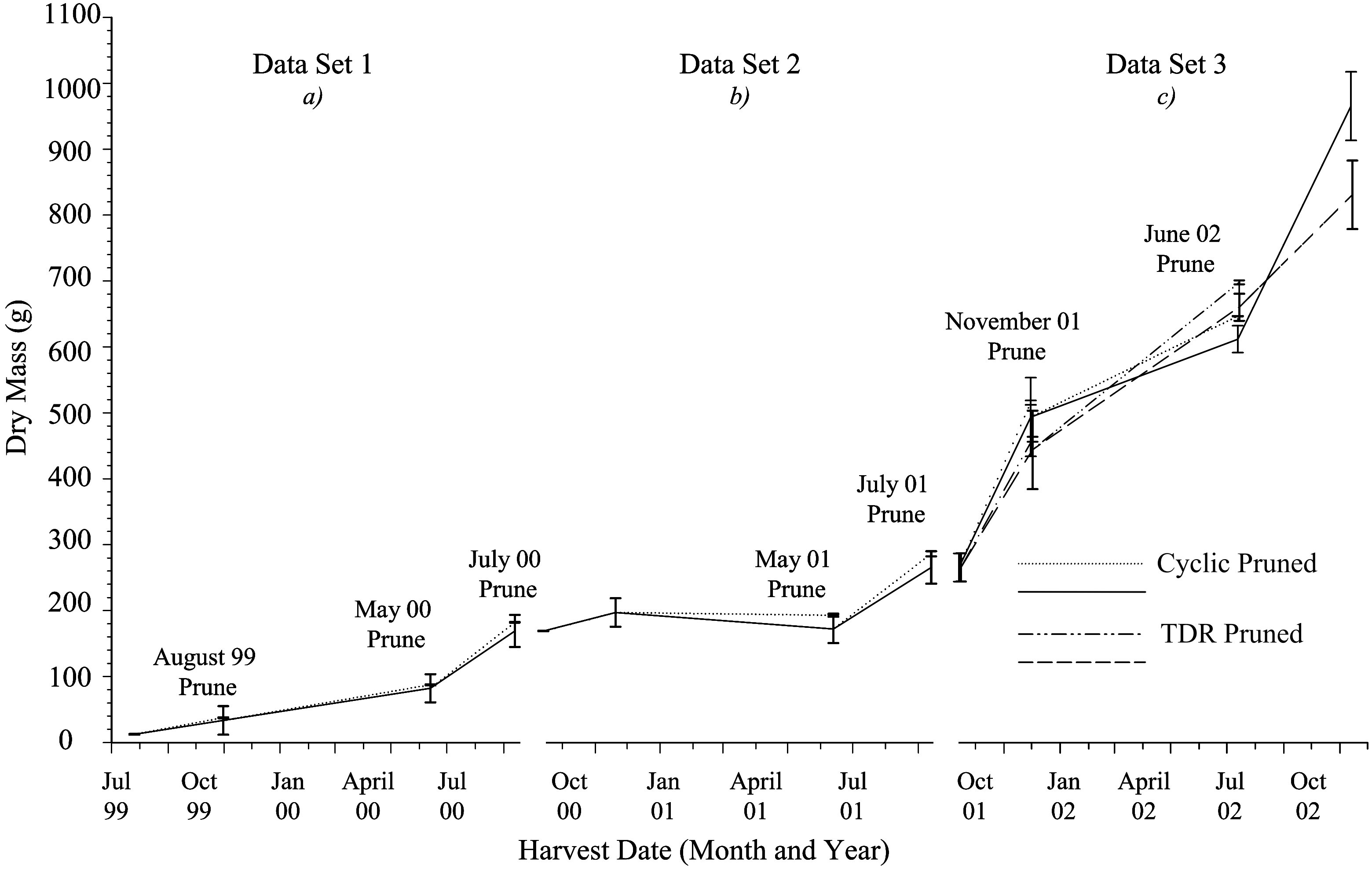
comparison showed that dry mass changes in holly under TDR-controlled drip were less than holly under cyclic overhead irrigation.

Figures 4-1 (a, b and c) show the cumulative increase in dry mass for azalea under drip irrigation for all three data sets. Figures 4-2, a, b and c show the dry mass for holly under overhead irrigation for all three data sets. In data sets 1 and 2, the irrigation scheduling was cyclical, i.e. plants were watered twice a day for 30 minutes (overhead) and for 15 minutes a day (for drip). Cyclic and TDR scheduled treatments are overlaid for data set 3 (Figs. 4-1c, 4-2c), since these plants were derived from the same treatments during the previous two data sets. Dry mass figures for the other treatment combinations are presented in Appendix B Figs B4-1 and B4-2.

Figures 4-1 and 4-2, a, b, and c, depict the seasonal increase in dry mass of azalea under drip and holly under overhead irrigation as contrasts. These patterns are also evident in the other two treatments (Appendix B, Figures B4-1; B4-2). An additional harvest before the spring flush might have shown negligible growth during the winter and a larger increase in dry mass into the early summer. More importantly, there seems to be strong accumulation of dry mass during the late summer and fall season compared to spring growth in all data sets. These graphs show comparative dry mass added during the late summer fall period for both species and all treatment combinations. The pruned dry mass data indicates the amount of dry mass taken off the plants in order to control and shape canopy growth, especially for azalea. However, the data does not try to estimate dry mass at harvest time, had pruning not been performed. These data exemplify the large potential loss in growth for both species by regular pruning.



Figures 4-1 a, b, c Mean cumulative dry mass of azalea under drip irrigation for data sets 1, 2, and 3. Figure 4-1 c shows dry mass for both cyclic (solid line) and TDR (dashed line) irrigation scheduling treatments. Dry mass pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures 4-2 a, b, c Mean cumulative dry mass of holly under overhead irrigation for data sets 1, 2, and 3. Figure 4-2 c shows dry mass for both cyclic (solid line) and TDR (dashed line) irrigation scheduling treatments. Dry mass pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

4.3.2 Nitrogen Uptake, and Partitioning

Nitrogen uptake was calculated as the amount of N taken up during each data set period by the plants and includes the N pruned from plants during each data set. In data set 1 (Table 4-2), there were no differences in N uptake between irrigation treatments for both azalea ($P>0.81$) and holly ($P>0.92$). In data set 2 (Table 4-3), azalea N uptake was significantly greater for overhead irrigation, compared to drip irrigation ($P<0.03$). No differences were found in holly N uptake between irrigation methods ($P>0.89$).

In data set 3, there was significant interaction between treatments (Table 4-4) for azalea N uptake ($P<0.05$), so simple treatment effects were examined. Nitrogen uptake was greatest in azalea under cyclic overhead irrigation ($P<0.02$), but there were no differences in N uptake between other treatments for azalea.

In holly, there was no interaction between treatments ($P>0.08$). Main effect differences for N uptake were significant between cyclic and TDR scheduling ($P<0.03$) only. Holly under cyclical scheduling had significantly greater N uptake than holly under TDR-controlled irrigation.

Figures 4-3 and 4-4, a, b, and c, show N content and plant tissue N partitioning for azalea under drip – cyclic irrigation and holly under overhead – TDR irrigation. Additional N partitioning data for other treatment combinations are given in Appendix B, Figures B4-3 through B4-8). Nitrogen partitioning was very consistent in both species throughout all data sets (indicated by Figures 4-3 and 4-4, a, b). Nitrogen is predominant in leaf and secondary branch tissue, with these two tissues containing over half of the total N content of the plants.

Table 4-2. Nitrogen application, plant N uptake, N remaining in substrate at end of data set, cumulative N from runoff/leachates, percent N recovered and plant N uptake efficiency on a per plant basis for azalea and holly plants at a spacing of 16.7 plants • m^{-2}, irrigated with drip and overhead irrigation systems from August, 1999 to September, 2000 (data set 1). Standard error values in parenthesis, means based on n=2. P values shown for effects of irrigation on response variable.

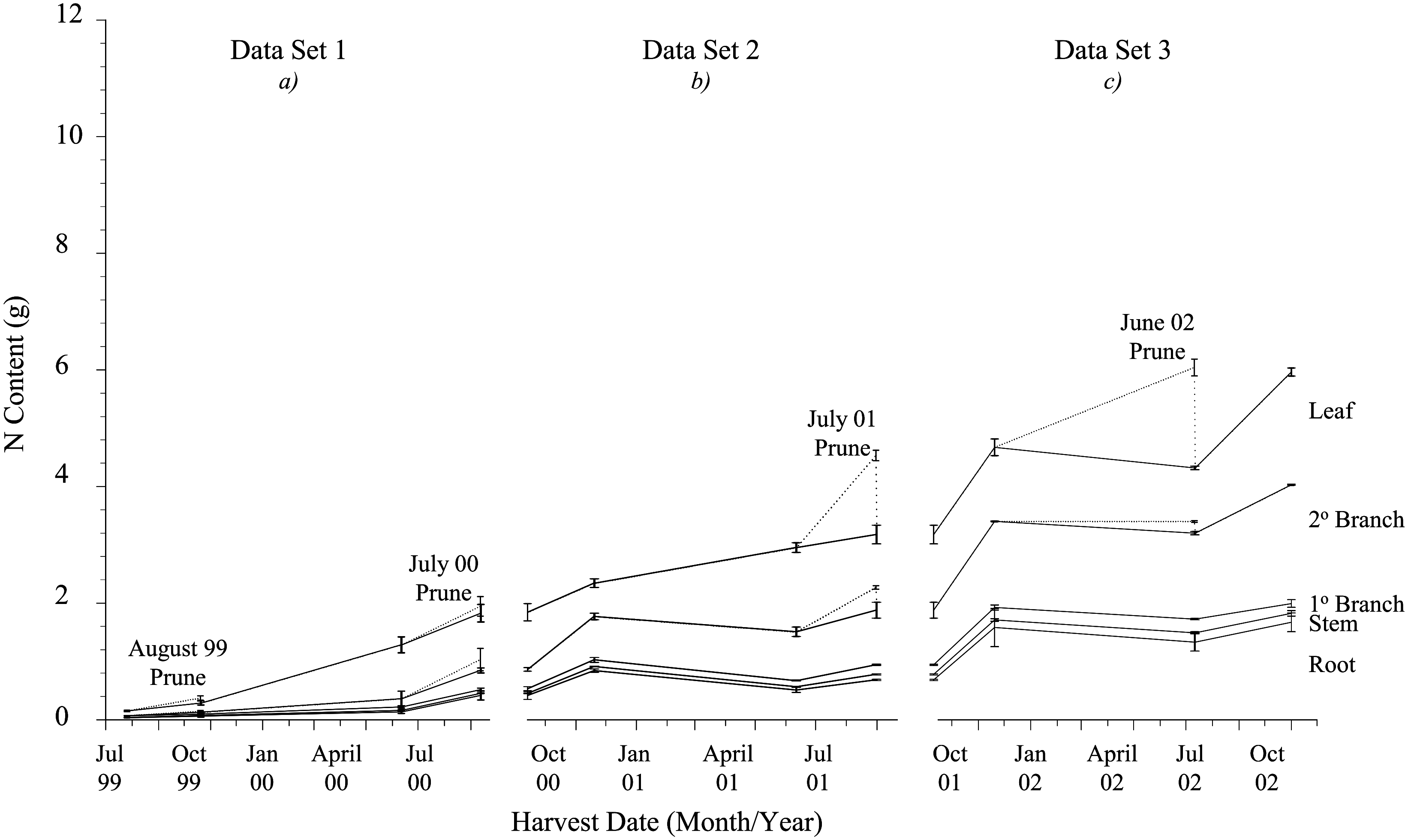
Treatment	**Total N Applied ($NH_4 + NO_3$)**		**Total Plant N Uptake**	**N Pruned**	**Substrate N ($NH_4 + NO_3$)**	**Runoff/Leachate ($NH_4 + NO_3$)**	**N Recovered**	**Plant N Uptake Efficiency**
	CRF (g)	**Soluble (g)**	**(g)**	**(g)**	**(g)**	**(g)**	**(%)**	**(%)**
Azalea – Drip	9.82	2.35	2.05 (± 0.25)	0.41	0.02	0.69 (± 0.18)	22.7 (± 3.4)	**16.9** (± 2.0)
Azalea – Overhead	9.82	2.44	2.02 (± 0.06)	0.44	0.00	2.41 (± 0.46)	36.4 (± 4.1)	**16.6** (± 0.5)
P	-	-	> 0.81	-	-	< 0.07	> 0.12	> 0.89
Holly – Drip	11.06	2.22	3.02 (± 0.12)	0.49	0.04	0.79 (± 0.09)	29.0 (± 1.6)	**22.8** (± 0.9)
Holly – Overhead	11.06	2.33	2.89(± 0.37)	0.32	0.03	2.59 (± 0.15)	41.5 (± 3.9)	**21.8**(± 2.8)
P	-	-	> 0.92	-	-	< 0.01	> 0.09	> 0.76

Table 4-3. Nitrogen application, plant N uptake, N remaining in substrate at end of data set, cumulative N from runoff/leachates, percent N recovered and plant N uptake efficiency on a per plant basis for azalea and holly plants at a spacing of 8.4 plants • m^{-2}, irrigated with drip and sprinkler irrigation systems from September, 2000 to September, 2001 (data set 2). Standard error values in parenthesis, means based on n=4. P values shown for effects of irrigation on response variable.

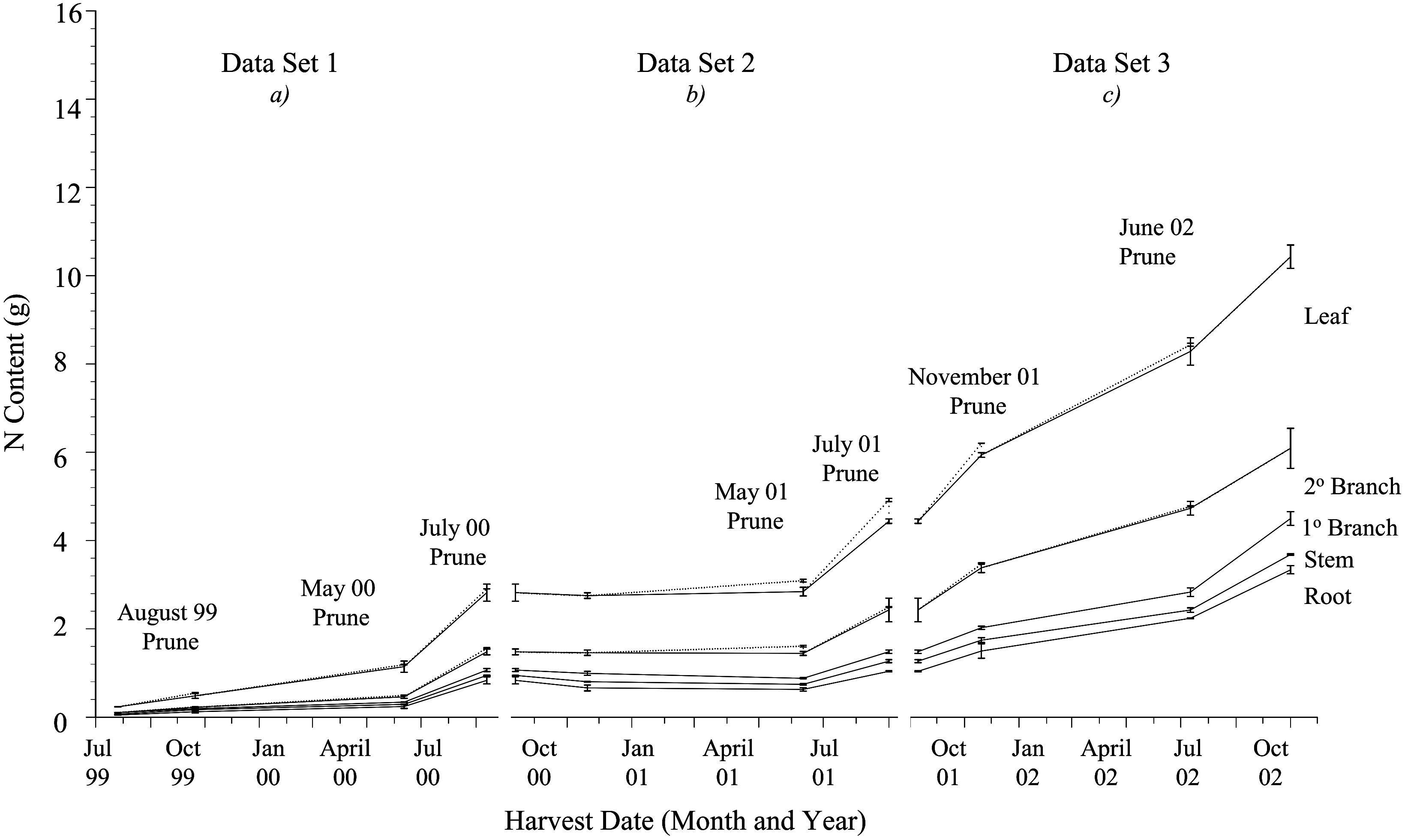
Treatment	**Total N Applied ($NH_4 + NO_3$)**		**Plant N Uptake**	**N Pruned**	**Substrate N ($NH_4 + NO_3$)**	**Runoff/Leachate ($NH_4 + NO_3$)**	**N Recovered**	**Plant N Uptake Efficiency**
	CRF (g)	**Soluble (g)**	**(g)**	**(g)**	**(g)**	**(g)**	**(%)**	**(%)**
Azalea – Drip	6.12	7.69	3.13 (± 0.31)	1.74	0.87 (± 0.08)	1.40 (± 0.16)	39.3 (± 4.0)	**22.9** (± 3.3)
Azalea – Overhead	6.12	27.43	4.06 (± 0.35)	2.14	0.87 (± 0.19)	7.53 (± 1.25)	37.5 (± 4.6)	**12.3** (± 1.2)
P	-	-	< 0.03	-	-	< 0.01	> 0.37	< 0.01
Holly – Drip	6.12	7.32	2.83 (± 0.18)	1.12	0.17 (± 0.05)	2.01 (± 0.19)	37.4 (± 3.7)	**21.9** (± 3.1)
Holly – Overhead	6.12	27.05	2.60 (± 0.26)	0.96	0.31 (± 0.15)	9.29 (± 1.08)	37.0 (± 2.6)	**8.0** (± 0.9)
P	-	-	> 0.89	-	-	< 0.01	> 0.86	< 0.01

Table 4-4. Nitrogen budget presented on a per plant basis. N application, Plant N uptake, N remaining in substrate by end of data set N, cumulative N from runoff/leachates, percent N recovered and plant N uptake efficiency for azalea and holly plants at a spacing of 5.2 plants • m^{-2},irrigated with drip and sprinkler irrigation systems with TDR and cyclic scheduling from September, 2001 to November, 2002, (data set 3). Standard error values in parenthesis, means based on n=2. P-values shown for main effects and interactive effects of irrigation and scheduling on response variable.

Treatment	**Total N Applied ($NH_4 + NO_3$)**		**Plant N Uptake**	**N Pruned**	**Substrate N ($NH_4 + NO_3$)**	**Runoff/Leachate ($NH_4 + NO_3$)**	**N Recovered**	**Plant N Uptake Efficiency**
	CRF	**Soluble (g)**	**(g)**	**(g)**	**(g)**	**(g)**	**(%)**	**(%)**
Azalea – Drip	0	21.51	4.71 (± 0.56)	1.92	0.10 (± 0.03)	11.12 (± 2.75)	73.3 (± 5.6)	**21.9** (± 0.4)
Azalea – Overhead	0	94.47	8.66 (± 1.02)	1.93	0.38 (± 0.03)	56.49 (± 6.18)	69.2 (± 6.0)	**9.1** (± 0.9)
Azalea – Drip/TDR	0	15.73	5.45 (± 0.05)	1.71	0.49 (± 0.36)	10.03 (± 0.52)	102.1 (± 5.1)	**35.0** (± 3.5)
Azalea – Overhead/TDR	0	48.86	4.96 (± 0.17)	1.64	0.18 (± 0.01)	29.40 (± 5.24)	70.6 (± 0.9)	**10.3** (± 1.1)
P: irrig.	-	-	> 0.03	-	-	> 0.01	> 0.04	> 0.01
P: schedule	-	-	> 0.05	-	-	> 0.05	> 0.06	> 0.04
P: irrig. x schedule	-	-	> 0.02	-	-	> 0.06	> 0.07	> 0.05
Holly – Drip	0	25.78	8.18 (± 1.20)	0.65	0.32 (± 0.21)	16.84 (± 1.55)	99.5 (± 6.7)	**31.9** (± 1.2)
Holly – Overhead	0	106.60	10.95 (± 0.36)	0.89	0.12 (± 0.02)	67.29 (± 10.73)	73.7 (± 0.9)	**10.1** (± 1.3)
Holly – Drip/TDR	0	20.40	6.51 (± 0.23)	0.55	0.12 (± 0.01)	11.89 (± 0.72)	90.7 (± 2.2)	**31.9** (± 0.2)
Holly – Overhead/TDR	0	58.22	7.17 (± 1.67)	0.81	0.13 (± 0.03)	31.68 (± 5.60)	69.5 (± 8.5)	**12.6** (± 0.9)
P: irrig.	-	-	< 0.08	-	-	< 0.01	> 0.02	< 0.01
P: schedule	-	-	> 0.03	-	-	< 0.02	> 0.28	> 0.22
P: irrig. x schedule	-	-	< 0.22	-	-	> 0.08	> 0.67	> 0.22



Figures 4-3 a, b, c Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of azalea plants under drip irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures 4-4 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of holly plants under cyclic overhead irrigation for data sets 1, 2, and with TDR scheduling for data set 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

While this fact is relatively well documented in the literature for other crops, the quantity of N lost with pruning has not been documented. Typically, pruning is practiced in most ornamental nurseries as a growth and quality management tool; from these data, it can be seen that a large proportion of the total N uptake for the year can be removed with a single pruning, especially for azalea. Seasonal uptake is well depicted in Figures 4-3 and 4-4 (also for other treatment combinations: Appendix B Figures B4-3 through B4-8). In both summer and fall seasons, a large accumulation of N was observed for both species and all treatments. A surprisingly large amount of N is taken up during the late summer and fall periods compared to the spring season, contrary to the notion that spring is the principal time to fertilize with higher N rates.

4.3.2 Uptake Efficiency

Efficiency data presented in Tables 4-2 to 4-4 were calculated using the treatment replicates to derive standard errors, therefore, they cannot be correctly calculated from the table data itself. Uptake efficiency is defined as the proportion of nutrient taken up by the plant to the amount of nutrient applied. In data set 1 (Table 4-2), N uptake efficiencies were not different for azalea ($P>0.89$) or holly ($P>0.76$), irrespective of irrigation method. Azalea had average N uptake efficiencies of 18.2 and 17.9% for drip and overhead irrigation, respectively. Holly was slightly more efficient with average uptake efficiencies of 23.5 and 24.0% for drip and overhead irrigation, respectively.

In data set 2, N uptake efficiencies were greater for drip irrigation than for overhead irrigation in azalea ($P<0.01$) and holly ($P<0.01$). Nitrogen uptake efficiencies under overhead irrigation dropped to 12.1% for azalea and 7.8% for holly. This drop was significant compared to efficiencies observed for plants under drip irrigation (23% vs. 22% for azalea and holly, respectively).

In data set 3 (Table 4-4), there was significant interaction between treatments for N uptake efficiency in azalea ($P<0.05$). Simple treatment effects showed that N uptake efficiencies were different between all treatments ($P<0.03$) except between cyclic and TDR scheduled overhead treatments ($P>0.68$). Nitrogen uptake efficiencies ranged between 9.3% and 35.0% for azalea, depending on irrigation method and scheduling.

There was no treatment interaction on N uptake efficiencies in holly in data set 3 ($P<0.22$). Differences in holly N uptake efficiency were due to irrigation method alone ($P<0.01$). Nitrogen uptake efficiencies in holly under drip irrigation were significantly greater than efficiencies under overhead treatments regardless of scheduling method.

4.3.3 Cumulative Runoff/Leachate

Cumulative N runoff/leachates for azalea and holly for data sets 1, 2 and 3 are shown in Tables 4-2, 4-3 and 4-4 respectively. Total N runoff/leachate in azalea was marginally different between irrigation methods during data set 1 ($P<0.07$), and total N runoff/leachate for holly under overhead irrigation was significantly greater than with drip irrigation ($P<0.01$). In data set 2, total N runoff/leachate was significantly greater for both azalea ($P<0.01$) and holly ($P<0.01$) under overhead irrigation than under drip irrigation, principally due to higher soluble N applications during this period. In data set 3, there was interaction between treatments for the total N runoff/leachate from azalea ($P<0.06$). Simple effects showed that runoff/leachates from cyclical overhead irrigation was significantly greater than all other treatments ($P<0.03$). There was no difference in N runoff/leachate between the cyclic drip and TDR-controlled drip treatments ($P>0.86$), but TDR scheduled drip irrigation had lower N runoff/leachate totals than from TDR-controlled overhead irrigation ($P<0.05$).

In holly, there was no interaction between treatments ($P< 0.08$). Both irrigation method ($P<0.01$) and scheduling ($P<0.01$) treatments had a significant affect on N runoff/leachate. Cyclical overhead had significantly greater total N runoff/leachate than all other treatment combinations ($P<0.02$). Total nitrogen runoff/leachates for all other treatments were not different from each other ($P>0.08$).

Figure 4-5 compares the cumulative N runoff/leachate on a per plant basis during data set 1 for both azalea and holly under drip and overhead irrigation. Nitrogen runoff/leachate accumulation was slow for all treatments during the fall and accelerated over the following spring and summer periods when fertigation N concentrations were increased to 150 $mg \cdot l^{-1}$. The loss of N over time via runoff/ leachate was much slower under drip irrigation.

Figure 4-6 shows the cumulative loss of runoff/leachate N on a per plant basis during data set 3 for holly under overhead and drip irrigation, comparing cyclic and TDR scheduled irrigations. Data set 3 had a similar pattern for N loss as in data set 1, but because of the constant soluble applications of N over the year, data set 3 had *25 times* the potential N runoff of data set 1.

Potential N runoff was minimized and accumulated leaching virtually leveled off during the fall of 2001, spring of 2002 and fall of 2002 with both drip irrigation treatments and the TDR overhead treatment. However, cyclical overhead irrigation

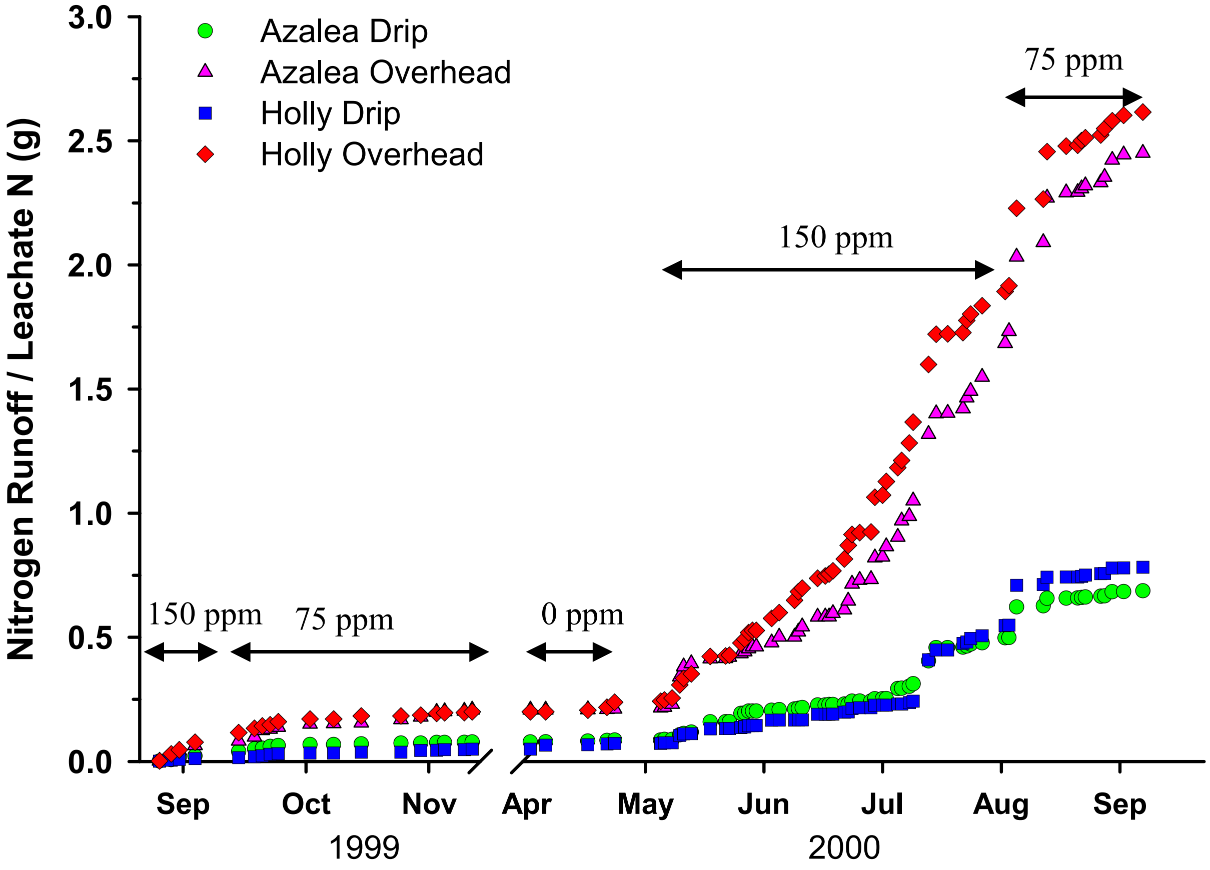


Figure 4-5. Mean cumulative runoff of N from drip and overhead cyclic irrigation on a per plant basis over a fourteen month period between August 1999 and September 2000, (data set 1). Three different soluble rates were applied. Averages based on n=2.

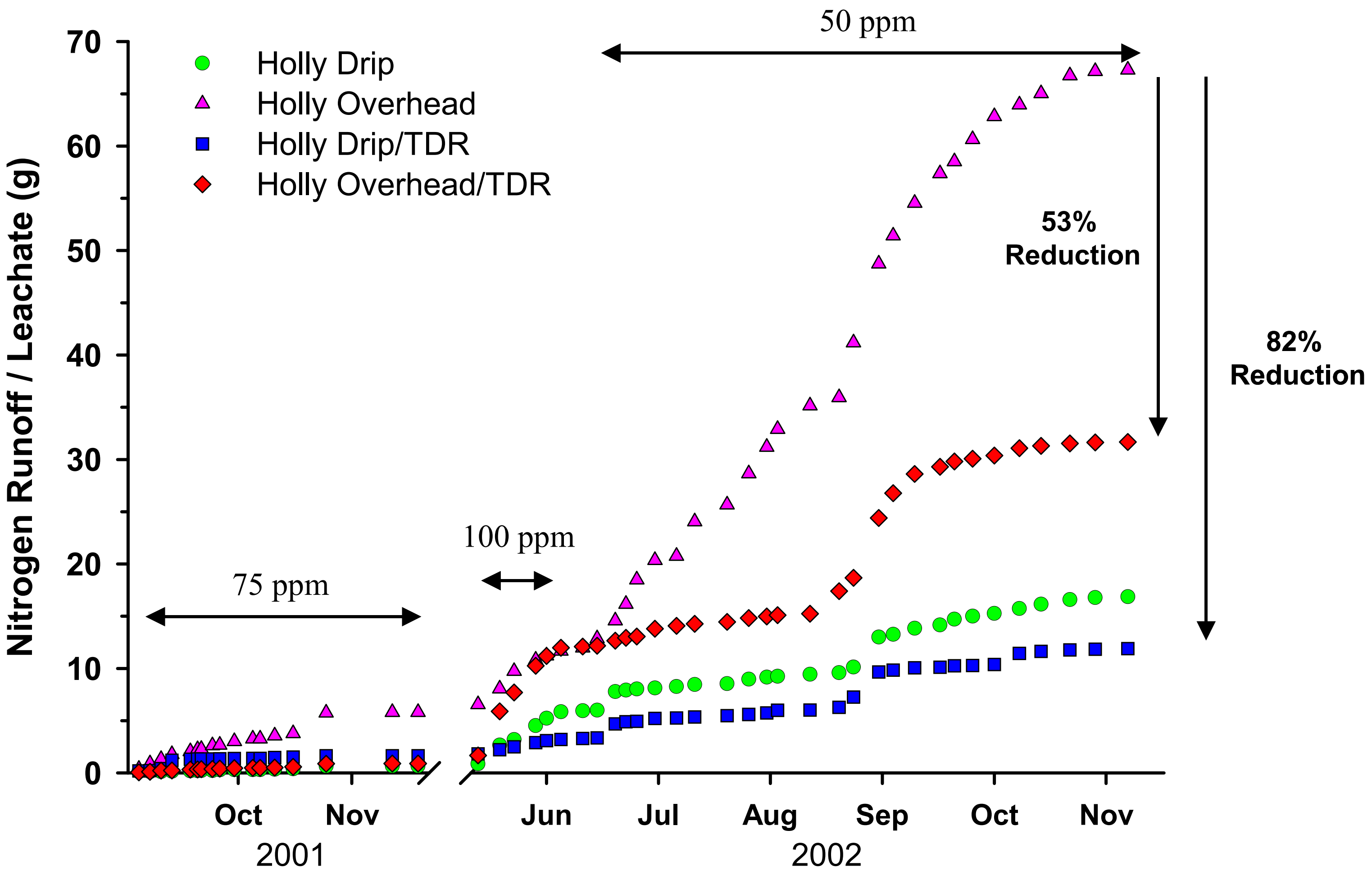


Figure 4-6. Mean cumulative runoff of N from holly under cyclic and TDR controlled drip and overhead irrigation on a per plant basis over a fourteen month period between September 2001 and November 2002, (data set 3). Three different soluble rates were applied as shown. Averages based on n=2.

continued to accumulate N runoff during data set 3 (Fig. 4-6), as N was applied well in excess of plant requirements.

The use of TDR scheduling halved the accumulation of potential N runoff in overhead irrigation as compared to cyclical scheduling when constant fertigation was used in data set 3 (Fig 4-6), since the reduction of water application had a direct effect on potential N runoff. Cyclical drip irrigation averaged four times less N runoff than cyclical overhead by the end of the data set and N runoff under TDR-controlled drip irrigation was almost six fold less than cyclical overhead. By scheduling irrigation based on plant needs, the potential of N runoff was cut in half while still using overhead fertigation. Even though TDR works well in reducing N runoff with overhead irrigation, its' effect on drip irrigation was not as great in this data set, indicating that the cyclical drip irrigation scheduling was already closely approximating plant water needs.

4.3.4 N Budgets – A Summary

Table 4-2 shows the nitrogen budget for data set 1 on a per plant basis. Total N recoveries were not different for either azalea ($P>0.12$) or holly ($P>0.09$) regardless of irrigation method. Interestingly, about 70% of the N recovered was found in the plants under drip and about 20% of the recovered N was found in the runoff/leachates. In contrast, only half of the total N recovered from overhead irrigation treatments was contained in plant tissue, and most of the other half was found in the runoff/leachates. Pruning removed a fifth of total N uptake for azalea and between 10 and 15% of total N uptake by holly. The loss of N in runoff/leachate for overhead irrigation was nearly 20%

of the total N applied to holly and azalea, compared to no more than 6% of the N applied to either azalea or holly by drip irrigation.

Table 4-3 shows the N budgets for data set 2 on a per plant basis. Total N recovery was not significantly different for either azalea (P>0.37) or holly (P>0.86) regardless of irrigation method. Of all N taken up during the second season, over 50% was pruned from the azalea and nearly 40% was pruned from holly. Recovery of N from substrates after the last harvest was approximately 7% of what was applied to each plant under drip irrigation and less than 3% of what was applied to plants under overhead irrigation. Nitrogen recovered in runoff/leachate from drip irrigation accounted for no more than 15% of the total N supplied to either azalea or holly. However, between 22 and 29% of the N supplied by overhead irrigation to azalea and holly was found in the runoff/leachate and accounted for an average of 60 and 76% of total N recovery for azalea and holly, respectively. In this data set, plant N uptake by both species under drip accounted for about 60% of the N recovered. This was in contrast to overhead irrigation where plant N uptake only accounted for 33% of N recovered in azalea and 23% of N recovered in holly.

Table 4-4 shows the N budget for data set 3, again on a per plant basis. The addition of the TDR-scheduled treatment had a profound effect on reducing soluble N application by overhead irrigation. Both azalea and holly under TDR-controlled overhead irrigation only received half the N as plants under standard cyclic scheduling. For drip irrigation, N application was reduced by 21% for azalea and 27% for holly by using TDR compared to cyclic scheduling. The total recovery of N in data set 3 was two to three times the amount recovered in other data sets, due to the large amount of N supplied over the season. For azalea there was possible treatment interaction (P>0.07) for N recovery. Nitrogen recovery from azalea under drip scheduled by TDR was significantly greater than all other treatments (P<0.03) and interestingly, all N applied to this treatment was accounted for (102%). For holly, there was no treatment interaction (P>0.67) for N recovery. Main effect differences in N recovery for holly were due to irrigation method (P<0.02) alone. Total N recovery averaged between 67% and 102% for each treatment, with the largest proportion in runoff/leachates, which averaged no less than 82% from overhead treatments. In data sets 1 and 2, N recovery from runoff/leachate averaged no more than 20% of N applied for any irrigation treatment. The contribution to total N recovery from runoff/leachates with the drip irrigation treatments averaged 63 to 73%. The pruning of N accounted for approximately 23 to 34% of total N uptake for azalea treatments, but less than 10% for all holly treatments. Of the total N applied during this data set, less than 1% was recovered from the substrates at final harvest. Plant uptake for each drip treatment accounted for an average of 26 to 35% of N recovered. The nitrogen uptake for plants under each overhead irrigation treatment accounted for an average of 18% or less of the total N recovered.

4.3.6 Interception efficiency

See Chapter 3 for details on the calculation of interception efficiency (IE). Table 4-5 compares N uptake efficiency based on theoretical and empirically calculated IE for overhead irrigation treatments in data sets 1, 2, and 3 as explained in Chapter 3. The theoretical IE for data set 1 was 38.8%. In data set 2, the plant density was halved since

Table 4-5. Comparison of plant N Uptake Efficiency based on theoretical Interception Efficiency (IE) for overhead irrigation treatments for azalea and holly in data sets 1, 2, and 3. Table includes N application both CRF and soluble, container spacing, Theoretical or Empirical (data set 3 only) IE, soluble N intercepted by each container, Total N captured per plant after IE recalculation, plant N uptake and plant N uptake efficiency.

Data Set	**Treatment**	**Total N Applied ($NH_4 + NO_3$)**		**Container Spacing**	**IE**	**Soluble N Intercepted**	**Total N Captured**	**Plant N Uptake**	**Plant N Uptake Efficiency**
		CRF	**Soluble (g)**	**Containers Per m^2**	**(%)**	**(g)**	**(g)**	**(g)**	**(%)**
1	**Azalea – Overhead**	9.82	2.44	16.7	39.8	0.95	10.77	2.02	**18.72**
	Holly – Overhead	11.06	2.33	16.7	39.8	0.90	11.96	2.89	**24.17**
2	**Azalea – Overhead**	6.12	27.43	8.4	19.4	5.32	11.44	4.05	**35.43**
	Holly – Overhead	6.12	27.05	8.4	19.4	5.25	11.37	2.60	**22.83**
3	**Azalea – Overhead**	0	94.47	5.2	49.5	46.76	46.76	8.80	**18.81**
	Holly – Overhead	0	106.60	5.2	63.5	67.69	67.69	10.78	**15.92**
	Azalea – Overhead/TDR	0	48.86	5.2	49.5	24.18	24.18	5.05	**20.89**
	Holly – Overhead/TDR	0	58.22	5.2	63.5	36.97	36.97	7.03	**19.03**

plants were space for canopy growth, and the theoretical efficiency was therefore reduced to 19.4%.

In data set 3 we were able to empirically calculate IE by TDR schedule overhead treatment (see Chapter 2.1), which ensured that the irrigation cycle stopped when the substrate was at water holding capacity. This meant that the plants had minimal to zero leaching, except during rainfall events. Interception efficiency calculated during no-rain periods indicated that IE averaged 63.5% for holly and 49.5% for azalea. Total N captured (Table 4-5) is the sum of both CRF applied N and the fraction of soluble applied N captured by the plant (interception efficiency). Nitrogen uptake efficiencies (Table 4-5) increase over those calculated before utilizing IE (Tables 4-2, 3 and 4) because only a fraction of the soluble N applied was captured by the plant.

4.3.7 Seasonal Tissue Nitrogen Oscillation

Figure 4-7 shows seasonal oscillation of N as a fraction of total N partitioned between the roots, second-degree (2^o) branches, and leaves in azalea under drip irrigation. These data indicate that azalea var. ‘Karen’ is a semi-deciduous species under Maryland conditions. During late fall and winter, a portion of azalea shoot N was reallocated to roots for storage and for root growth. A large proportion of the leaves senesced and dropped during the winter. A winter harvest in azalea showed that those leaves that were retained decreased their N concentrations to 80% of the previous growing season levels, while root N increased by 37% above that of previous growing season levels.

Figure 4-8 shows seasonal oscillation of N as a fraction of total N partitioned between the roots, 2^o degree branches, and leaves in holly under drip irrigation. Average

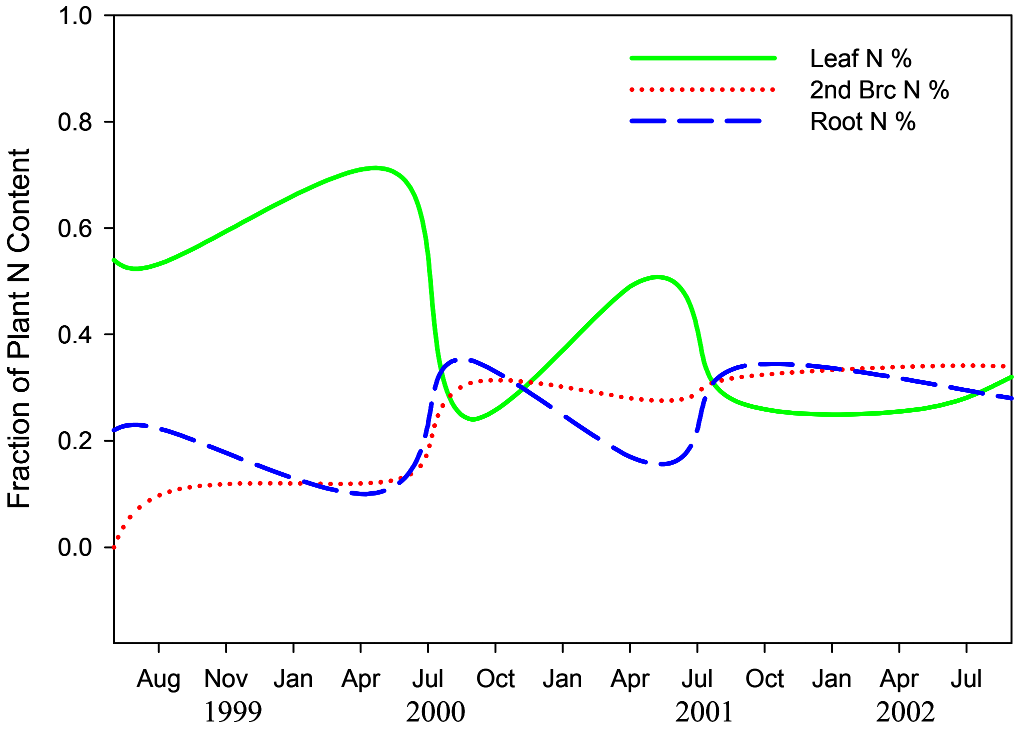


Figure 4-7. Oscillation of the fraction of N content allocation in Azalea/Drip through all data sets.

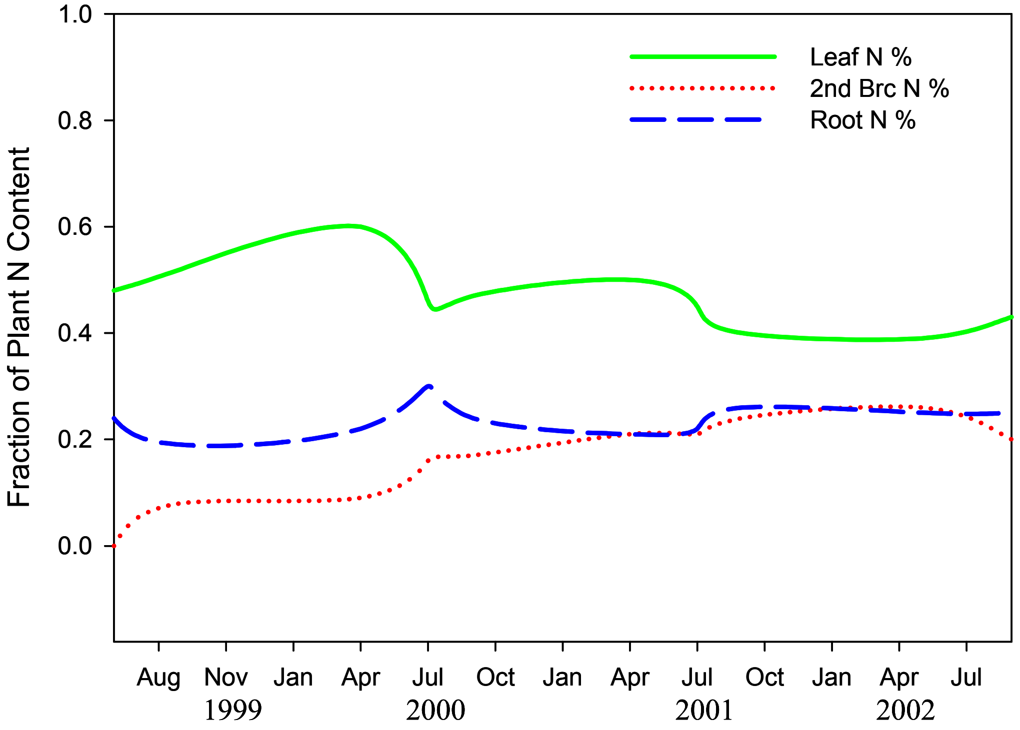


Figure 4-8. Oscillation of the fraction of N content allocation in Holly/Drip through all data sets.

late fall leaf N concentrations dropped to 85% previous growing season concentrations, but unlike azalea, average holly root tissue concentrations did not change before winter.

4.4 Discussion

Dry mass and N uptake in azalea and holly varied in response to irrigation treatment throughout the study. In the first data set, azalea and holly did not show differences in growth between irrigation methods. In data set 2, azalea accumulated significantly more dry mass and N with overhead irrigation compared to drip irrigation, while holly showed no differences between irrigation treatments. Data set 3 showed that in general, cyclic overhead seemed to significantly increase dry mass and plant N uptake, albeit at the cost of large runoff losses and poor plant uptake efficiencies. This is due to greater water and N applications over time.

In our study, cyclical overhead irrigation was the most inefficient method for delivering irrigation water and soluble N, and those inefficiencies increased when plants were spaced in later years. In some, but not all instances, plant species responded to cyclical overhead irrigation with increased growth and N uptake compared to drip irrigation. This may have been due to transient water limitations, when drip could not supply enough water or when water channeled through, or did not properly wet the substrate. Overhead irrigation applied water at higher rates for longer periods to fully wet the container compared to drip, but with greater runoff volumes. Since all these data sets had at least some proportion of the total N as soluble fertigation, overhead irrigation significantly increased the N runoff potential. At this time there are no data to suggest that overhead irrigation increases the proportion of N leaching from the CRF fraction, although this could be speculated upon depending on the overall leaching fraction. Drip irrigation applied about 4 times less N and resulted in about 4 times less potential runoff, on average. We theorize that under drip irrigation, N runoff could also have been reduced by denitrification and other forms of N loss, since the residence time of N in the root zone was greater, which may have resulted in potentially less N runoff.

The use of TDR in data set 3 had large beneficial effects by reducing N runoff under soluble fertigation. These results show that TDR schedule overhead irrigation reduced N applications by half that of cyclical overhead irrigation treatments. The N runoff by the end of the data set was also reduced by more than half that of standard cyclic overhead irrigation. This is especially significant as cyclic irrigation is presently considered the best management practice for water and nutrient conservation by the industry. Further more, I showed that plant N uptake efficiencies were not different between TDR and cyclic timed overhead irrigation. While TDR had no effect on uptake efficiencies compared to cyclic irrigation, N applications with TDR-controlled timed overhead seemed to track seasonal plant requirements more efficiently than cyclical overhead during the late summer and fall season. This was evident from Fig. 4-6, as the potential N runoff accumulation slowed during those seasons, perhaps as the plant demand for frequent irrigation slowed.

Nitrogen uptake efficiencies for all data sets were surprisingly low; nevertheless, they are supported with other recent N uptake efficiency studies cited in the ornamental and agronomic literature (Ivey et al., 2002; Yeager, 1996; Struve 1995). I found a general trend within each data set that the greater the rate of N applied on plants, the less efficient the plants were in taking up N. Total N recoveries in data set 3 were substantially higher, compared to the previous two data sets, indicating that N applications were well in excess of plant N requirements. It is possible that continuous fertigation saturated microbial and other loss mechanisms, which had possibly reduced total N recoveries in the two previous data sets.

Potential N runoff was significantly affected by interception efficiency. Since containers and plants occupy only a portion of the area under overhead irrigation, a fraction of the water and soluble fertilizer applied is captured by the plant. In data set 2, plants were spaced apart to accommodate growth. Soluble N was being applied to half the plants compared to data set 1, therefore doubling the theoretical *per plant* N application and increasing the potential N runoff. To illustrate this point, in data set 1, when containers were side-by-side, approximately 20% of the recovered N from overhead irrigation came from runoff. In data set 2, where plant density was half that of data set 1, between 60 and 76% of the recovered N from azalea and holly overhead was from non-intercepted runoff.

Until now, I have discussed N application and uptake efficiency without considering interception efficiency as discussed in Chapter 3. The question should therefore be asked – why are the data not normalized for interception efficiency between overhead and drip irrigation treatments, since plants only capture a portion of the N applied by overhead irrigation? In answer to this, the theoretical IE in data set 1 was calculated to be to about 38.8% for overhead irrigation. During that data set, uptake efficiencies were 16.6% and 21.8% in azalea and holly under overhead irrigation. After spacing plants in data set 2, theoretical IE dropped to 19.4% and uptake efficiencies decreased to 12.1% and 7.8% in azalea and holly. In data set 3, empirical IE were calculated using TDR as described earlier. If properly calibrated, TDR should stop irrigation when the substrate is just below container capacity (-1 KPa matric potential). So assuming water was evenly distributed over the container surface by overhead irrigation, minimal leaching should have occurred. Thus, from these data, the empirical interception efficiencies of TDR-timed overhead irrigation were calculated to be 63% for holly and 49.5% for azalea (Chapter 3), compared to the theoretical 27% interception efficiency. So, interestingly, although interception efficiencies increased between data sets 2 and 3, uptake efficiencies did not. Anecdotal evidence suggested that canopy size and leaf shape greatly increased the interception efficiency over the theoretical value for data set 3.

The data in Table 4-4 show that plant N uptake efficiency increased after recalculation, since a greater fraction of the N applied was actually intercepted. This was especially true for data set 3, given the total amount of N applied over time. So these data show the importance if accurately quantifying IE, since interception of nutrients with overhead is greatly influenced by these dynamics.

While the three data sets in this study had unequal N fertilization regimes, the cumulative pattern of N runoff presented in figures 4-5 and 4-6 and Appendix B figures B4-9 and 10 show seasonal similarities. The rate of N runoff/leachate accumulation seemed to coincide more with season than with soluble fertilizer regime. The data show important long-term seasonal growth and uptake patterns, which to my knowledge have not been published before in the ornamental literature. Surprisingly, the rate of late summer and fall dry mass and N accumulation was as great or higher than that for spring N uptake and growth, in both species. Interestingly, soluble fertilization concentrations applied in the fall season were less than spring concentrations (according to standard industry practice), and yet fall growth and N uptake appeared not to be compromised, compared to spring uptake and growth rates. Thus, with lower rates and similar growth and uptake, the cumulative loss rate of N runoff/leachates for all data sets was lower in the fall than in spring and summer. Therefore, in considering seasonal runoff accumulation, fall growth therefore appeared to be more nutrient efficient. It is plausible that potential N runoff was minimized in the fall by better matching plant N requirements during fall growth periods.

Applying nutrients at critical growth periods can lesson potential runoff. Early research showed that root growth favors cooler temperatures (Good and Tukey, 1969; Meyer and Tukey, 1967). Recent work has had similar results in Freeman maple (*Acer x freemanii*) (Rose and Biernacka, 1999), 'Calocarpa' crabapple [*Malus x zumi* (Rehd.) 'Calocarpa'] (Rose et al., 1999) and in *Cotoneaster dammerii* 'Skogholm' (Bilderback et al., 1997), and during late summer/fall nutrient uptake is more efficient than in warmer months (Rose and Biernacka, 1999). In all data sets, N runoff accumulation slowed during the spring as well as late-summer/fall.

Seasonal reallocation of N in tissues was active in all azalea treatments (Fig. 4-7). Most striking was the switch in N status of leaf and root tissue during certain growing periods. Figure 4-7 illustrates this seasonal oscillation of tissue N allocation in azalea under drip irrigation. Of particular interest was the difference in leaf drop between azalea under drip and overhead irrigation. Azalea under drip irrigation exhibited leaf senescence earlier than azalea under overhead irrigation. Data captured by an intermediate harvest of azalea in February 2001however, showed that azalea under overhead irrigation eventually lost similar amounts of leaf tissue (data not shown).

Evergreen seasonal N allocation in holly (Figure 4-8) was very different to that of azalea. Average late fall leaf N concentrations dropped to 85% of previous growing season concentrations, but unlike azalea, average holly root tissue concentrations did not change before winter. As an evergreen species, holly tends to conserve nitrogen by retaining leaves within the canopy and keeping translocation to a minimum.

Pruning one to three times a year was found to remove an average of 25% of the N acquired by azalea over the 40-month study. The leaf and secondary branch tissue in azalea can hold up to 80% of the total plant N content. In holly, those tissues may hold an average of 60% of the total plant N. The differences in N loss from pruning between azalea and holly may be due to differences of canopy architecture between the species. Unlike holly where leaves are distributed relatively evenly throughout the canopy, azalea leaves are concentrated (in a shell) around the outside perimeter of the canopy. Pruning thus, removed more leaves from azalea than holly. Pruning affects nutrient loss on a species basis, possibly requiring different management strategies for the various species grown in nurseries. Pruning is typically done during the growing season, when N is at its highest concentration in upper shoots. This, in many respects, is necessary because pruning during the dormant season can remove flower buds. Many plants are held for two or three years in nurseries to attain marketable size. Winter pruning up to one year before the spring sale may be advantageous in retaining N. While growth regulators are available, their cost is probably considered uneconomic by most growers. However, given the loss in plant growth, the loss in net productivity and labor involved in pruning, it is likely that the cost of growth regulators on a per plant basis would be a minimal investment, especially given the potential gain in N efficiency. In our studies, we noted that plants under cyclical overhead irrigation were taller and more vegetative compared to plants under TDR overhead, drip and cyclical drip irrigation. This is likely due to greater succulence, due to large amounts of water and nutrients used in this treatment. Some research (Cameron et al., 1999) suggests that water can be used as a growth regulator and our anecdotal evidence from the last data set supports this contention.

Methods of fertilization come into question as nurseries switch over to CRF sources and away from soluble applications. A recent survey of containerized nurseries in the southern United States, 100% used CRF as their primary source of N (Fain et al., 2000; Ivey et al., 2002). Nevertheless, many nurseries in the US still use overhead fertilization. In our studies, the principle source of N was in CRF for data set 1. In data set 2, CRF and soluble were applied in similar rates to containers (taking into account interception efficiency for overhead). Soluble fertilizer completely replaced CRF as the sole source of N in data set 3, as we chose to illustrate the worst-case nutrient management scenario.

Interestingly, Ivey et al. (2002) found no greater plant N uptake efficiencies with CRF fertilizer sources than what we have documented with a soluble/CRF mix or just a soluble source. In some cases as shown in data set 3, soluble fertilizer, used together with suitable technologies such as TDR and microirrigation, can improve N uptake efficiencies, compared to a soluble/CRF mix. On the other hand, soluble fertilizer applications with poor irrigation management can lead to high potential N runoff and low N uptake efficiencies, as typified by the cyclic overhead irrigation treatment in data set 3.

The use of CRF as a primary N source could be of potential benefit to the environment, but this is solely dependent upon sound irrigation management, e.g., restricting leaching fraction, using application rates suited to the plant species and growth rate, and by using appropriate nutrient ratios within the CRF prill (i.e. using custom blends).

4.5 Conclusions

The main objectives of this research were to improve our understanding of N dynamics in a containerized nursery system by integrating N application, leaching, and uptake data into a single study. This is the first study in the ornamental literature that has simultaneously documented all these data. The data offers important insights into improving cultural management practices towards an ultimate goal of improving N uptake efficiency and decreasing potential N losses, without adversely affecting plant growth.

Although our results showed that drip irrigation is more efficient in delivering nutrients to the root zone, thereby reducing N runoff and increasing uptake efficiency, overhead irrigation however remains the least problematic and most economic method of irrigation. Increased growth and N uptake with overhead irrigation was evident in some instances, but the question should be asked whether small increases in growth are worth the environmental cost in runoff and water use, especially when these small increases in productivity may be then pruned off for aesthetic/marketing reasons. Given these issues, cultural practices must change in container nurseries, which will reduce the impact of overhead irrigation on the environment.

Nitrogen application was most efficient in drip systems, but management issues make this an impractical irrigation method for most operations. While the use of TDR in overhead irrigation did not improve uptake efficiency compared to cyclical overhead, TDR did decrease overhead application and runoff by half for both species.

In summary, efficient cultural practices were shown to increase plant N uptake efficiency. Nitrogen uptake efficiency is a function of interception efficiency, as indicated by drip irrigated plants and by recalculating overhead irrigation efficiencies based on total capture. Increasing interception efficiency reduces the potential runoff of N and increases overall N uptake efficiency. Additionally, seasonal timing of fertilizers is recommended to increase N uptake efficiency, based on plant growth rate. Evidence from reduced runoff and fall growth rates suggests that fall fertilization of azalea and holly was equally efficient as spring and summer fertilization. Pruning removes a large amount of potential growth from plants and can greatly increase the time to sale, which would have negative economic consequences. The use of growth regulators or reduction in water application may ultimately reduce the production time for many woody plant species.

Chapter Five

Field Study – Long Term Phosphorus Dynamics

5.1 Introduction

Nearly 75% of the P loading into the Chesapeake Bay watershed arrives by non-point sources, the majority being of agricultural origin (Taylor and Pionke, 2000). While major reductions in P loading have been accomplished in the past decade, further progress has been slow and P continues to be a nutrient that reduces water quality in the Chesapeake Bay. Unlike N, which can be both mineralized from the diatomic state and converted back to the inert atmospheric form (via denitrification), P is conserved in most natural environments. Phosphorus is especially troublesome in fresh water and in some cases, estuarine ecosystems like the Chesapeake Bay where seasonal cycles switch nutrient limitations between N and P.

Presently, P fertilization in many nursery and greenhouse operations likely is in excess of plant requirements. The probability of P over-application is apparent from nutrient rates found in brand name soluble and controlled release fertilizers containing N/P ratios that far exceed most plant requirements. Marconi and Nelson (1984) cited Beckwith (1964) and Nishimoto et al, (1975), who determined the critical P soil solution to be 6.5µM (0.2 ppm) for plants. Lynch et al. (1991) suggested that P substrate solution can be as low as 3 µM (0.1 ppm), yet still satisfy P requirements of Phaseolus (bean). Achieving constant P solution levels at these concentrations in organic substrates using conventional fertilizer sources is most likely impossible. Organic potting substrates have little PO_4^{-3} (anion) retention qualities, especially those that are pine bark or peat based (Marconi and Nelson, 1984). Excess and non-utilized soluble P (orthophosphate) tends to leach out of the container when plants are irrigated to excess. In addition, the release of P from controlled released fertilizers (CRF) is dependent upon temperature and/or moisture content, and release may be not be synchronous with plant requirements. On the other hand, buffered P fertilizers (e.g. P-charged alumina) slowly release P based on concentration gradients (Lin et al., 1996).

Like N, P fertilization in container nurseries tends to be far greater per hectare than typical P rates used for agronomic crops or in field nursery production. While applied P rates are dependent upon crop removal and residual soil P, corn typically requires approximately about 33 kg P ha^{-1} yr^{-1}. A typical container nursery can apply an average of 100 kg ha^{-1} yr^{-}1 P, assuming 100,000 11.7 l (3 gal) containers per hectare, with moderate industry (Osmocote CRF) fertilization rates of 1 g P per plant.

Until now, there have been no integrated studies of P fertilization in container nursery systems, and few P utilization studies published for ornamental species. Consequently, no definitive knowledge base has been developed that follows the dynamics of P fertilization, from application to uptake efficiency and potential runoff. Some unanswered questions are --- do current application rates pose a risk for P leaching and runoff, and if so, how do cultural and irrigation practices affect P utilization efficiency in ornamental plants and what changes can be made to those practices to make P fertilization more efficient? In concert with the N dynamics (Chapter 4), the following data illustrate the dynamics of P within a container nursery system.

5.2 Materials and Methods

This three-year study was initiated in 1999 to gather long-term data on P movement in a container-nursery production setting. Chapter 2.1 and Chapter 4.2 provide pertinent details for the general materials and methods used n this study. Data were normalized for differences in plant growth and leaching volumes over time, and are based on absolute values of P, similar to the N data (Chapter 4). To summarize, P concentrations (mg per liter or %) were converted to actual content values (in mg) by multiplying either the volume or dry mass data (in liters or in grams), respectively. All data were normalized before statistical analysis.

Phosphorus was applied as CRF and as soluble ammonium polyphosphate (APP) via irrigation in all data sets except data set 3, where only soluble APP was applied. Phosphorus fertilization began with an initial incorporation of Osmocote 19-5-9 which translated into 0.42 g P per azalea plant and 0.57 g P per holly plant (see Chapter 2.1.6). Additional P in the form of CRF was applied to each plant as winter top-dress during data sets 1 and 2. This amounted to between 0.78 and 1.00 g P since various CRF formulations were applied as part of a winter CRF study (data not shown). Throughout data sets 1 and 2, supplemental soluble P was applied as shown in Table 5-1, 2. During the third data set, soluble P was the primary P source as shown in Table 5-3. Additional information on soluble fertilization rates is in Appendix A Table 2A-1.

Ammonium polyphosphate was in liquid form at a N:P_2O_5 ratio of 11:34.. Ammonium polyphosphate is an agricultural grade fertilizer, produced by reacting ‘wet process’ superphosphoric acid (super acid) and anhydrous ammonia under controlled conditions. The process is known as the TVA-tee reactor process. When the ammonia, a strong base, mixes with the super acid the resulting exothermic reaction produces a large amount of heat. This heat is necessary to produce the high “poly” content and ensures good product shelf life characteristics. The result is long chains of ammonium phosphate, which contain 70% polyphosphate and 30% orthophosphate. (Agrium Industries, Calgary AB, Canada). This means that all phosphorus in APP is not readily available (orthophosphate) upon application. Phosphorus chains dissociate in time, depending on pH and other soil conditions. While the target concentration for soluble applied P was 6 ppm as prescribed by our consulting nursery, fertigation grab samples did not contain more than 2.5 ppm orthophosphate (OP) during the first and second data sets, and contained no more than 4.5 ppm OP during the last data set.

At the onset of the field study, substrates were of different quality between holly and azalea (e.g. hardwood vs. pine bark). Additionally, the holly substrate was amended with a higher N and P rate than the azalea, as described in Table 2.1. All response variables were therefore analyzed by species and no comparisons between azalea and holly are made. Statistical analysis for data set 1 was one-way ANOVA. Irrigation method was the treatment with two levels: drip and overhead. Response variables included P uptake, P pruned, P runoff/leachate, P recovery and P uptake efficiency. Data set 2 was analyzed similarly, but block was added as a random variable. In data set 3, a two-way ANOVA was performed adding scheduling treatment with two levels, cyclic and TDR, making this a factorial design. Blocks remained as a random variable. Response variables were same as data set 1 and 2. If treatment interaction was not significant, main effects were reported and discussed. However, if treatment interaction was significant, simple effects were reported and discussed. Pairwise comparisons were done under LSD criterion at $p<0.05$. Assumption of variance homogeneity was carried out by Corr Spearman procedure in SAS systems (SAS Institute, Cary, NC).

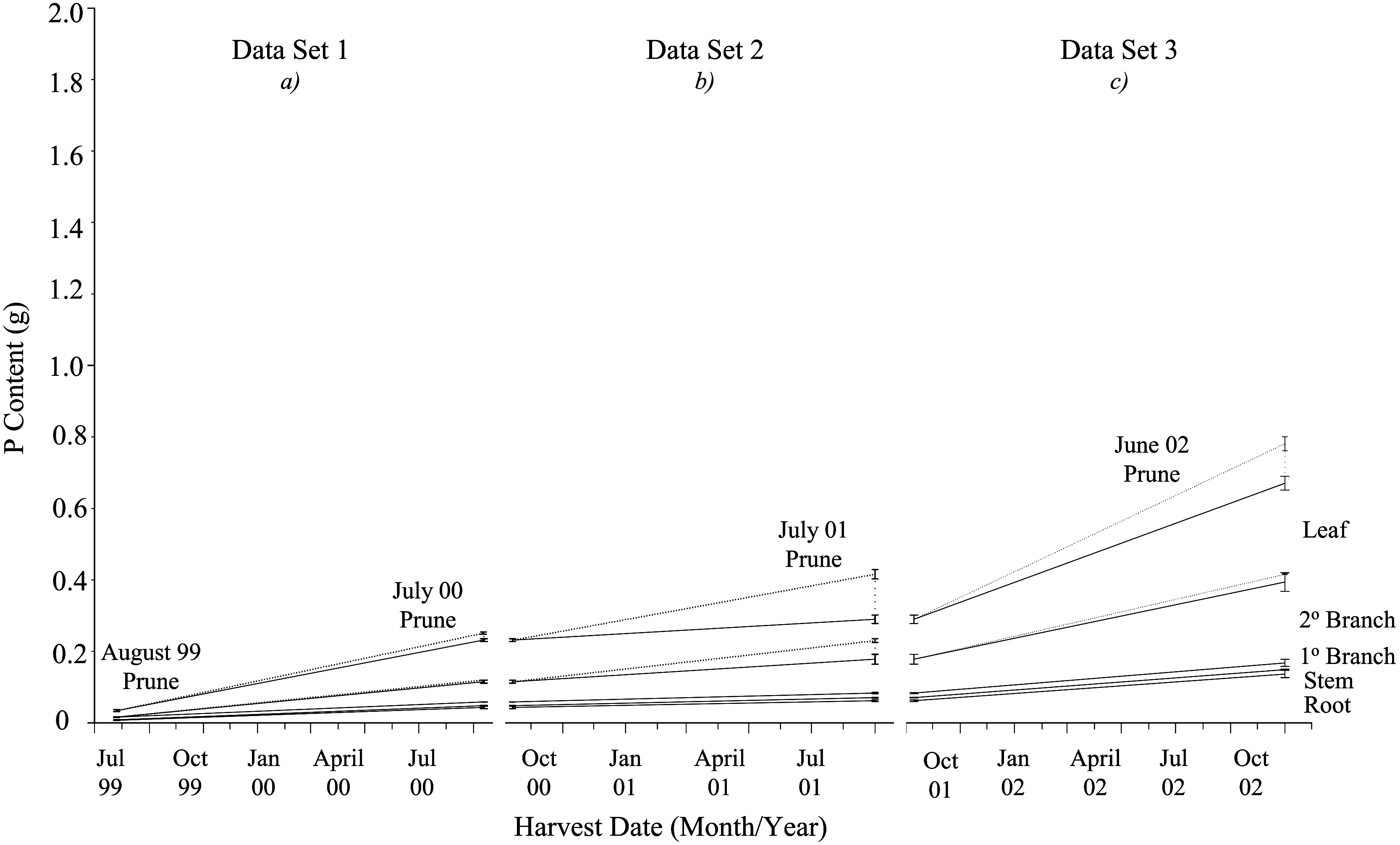
In analyzing P uptake by ANOVA, an assumption, in addition to the usual ANOVA assumptions was made. When analyzing the difference between pre and post, the assumption is that the relationship between pre and post is linear, with a slope of one. An ANCOVA, in which post data would be treated as the response and pre-data would be the covariate would have been the most appropriate method for analysis of such data.

5.3 Results

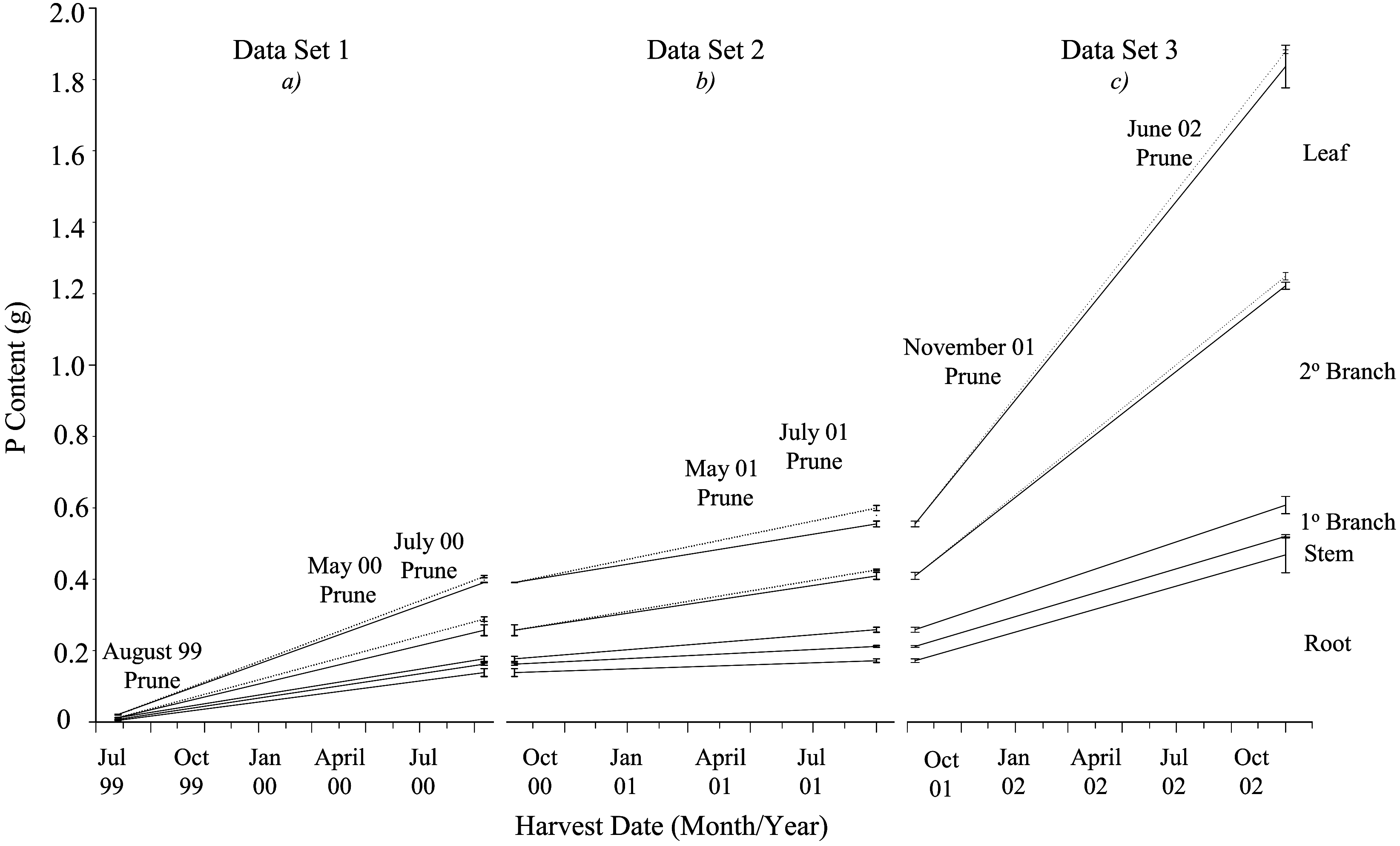
5.3.1 Phosphorus Partitioning and Uptake

Total plant P uptake represents the average total amount of P taken up by each treatment combination during each data set and includes the P pruned from plants during each data set. Figures 5-1 and 5-2, a, b, and c, show average P content and plant tissue P partitioning for azalea under cyclic drip irrigation and holly under TDR overhead irrigation as examples of the treatment dynamics. Additional P partitioning data for other treatment combinations are given in Appendix Figures B5-1 through B5-6 a, b, and c). As previously shown with N, P is predominantly found in leaf, secondary branch and root tissues of both species. Content patterns are similar for each species, although in most cases, plants under overhead irrigation averaged higher content values. Holly had a higher P content in all tissues, compared to azalea.

Table 5-1, 2 and 3, show the P budgets on per plant basis for data sets 1, 2 and 3 respectively. Phosphorus uptake was marginally greater in azalea under overhead irrigation than under drip irrigation ($P<0.07$), but was not different in holly ($P>0.24$)



Figures 5-1 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of azalea plants under drip irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures 5-2 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of holly plants under overhead irrigation with cyclic scheduling for data sets 1 and 2 and TDR scheduling for data set 3. Area under each line represents tissue P content in grams. Dotted lines indicate P taken off from pruning. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

Table 5-1. Phosphorus budget for presented on a per plant basis. Phosphorus application, plant P uptake, P remaining in substrate at end of data set, cumulative P from runoff/leachates, percent P recovered and plant P uptake efficiency for azalea and holly plants at a spacing of 16.7 plants $\bullet$ m^{-2}, irrigated with drip and overhead irrigation systems from August, 1999 to September, 2000, data set 1. Standard error values in parenthesis, means based on n=2. P-values shown for effects of irrigation on response variable.

Treatment	**Total P Applied (PO_4-P)**		**Plant P Uptake**	**P Pruned**	**Substrate P (PO_4-P)**	**Runoff/leachate (PO_4-P)**	**P Recovered (PO_4-P)**	**Plant P Uptake Efficiency**
	CRF (mg)	**Soluble (mg)**	**(mg)**	**(mg)**	**(mg)**	**(mg)**	**(%)**	**(%)**
Azalea – Drip	1380	28	270 (±12)	73 (± 3)	15 (± 0.7)	59 (± 11)	24.9 (± 1.7)	**19.1** (± 0.9)
Azalea – Overhead	1230	74	330 (±11)	99 (± 20)	4 (± 0.3)	89 (± 9)	35.6 (± 8.0)	**26.1** (± 5.9)
P	-	-	< 0.07	> 0.32	-	> 0.16	> 0.31	> 0.32
Holly – Drip	1570	28	390 (±15)	62 (± 4)	5 (± 0.8)	29 (± 2)	26.8 (± 0.5)	**24.2** (± 0.3)
Holly – Overhead	1350	73	420 (±10)	48 (±10)	3 (± 2.3)	89 (± 27)	38.8 (± 8.3)	**29.9** (± 5.1)
P	-	-	> 0.24	> 0.29	-	> 0.15	> 0.28	> 0.34

Table 5-2. Phosphorus budget presented on a per plant basis. Phosphorus application, plant P uptake, P remaining in substrate at end of data set, cumulative P from runoff/leachates, percent P recovered and plant P uptake efficiency for azalea and holly plant sat a spacing of 8.4 plants • m^{-2}, irrigated with drip and overhead irrigation systems from September, 2000 to September, 2001 (data set 2). Standard error values in parenthesis, means based on n=4. P-Values shown for effects of irrigation on response variable.

Treatment	**Total P Applied (PO_4-P)**		**Plant P Uptake**	**P Pruned**	**Substrate P (PO_4-P)**	**Runoff/leachate (PO_4-P)**	**P Recovered (PO_4-P)**	**Plant P Uptake Efficiency**
	CRF (mg)	**Soluble (mg)**	**(mg)**	**(mg)**	**(mg)**	**(mg)**	**(%)**	**(%)**
Azalea – Drip	960	190	240 (± 43)	178 (± 0.017)	69 (± 8)	100 (± 11)	35.1 (± 4.1)	**20.5** (± 4.0)
Azalea – Overhead	820	660	320 (± 32)	251 (± 0.014)	61 (± 16)	220 (± 30)	41.2 (± 1.7)	**21.9** (± 1.8)
P	-	-	> 0.08	< 0.02	-	< 0.01	> 0.12	> 0.71
Holly – Drip	1000	190	300 (± 38)	90 (± 8)	16 (± 4)	110 (± 21)	36.0 (± 2.3)	**25.2** (± 2.5)
Holly – Overhead	780	680	250(± 39)	61 (±15)	10 (± 5)	270 (± 31)	37.3 (± 4.3)	**17.6** (± 3.2)
P	-	-	> 0.38	> 0.10	-	< 0.01	> 0.79	> 0.12

Table 5-3. Phosphorus budget presented on a per plant basis. P application, plant P uptake, P remaining in substrate at end of data set, cumulative P from runoff/leachates, percent P recovered and plant P uptake efficiency for azalea and holly plants at a spacing of 5.2 plants · m^{-2},irrigated with drip and overhead irrigation systems with TDR and cyclic scheduling from September, 2001 to November, 2002 (data set 3). Standard error values in parenthesis, means based on n=2. P-values shown for main effects and interactive effects of irrigation and scheduling on response variable. *Log10 transformed.

Treatment	**Total P Applied (PO_4-P)**		**Plant P Uptake**	**P Pruned**	**Substrate P (PO_4-P)**	**Runoff/leachate (PO_4-P)**	**P Recovered (PO_4-P)**	**Plant P Uptake Efficiency**
	CRF	**Soluble (mg)**	**(mg)**	**(mg)**	**(mg)**	**(mg)**	**(%)**	**(%)**
Azalea – Drip	0	1450	500 (± 40)	132 (± 21)	60 (± 11)	140 (± 11)	48.2 (± 0.6)	**34.6** (± 0.8)
Azalea – Overhead	0	6710	630 (± 190)	156 (± 2)	60 (± 2)	840 (± 10)	22.9 (± 3.8)	**9.5** (± 3.2)
Azalea – Drip/TDR	0	1220	360 (± 30)	138 (± 9)	80 (± 6)	220 (± 37)	53.4 (± 4.9)	**30.5** (± 5.7)
Azalea – Overhead/TDR	0	3230	340 (± 20)	136 (± 6)	70 (± 20)	440 (± 1)	26.1 (± 1.4)	**10.5** (± 0.1)
P: irrig.	-	-	> 0.63	> 0.26	-	< 0.01	< 0.01	< 0.01
P: schedule	-	-	> 0.12	> 0.43	-	< 0.01	> 0.24	> 0.57
P: irrig. x schedule	-	-	> 0.49	> 0.20	-	< 0.01	> 0.74	> 0.39
Holly – Drip	0	1720	790 (± 220)	47 (± 12)	80 (± 12)	230 (± 40)	64.3(± 17.9)	**46.5** (± 15.2)
Holly – Overhead	0	7710	1390 (± 130)	68 (± 15)	70 (± 6)	990 (± 152)	32.0 (± 1.4)	**18.3** (± 1.3)
Holly – Drip/TDR	0	1330	590 (± 110)	50 (± 14)	90 (± 8)	140 (± 12)	62.8 (± 14.1)	**45.5** (± 13.6)
Holly – Overhead/TDR	0	3640	610 (± 20)	68 (± 6)	80 (± 27)	450 (± 26)	32.4 (± 5.9)	**17.3** (± 3.0)
P: irrig.	-	-	> 0.10	> 0.21	-	< 0.01	< 0.01*	< 0.01*
P: schedule	-	-	< 0.04	> 0.90	-	< 0.01	> 0.94*	> 0.77*
P: irrig. x schedule	-	-	> 0.12	> 0.87	-	< 0.07	> 0.98*	> 0.83*

regardless of irrigation method in data set 1. In data set 2, P uptake was not greater in azalea (P>0.08) or holly (P>0.38) regardless of irrigation methods.

In data set 3, there were no main effect treatment differences in P uptake between irrigation methods (P>0.12) or irrigation scheduling (P>0.49) for azalea and hence, no treatment interaction. Similar effects were seen for holly, i.e ., there was no treatment interaction between irrigation method and scheduling for P uptake in holly (P>0.12) and no effects of irrigation method (P>0.10). However, holly showed differences in P uptake between scheduling methods (P<0.04). Pairwise comparisons showed holly under cyclic overhead irrigation having greater P uptake than holly under TDR scheduled drip (P<0.04) and overhead (P<0.03) but not holly under cyclic scheduled drip.

Dotted lines on Figs. 5-1 and 2 a, b, and c show P pruned from plants on pruning dates, but do not estimate potential P content at harvests. There were no significant differences between irrigation treatments on the amount of P pruned from either azalea (P>0.32), or holly (P>0.29) in the first data set (Table 5-1). In the second data set (Table 5-2), more P was pruned from azalea under overhead than drip irrigation (P<0.02) but there was no difference in P pruned between irrigation methods for holly (P>0.10). In the third data set (Table 5-3), there were no main effect differences in P pruned from azalea between irrigation method (P>0.25), or irrigation scheduling (P>0.43). There were also no main effect differences in P pruned from holly between irrigation method (P>0.21), or irrigation scheduling (P>0.90). During the three data sets, approximately 40% of the P taken up by azalea under either irrigation method was pruned off. The amount of P pruned from holly plants was between 9 and 12% of total P uptake.

5.3.2 Uptake Efficiency

Phosphorus uptake efficiencies in data set 1 ranged from 19.5 to 27.7% for azalea (Table 5.1) and were not different between irrigation methods ($P>0.32$). For holly, P uptake efficiencies ranged from 24.6 and 31.5% and were not different between irrigation methods ($P>0.34$).

In data set 2 (Table 5-2), P uptake efficiencies for azalea ranged from 20.5% and 21.9% and were not different between irrigation methods ($P>0.71$). In holly, P uptake efficiencies ranged from 17.6 to 25.2% and were not different between irrigation methods ($P>0.12$).

In data set 3 (Table 5-3), there was no treatment interaction in azalea ($P>0.39$), nor in holly ($P>0.83$: $\log_{10}$ transformed). Differences between P uptake efficiencies were solely due to the main effects of irrigation, for both azalea ($P<0.01$) and holly ($P<0.01$: $\log_{10}$ transformed), i.e., not between cyclic and TDR scheduling. Average P uptake efficiencies were between three and four times greater in azalea and nearly three times greater for holly under drip than under overhead irrigation due to large overhead P applications in this data set. Efficiencies between cyclic and TDR drip were not different with either azalea or holly, since plant P uptake was lower for TDR-irrigated plants of both species. Drip irrigation scheduling controlled by TDR did not appear to have an impact on overall leaching or uptake efficiency compared to cyclical drip irrigation.

5.3.3 Cumulative Runoff/Leachate

Phosphorus runoff results for the various treatment combinations during data sets 1, 2 and 3 are shown in Tables 5-1, 5-2 and 5-3, respectively. Phosphorus runoff/leachate was not significantly different between irrigation methods for either azalea ($P>0.16$) or holly ($P>0.15$) during data set 1 (Table 5-1). In data set 2 (Table 5-2), P runoff/leachate was significantly greater from overhead irrigation than drip irrigation in both azalea ($P<0.01$) and holly ($P<0.01$) (Table 5-2), due to higher soluble applications. In data set 3 (Table 5-3), there was significant interaction between irrigation method and scheduling on P runoff/leachates from azalea ($P<0.01$). Simple treatment effects showed that significant differences existed between all azalea treatments ($P<0.01$), and marginal differences in P runoff/leachate existed between cyclic drip and TDR drip ($P<0.06$). With cyclic scheduling, the P runoff totals from overhead fertigation were over 6 times greater than from cyclic drip. Additionally, TDR significantly decreased average P runoff from azalea under overhead irrigation to half that of cyclic overhead, and marginally reduced P runoff/leachates in drip irrigation compared to cyclic scheduled drip.

In holly, there may have been interaction between treatments ($P<0.07$). Main effect differences in P runoff/leachates were significant in both irrigation method ($P<0.01$) and scheduling ($P<0.03$). Because the interaction was nearly significant, simple effects will be reported. Cyclic overhead irrigation had the greatest average P runoff/leachates from all other treatments ($P<0.018$). Other treatment combinations were not different from each other. Phosphorus runoff/leachate from holly under cyclic drip was 7 times less than from cyclic overhead. Phosphorus runoff/leachate from TDR scheduled overhead was half that of cyclic overhead irrigation.

Figure 5-5 compares the cumulative P runoff/leachate on a *per plant* basis during data set 1 for both azalea and holly under drip and overhead irrigation. Phosphorus runoff/leachate loss was reduced under drip irrigation; and phosphorus runoff/leachate from holly under drip irrigation was half that of azalea under drip irrigation. This pattern was also seen initially under overhead. Loss of P through runoff/leaching for all treatments was slow during the fall, accelerated over the following summer, and began to slow again in the fall. Between 33 and 55% of P leached from all treatments occurred in a limited period between mid-July and mid-August. This pattern was also evident in data set 2 (Appendix B, Figure B5 –7). Interestingly, there was no significant increase in rainfall between July and mid-August of either data set.

Figure 5-6 shows the average cumulative P runoff/leachate on a *per plant* basis during data set 3, for holly under overhead and drip irrigation, with cyclic and TDR scheduling comparisons. As in data set 1, data set 3 has a similar pattern for P accumulation, but as soluble P was constantly applied during the irrigation events, data set 3 had ten times the potential P runoff under overhead irrigation as compared to data set 1. Potential P runoff was minimized and P loss tapered off in the fall of 2001, spring of 2002 and fall of 2002 with all treatments; the notable exception to this was the cyclic overhead treatment, which applied P inefficiently and well in excess of plant requirements.

Time domain reflectometry scheduling halved P runoff from overhead compared to cyclic scheduling (Fig. 5-6). The reduction of irrigation water applications had a direct

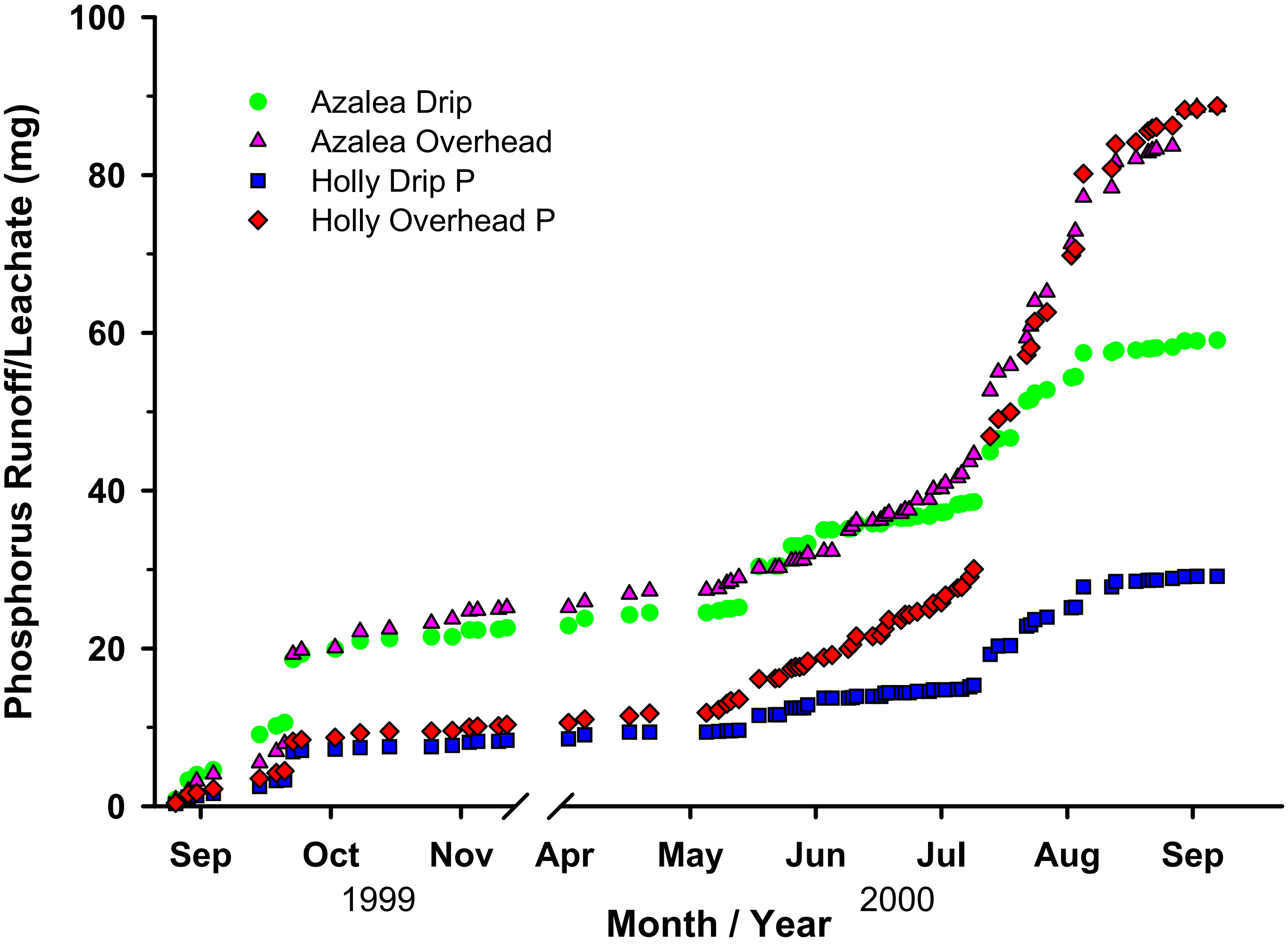


Figure 5-5. Mean cumulative runoff of P from drip and overhead cyclic irrigation on a per plant basis over a fourteen month period between August 1999 and September 2000 (data set 1). One soluble rate was applied at 1.5 mg/l. Averages based on n=2 per treatment.

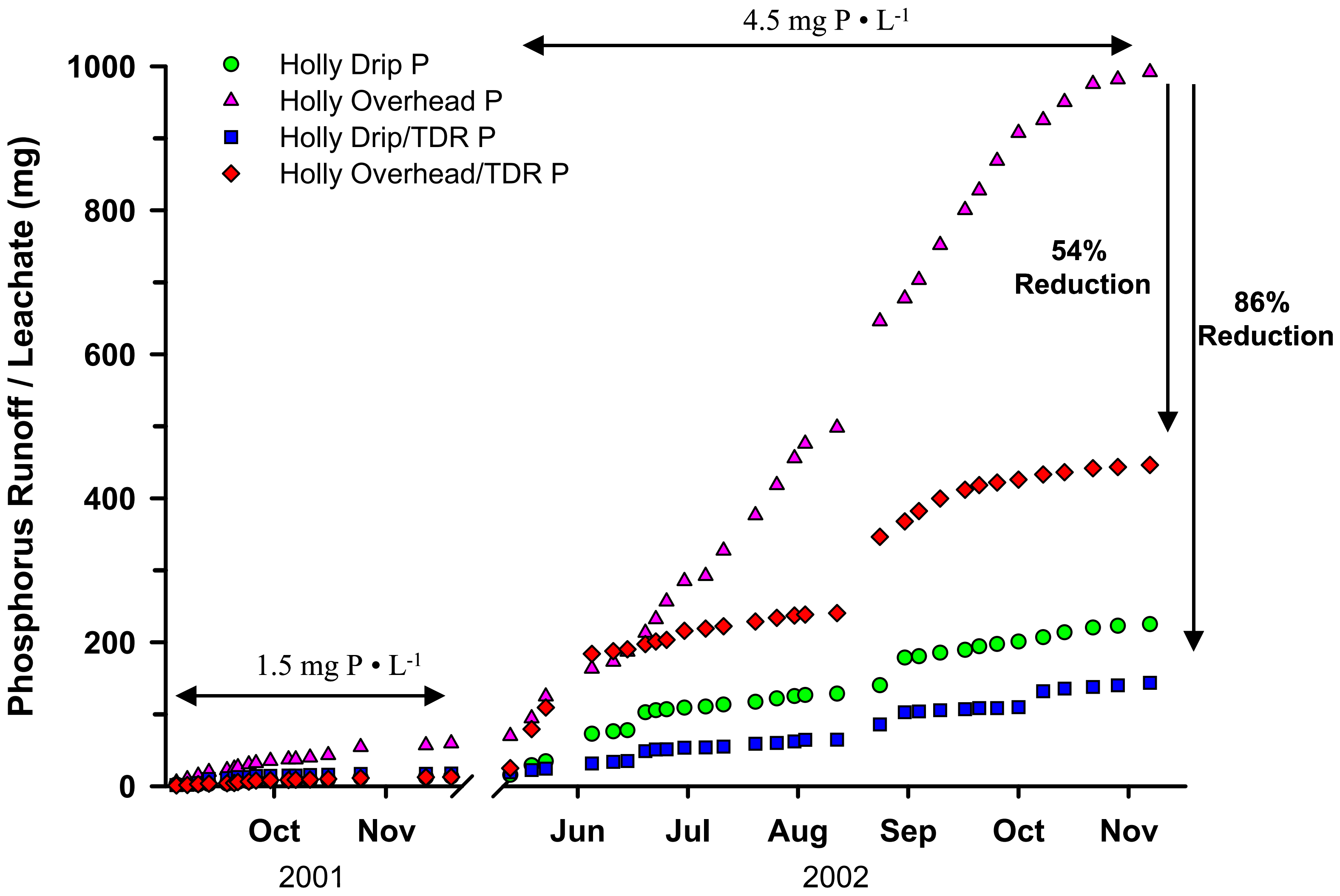


Figure 5-6. Mean cumulative runoff of P from holly under cyclic and TDR controlled drip and overhead irrigation on a per plant basis over a fourteen month period between September 2001 and November 2002, (data set 3). Two different soluble rates were applied as shown. Averages based on n=2 per treatment.

effect on soluble P application and hence, runoff. Cyclical drip irrigation averaged four times less P runoff than cyclical overhead by the end of the data set 3; P runoff under TDR drip irrigation was over seven fold less than cyclical overhead (Fig. 5-6). As with N runoff, irrigation scheduling based on actual plant water requirements reduces the potential P runoff in half even with overhead irrigation.

5.3.4 Phosphorus Budgets – A Summary

Table 5-1 shows the total phosphorus budget for data set 1 on a per plant basis. Phosphorus recoveries were not different between irrigation methods for azalea ($P>0.31$) or holly ($P>0.28$). In azalea, plant uptake accounted for 78% of total P recovered and in holly, uptake accounted for over 81% of recovered P. During the first 14 months (data set 1), pruning removed between 27 and 30% of the P taken up by azaleas and between 11 and 16% of P taken up by hollies. Average recovery of P from substrates after the last harvest of data set 1 was 1% or less than the total P applied to both azalea and holly under either irrigation method. Phosphorus remaining in the substrate accounted for less than 5 % of total P recovered. The average accumulation of P runoff/leachate was no more than 7% of the P applied for any treatment and only accounted for between 7 and 21% of total P recovered.

Table 5-2 shows the total P budget for data set 2 on a per plant basis. Soluble P application in this data set was 6 to 7 times greater than in data set 1. Containers were also spaced at half the density of data set 1. For these reasons, runoff/leachate P totals for overhead irrigation were significantly higher than drip treatments. Phosphorus recoveries were not different between irrigation methods in azalea ($P>0.12$) and in holly ($P>0.79$).

In azalea, plant P uptake averaged between 53 and 58% of the P recovery for both irrigation methods. This was in contrast to holly, where uptake averaged 70% of recovery from drip and 47% of recovery from overhead irrigation. Of the total P taken up during data set 2, an average of 77% was pruned from azalea and 27% pruned from holly. This significant difference in lost P was primarily due differences in canopy structure between the two species, as further discussed below. Recovery of P from substrates after the last harvest was less than 6% of what was applied to azalea, and less than 1.5% of the total P applied to holly. The accumulation of P runoff/leachate for data set 2 accounted for no more than 9% of the P supplied to azalea and holly under drip irrigation. Recovered P runoff/leachate from overhead irrigation accounted for approximately 15% of applied P to azalea and 19% of the P applied to holly. One quarter of the recovered P came from runoff/leachate in both azalea and holly under drip. On the other hand, runoff/leachates accounted for an average of 37% of P recovery for azalea and 51% from holly under overhead.

In data set 3 (Table 5-3), both azalea and holly under TDR-controlled overhead irrigation received half as much P than plants under cyclic controlled treatment due to lower irrigation water applications (see Chapter 3). For drip irrigation, P applications were reduced by 16% for azalea and 23% for holly by using TDR compared to cyclic scheduling. There was no interaction between treatments for P recovery in azalea ($P>0.74$) or holly ($P>0.98$: $\log_{10}$ transformed). The main effect of irrigation method was significant in total P recovered for both azalea and holly as P recovery was significantly greater from drip irrigation than overhead for both azalea ($P<0.01$) and holly ($P<0.01$: $\log_{10}$ transformed). Under drip treatments, between 48 and 53% of the P was accounted for with azalea, and 63 to 64% was accounted for with holly, whereas less than a third of the P applied by overhead irrigation was recovered by either species. Phosphorus uptake accounted for between 63 and 73% of P recovered by plants under drip irrigation. Uptake in azaleas under overhead accounted for only 40% of recovered P, but in holly, uptake accounted for over 50% of recovered P. The P pruned from azaleas accounted for between 19% and 22% of total P recovered from drip treatments and between 10 and 16% of P recovered from overhead irrigation treatments. In contrast, pruning accounted for less than 6% of P recovered from any holly treatment combination. Substrate P accounted for less than 11% of P recovered from either species or treatment at final harvest. A higher percentage of P from runoff/leachate was accounted for from plants under overhead irrigation than drip. For instance, one fifth of the recovered P was found in runoff/leachates of azaleas under cyclic drip compared to 50% recovered from cyclic overhead runoff.

5.4 Discussion

In this study, several P fertilization rates and delivery methods were examined. In data sets 1 and 2, the majority of applied P came from CRF. In data set 3, the sole source of P was soluble and applied via irrigation. In this study, plant P uptake was not significantly influenced by irrigation method. However, holly under cyclic overhead did take up significantly more P than under TDR drip or TDR overhead in the last data set, and this difference was due to scheduling method alone. Since P is required by most plants in minimal concentrations, P applied to both drip and overhead appeared to satisfy plant P requirements. In most cases greater P application increased uptake, but in general, this decreased uptake efficiency and increased loss through runoff.

During this 40 month experiment (all data sets), azalea only accumulated between 0.86 and 1.28 g P and holly only accumulated between 1.28 and 2.08 g P, when up to a total of 9.8 g P was applied, depending on irrigation and scheduling method. Overall P uptake efficiencies ranged from 9.5 to 46.5% for these plants. Phosphorus uptake efficiency appeared to be influenced by the combination of fertilization and irrigation method. When the majority of the P was applied in the form of CRF (data sets 1 and 2), average uptake efficiencies were not significantly different between overhead and drip irrigation. On the other hand, P uptake efficiency was improved by the use of drip irrigation only when the sole source of P was soluble as in data set 3. Time domain reflectometry did not improve P uptake efficiency in either drip or overhead irrigation, as overall P supply was in excess of all plant requirements.

Phosphorus uptake efficiency was also affected by interception efficiency from overhead irrigation. Average P uptake efficiencies (comparing data sets 1 and 2) were decreased using overhead irrigation, especially with holly. Interception efficiency also affected P runoff; since the spacing density decreased two-fold in data set 2, the proportion of P in the runoff increased by 76% in azalea, and more than doubled in holly.

There is some evidence of species differences in P uptake from these studies. In data set 1 and 3, holly seemed to take up greater amounts of P than azalea, and average uptake efficiencies were in general, greater than azalea. Holly, given an excessive supply of P with overhead irrigation in data set 3, took up a greater amount of P; however, uptake efficiency was significantly lower compared to drip irrigated holly.

Most plants have not adapted the means to take up large quantities of P as they do N. This is probably due to P being a limiting nutrient in most terrestrial environments and from a physiological perspective, P is not needed in the same quantities as N. Having said that, plants will accumulate and store excess P in leaves and roots when available, although excess P may not be immediately utilized for growth. Common floriculture rates for soluble P are between 30 and 150 ppm (Borch et al., 1998). A study investigating P fertilization found that certain species, when fertilized with 100 ppm N showed adequate growth when soluble P is applied at rates of 10 ppm, but no lower (Dr. John Ruter, University of Georgia, Tifton, personal communication). On the other hand, one-year-old azaleas fertilized with soluble P rates one-fiftieth that of N exhibited growth rates no different from those fertilized with P rates one-tenth that of N (Chapter 6). Therefore, adequate and efficient P fertilization should be no more than one-tenth that of N, as long as N is applied at a sufficient rate.

During data sets 1 and 2, the majority of P fertilization came from CRF. The N/P rate was approximately 9 to 1 in the first data set and 11 to 1 during data set 2. In data set 3, where P was applied via irrigation at concentrations no higher than 4.5 ppm and where N/P ratios averaged 16 to 1, no apparent deleterious effects on growth were noted for either holly or azalea.

Several authors (Marconi and Nelson, 1984; Nishimoto et al., 1975; Beckwith, 1964) have shown that plants in general require very low solution concentrations of P to sustain growth (<0.2ppm or 6.5 uM), as long as that concentration is sustained in the soil solution. However, for the most part, conventional fertilization methods cannot sustain these minimal P concentrations in organic media, due to the supposed lack of anion-exchange capacity. We should therefore seek to use materials that offer long-term release characteristics, e.g. buffered P fertilizers such as P-charged alumina that release P dependent upon solution concentration, properties not unlike those of idealized soils. Acting as a buffer, alumina releases PO_4^{-3} based on solution equilibrium (Lin et al., 1996). As the concentration of PO_4^{-3} is reduced in solution by plant uptake or leaching, bound PO_4^{-3} goes into solution. In this manner, minimal concentrations in media can be maintained. In experiments growing chrysanthemums with a P-buffered alumina, only 0.1% of total applied P leached from the substrate (Williams et al., 2000). These types of fertilizers should therefore reduce P leaching, while maintaining viable concentrations for plant growth.

Seasonal fertilization (discussed in Chapter 4) has been shown to improve N uptake efficiency, and similar P runoff/leachate data presented in this chapter may give insight into seasonal P uptake. In Figure 5-5 (also Appendix Figure B5-7), the rate of runoff accumulation appears to slow during late summer and fall periods. However, P application did not change during data set 1 and remained constant from May to September in data set 2. Rain events during this period did not seem to leach any additional P, i.e. be the primary cause of the steady increase in runoff loss. It was possible that high air temperatures during this period caused CRF (applied the previous winter) to release more quickly during this time. Air temperatures from June were comparable to the July to mid-August period for both data sets (data not shown), and it is possible the release of nutrients from the CRF did not match the growth requirements of the plants, resulting in greater P runoff. This may indicate that during warmer periods (July through mid August) plant growth slowed and nutrient requirements decreased in the azalea and holly plants. Nitrogen partitioning and runoff accumulation data also supported the seasonal N uptake differences discussed in Chapter 4. It is during this period where nutrient applications should be reduced to match plant uptake requirements. Winter applied CRF should have shorter longevity so that the prills are near fully released before warmer temperatures slow plant growth.

Apart from maintaining low, seasonal P fertilization rates to increase uptake efficiency, irrigation management becomes a factor in reducing runoff. Drip irrigation proved to be most effective in reducing P runoff/leachate. . Interestingly, TDR was not as effective in improving runoff under drip irrigation, as the cyclic drip irrigation durations closely matched the TDR-scheduled events because scheduling of cyclic drip irrigation closely approximated plant water requirements (as noted in Chapter 3). With less efficient management of drip systems, leaching losses from cyclic irrigation events would likely have been larger. In most cases, drip generated two to six times less P runoff than overhead. Previously discussed management problems with drip irrigation preclude this method as an effective means of irrigating plants, so efficient management strategies for overhead irrigation must be investigated. In the third data set, P runoff from overhead irrigation was reduced by TDR to half that of cyclic scheduled irrigation. Water was applied to plants only when needed, whereby reducing P leaching and runoff. Figure 5-6 (also Appendix Figure B5-8) shows a decrease in P runoff from TDR controlled overhead irrigation during the fall period, when plant water requirements were reduced. In comparison, cyclically scheduled overhead irrigation continued to irrigate plants and P runoff accumulated at a faster rate. This exemplifies the importance of irrigation management in reducing nutrient runoff, especially with overhead irrigation.

Interestingly, P runoff from holly under drip irrigation was half that of azalea in the first data set. Dolomitic lime was added into the holly substrate as an amendment before planting liners, which may have bound PO_4^{-3} ions and reduced P leachate during that time.

In Chapter 4, the N results showed that pruning leaves and secondary branch tissue removed as much as 40% of the N taken up in a single year. This was further supported in this chapter where up to 77% of P taken up during the year could be removed by one or two pruning events. Like N, there is a substantial amount of P in leaves and secondary branches. The architecture of azalea made it very susceptible to P loss via pruning. Unlike holly where leaves are distributed relatively evenly throughout the canopy, azalea leaves are concentrated around the outside perimeter of the canopy. During pruning, a substantial amount of leaf tissue was removed from azalea, as compared to holly, hence nutrient loss via pruning is most likely species specific. Management strategies may be different for each species, but should focus on minimizing pruning when nutrient levels are highest during the growing season, the use of growth regulators, and efficient irrigation management as described in Chapters 3 and 4.

Finally, less P was recovered than expected from all data sets. Tyler et al. (1996b) recovered 50 to 80% of applied P in a field study examining leaching fractions and CRF rates on growth in containerized ornamentals. Unlike N, which can be denitrified, P should be conserved in the environment and total recoveries in this study were expected to be higher. One explanation may be that the study location was downwind of tilled fields. Wind born soil often lightly coated our growing pads. Some of the loss may be attributed to P bound to soil particles before analysis. Another possibility for low P recovery was the APP used as our soluble P source. Only a third of the P contained in APP is immediately available to plants (and detectable by our analysis) as ortho-phosphate. A combination of these factors is likely to have lowered our total P recovery.

5.5 Conclusions

This study incorporated several aspects of fertilization and irrigation research to develop an integrated analysis of P dynamics in a container nursery. These data offer insight to improving P fertilization management in container nursery systems.

No significant differences in uptake efficiency were found between drip and overhead irrigation until data set 3 when P fertilization was solely from soluble sources; uptake efficiency under drip irrigation then became significantly greater. While this study incorporated both CRF and soluble fertilization, the data suggest that P uptake efficiency may be improved with the sole use of CRF's under overhead irrigation, a best management practice that is being widely adopted by the industry. Matching fertilization rates to seasonal growth patterns would also be very effective in improving uptake efficiency. Control release fertilizers with shorter release times may be effective in providing nutrients when needed and be near fully released by the time warmer temperatures arrive, when plant growth and nutrient uptake slows. Additionally, top dressing plants with CRF during the fall instead of winter would increase uptake efficiency by supplying nutrients to the plants during an active period of nutrient uptake.

Drip irrigation is still more efficient in delivering P to the plant and in reducing P runoff, but the impracticality of this irrigation practice leads nurseries to improve upon overhead efficiency. As with the management practices suggested in Chapter 4, P runoff could be reduced by innovative practices. For example, plant-driven irrigation scheduling technology (TDR) has been shown to be effective in reducing P runoff from overhead irrigation, by reducing overall fertigation volumes. Seasonal timing and custom-blend formulations of P should improve P uptake efficiency and thus reduce potential runoff, and rethinking cultural practices such as pruning could reduce the requirements for P to support the growth of woody perennials.

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Chapter Six

Spring Nutrient Uptake

6.1 Introduction

There is a surprising lack of quantitative physiological data on nitrogen (N) and especially phosphorus (P) uptake by woody perennial species. Much has been published on the cellular and biochemical roles of N and P in the plant literature (see Marschner, 1995 for summary), but few studies have related N and P availability (from fertilization) to actual nutrient uptake and nutrient uptake-efficiency by these species. Little is also known of how woody ornamental perennials partition N and P in intensive production systems, in part because of the periodicity of their growth cycles and the fact that nutrient uptake is largely a function of other environmental variables, which have more pronounced effects on plant growth (such as water availability and temperature).

Among the nutrient elements required for plant growth, P is associated with growth of meristematic tissue and in particular, root growth (Tisdale et al., 1985; Wittwer, 1969). There is a widespread belief in the horticultural industry that P fertilization stimulates root growth over shoot growth. In a review on root:shoot ratios in trees, Harris (1992) cited seven examples of books or manuals on plant care that either stated or implied that P primarily promotes root growth and N promotes shoot growth. This belief that P fertilization preferentially stimulates root growth over shoot growth has led to the practice of providing high P content fertilizers to promote rapid transplant establishment of horticultural plants (Wittwer, 1969). However, there are few definitive experimental data in the literature to support this view. There are some data to show that P-starved roots grow and branch more profusely when P is added to their environment

(Drew and Saker, 1978), but there is no evidence to indicate that the addition of higher levels of P increases either root or shoot growth rates above that of minimally P-sufficient plants. Indeed, Anghinoni and Barber (1980) showed that minimal substrate P concentrations increased root to shoot dry weight ratios in corn. Dufault (1985) also found that root to shoot ratios decreased with increasing P fertilization levels in celery transplants. Evidence shows that low P fertilization improves root growth over high P rates in herbaceous species such as impatiens and marigolds (Borch et al. 1998), chrysanthemums (Hanson and Lynch, 1998), common bean (Lynch et al., 1991) and in some woody species (Zhang et al. 2002). Other studies have shown that P did not promote root growth or influence root to shoot ratio in a wide range of plants (Broschot and Klock-Moore, 2000; Dufault and Schultheis, 1994; Melton and Dufault, 1991; Weston and Zandstra, 1989; Yeager and Wright, 1981).

I hypothesize that current N and P application rates to most ornamental plants in container nurseries exceed normal plant N and P requirements, resulting in low uptake efficiencies and excessive nutrient loss via leaching. A review by Chen et al., (2001) found recommended N rates for azaleas at 2200 kg/ha/yr, over 10 times the agronomic rate for corn. This equates to applying 500 mg N per week to a plant in a 7.6 L (2 gal) container over a 40-week growing cycle (given 110,000 7.6 liter containers in a hectare). Borch et al. (1998) noted that levels of P fertilization are orders of magnitude greater than plant requirements and plants grow well at P concentrations 100-fold less than traditional rates used in container plant production (Lin et al. 1996; Lynch et al. 1991), as long as available P concentrations are held constant.

I also hypothesize that providing sufficient N and P fertilization (100 mg N and 5 mg per plant per week) would be adequate to maintain maximal shoot and root growth, and would increase nutrient uptake efficiency. Additionally, root growth is not improved with higher P fertilization rates in the ericaceous species, azalea. This experiment challenges the current dogma for fertilization by studying the lower limits of plant N and P requirements and the effects on uptake efficiency for an ericaceous species. .

6.2 Materials and Methods

General materials and methods for these greenhouse studies are given in Chapter 2.1 and 2.2. More specific experimental methods are given below.

6.1.1 Spring Study 2001

A three-month experiment was conducted over a 12-week period to investigate the uptake and partitioning of N and P by Rhododendron var. ‘Karen’ (azalea), an ericaceous, low nutrient use species, from March to May 2001. Five replicates of six treatments in a completely randomized 2 x 3 factorial design provided limiting and high rates of N (i.e. 25 and 250 mg N per week, respectively) combined with limiting, sufficient and high rates of P (0, 5 and 25 mg P per week, respectively).

Eight-month-old azalea liners were transplanted into 7.2-L (2-gal) plastic pots containing a composted pine bark media, amended only with micronutrients (0.50 kg micromax $\cdot$ m^{-3}) in late February 2001. These plants were not fertilized over the winter (dormancy) period prior to onset of this study, so that the plants and substrate did not have large N and P reserves.

Plants received 11 once-weekly applications of N and P in an otherwise balanced liquid fertilizer solution, at the rates specified above for each treatment for throughout the 12 week experimental period. The fertilizer was applied to each plant in 250 ml aliquots once per week. In addition, all plants were deficit irrigated i.e. with a zero leaching fraction twice a week (by hand), but were then all watered to excess the day prior to fertilization. This was designed to leach the excess N and P and any other accumulating salts remaining in the substrate from the previous week. The replicate plants designated for the final harvest were placed above catchment saucers to retain the expressed leachate. Leachate volumes were recorded and samples were taken within one hour for N and P analysis as described in Chapter 2.1.9.3.

Substrate analysis was as described in the general material and methods (Chapter 2.1.7.3). Harvest methods and tissue analysis are described in Chapter 2.1.9.2. Plant tissue phosphorus analysis included initial, third and last harvests only. The first harvest was performed prior to the onset of the study to provide baseline dry mass and nutrient content data. Five plant harvests were thereafter conducted every two weeks to provide sequential N and P uptake, partitioning and nutrient uptake-efficiency data. The baseline value for initial N, P and dry mass was subtracted from the final harvest value for each treatment, leaving total nutrient and dry mass accumulation for each treatment. In this study both total nutrient content and dry mass values have the same treatment variances as nutrient uptake and dry mass accumulation values.

All sample data were analyzed using a factorial analysis of variance using the PROC MIXED routine (SAS Institute, Cary, NC). If treatment interaction was not significant, main effects are reported and discussed. However, if treatment interactions were significant, simple effects are reported and discussed. Pairwise comparisons were done under LSD criterion at P<0.05. I used LSD (a liberal test) because this criterion is commonly found horticultural literature. I also wanted to increase the power of my test and protect my analysis interpretation from incorrectly accepting the null hypothesis (Type II error). The use of LSD increases the power of the test, and hence, increasing the probability of detecting a real effect. Assumption for variance homogeneity was carried out by Corr Spearman procedure of the SAS system (SAS Institute, Cary, NC).

6.1.2 Spring Study 2

A repeat experiment with improvements, was conducted over an 11-week period from the end of March through May 2002. In this study three replicates of nine treatments in a completely randomized 3 x 3 factorial design provided limiting, sufficient, and high rates of N (i.e. 25, 100, and 250 mg N per week, respectively) combined with limiting, sufficient and high rates of P (0, 5 and 25 mg P per week, respectively). Plants received 9, twice-weekly applications of N and P in an otherwise balanced liquid fertilizer solution, at the rates specified above for each treatment throughout the 11-week experimental period. The fertilizer was applied to each plant in 250 ml aliquots twice per week. All other methods were as in the first study. Several weeks into the study (at harvest 1), plants began showing signs of a leaf-tip necrosis in all treatments. An immediate foliar and substrate analysis revealed a high concentration of manganese in both leaves and substrate. It is possible that the manganese originated in the pine bark or rice hulls (Handreck and Black, 1994) used in the substrate. To counteract the effects of manganese accumulation in plant tissues, sodium silicate was added to each fertilizer solution at a 0.05M concentration. According to Marshner (1995), silicon tends to prevent Mn accumulation in any one area and promotes the distribution of Mn more evenly throughout plant tissues. The addition of sodium silicate ameliorated the Mn toxicity on all new leaf growth by the third harvest.

6.3 Results

6.3.1 Spring Study 2001

6.3.1.1.1 Dry Mass.

Azalea total dry mass results from the final harvest are summarized and compared in Table 6-1. Dry mass partitioning figures for each treatment are given in Appendix C, Figures C6-1 through C6-6. There was significant interaction on total dry weight between N and P treatments ($P<0.02$). Plants fertilized with 250 mg N and 25 mg P per week (250N:25P) had greater total dry mass ($P<0.01$) than all other treatment combinations except for the 250N:5P treatment ($P>0.33$). There was no interaction on leaf dry weight between N and P treatments ($P>0.09$). Differences in leaf dry mass were due to N treatment alone ($P<0.01$) with greatest leaf dry mass from plants fertilized with 250N treatments ($P<0.01$). There was significant interaction on root dry weight between N and P treatments ($P<0.02$). In contrast to total and leaf dry mass, the root dry mass of plants given the 25N:0P treatment was greater than other treatments ($P<0.04$) except plants given the 25N:5P treatment ($P>0.38$). Root/shoot ratios of the low N treatments were twice that of the high N treatments (Table 6-1).

Table 6-1. Average dry mass data (n=5) for the final 2001 plant harvest after 12 weeks. Standard errors are in parentheses (n=5). Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment mg week^{-1}	Total Dry Mass (g)	Leaf Dry Mass (g)	Root Dry Mass (g)	Root/ Shoot Ratio
N250:P25	25.2 (± 1.1) a	14.6 (± 0.8) a	3.3 (± 0.2) c	0.15
N250:P5	23.3 (± 1.9) a,b	14.0 (± 1.1) a,b	3.2 (± 0.4) b,c	0.16
N250:P0	19.8 (± 0.6) b,c	12.0 (± 0.5) b	2.5 (± 0.1) c	0.15
N25:P25	16.5 (± 1.7) c	7.2 (± 0.8) c	3.2 (± 0.3) b, c	0.24
N25:P5	18.6 (± 1.3) c	8.1 (± 0.5) c	3.7 (± 0.3) a, b	0.25
N25:P0	19.4 (± 1.3) c,b	8.1 (± 0.6) c	4.1 (± 0.2) a	0.26

6.3.1.2 Plant Nitrogen and Phosphorus

Table 6-2 shows average plant total, leaf, and root N and P per treatment. Plant nutrient uptake (Table 6-3) was the difference between a baseline average (average of 15 plants) and plant total N and P at end of study for all treatments. The initial harvest at the beginning of the experiment gave an average of 91.6 mg N and 20.9 mg P per plant. Nitrogen partitioning for the 6 treatments are given in Appendix C, Figures C6-7 through C6-12.

There was no treatment interaction for total plant N, leaf N and root N and differences were due to N treatment alone. As expected, total plant N and leaf N (Table 6-2) was significantly greater in the high N treatments at the final harvest ($P<0.01$). Root N content (Table 6-2) was also significantly greater in high N treatments ($P<0.01$), except for the 250N:0P treatment, which was not different from the N25:0P treatment ($P<0.09$). The similarity between plant N in the 250N:0P and 25N:0P was due to the latter treatment's greater root mass, not nitrogen concentration (data not presented).

Graphs of P partitioning for the 6 treatments are in Appendix C, Figures C6-13 through C-18. There was no treatment interaction for total plant P, leaf P and root P and differences were due to P treatment alone ($P<0.01$). Total plant P (Table 6-2) was significantly higher in the 250N:25P treatment than other treatments ($P<0.01$), and the zero P treatments had significantly lower leaf P than any other treatment ($P<0.01$).

Table 6-2. Average tissue N and P content as a function of dry mass and nutrient concentration for final harvest in 2001 (n=5). Standard errors are in parenthesis. Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment mg week^{-1}	Leaf N (mg)	Root N (mg)	Total Plant N (mg per plant)	Leaf P (mg)	Root P (mg)	Total P (mg per plant)	N/P Ratio
N250:P25	376.8 (± 26.0) a	68.0 (± 6.1) a	523.2 (± 30.1) a	40.3 (± 2.9) a	10.2 (± 0.9) a	62.7 (± 3.4) a	8.3
N250:P5	313.0 (± 47.7) a, b	59.6 (± 7.1) b	442.9 (± 51.8) a, b	31.0 (± 2.8) b	5.2 (± 0.7) c	43.3 (± 3.7) b	10.2
N250:P0	291.9 (± 44.5) b	39.6 (± 1.4) c,d	401.2 (± 41.8) b	18.8 (± 2.3) c	2.5 (± 0.3) d	26.4 (± 2.8) c	15.0
N25:P25	88.6 (± 6.1) c	27.0 (± 4.1) e	146.5 (± 8.9) c	32.9 (± 3.8) b	8.1 (± 1.4) a,b	51.7 (± 5.6) b	2.9
N25:P5	92.4 (± 8.3) c	27.7 (± 3.7) e	152.4 (± 10.1) c	32.6 (± 2.1) b	6.9 (± 0.8) b,c	47.5 (± 3.0) b	3.2
N25:P0	100.2 (± 13.3) c	33.1 (± 3.1) d,e	171.8 (± 52.4) c	15.4 (± 1.6) c	5.7 (± 0.5) c	28.1 (±2.2) c	6.3

Table 6-3. Nutrient budget and plant nutrient content after the 12-week experimental period. Nitrogen and P uptake efficiency is the percentage of applied nutrient that was taken up after 11 applications. Plant nutrient uptake (N and P) is the accumulation of nutrient from initial to final harvest. Initial plant N content was 91.6 mg N and initial plant P content was 20.9 mg. Differences between plant nutrient uptake are same as Total N and P in Table 6-2. Standard errors are in parenthesis (n=5). Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment (mg week^{-1})	Plant N Uptake (mg)	N Leachate (mg)	Substrate N (mg)	N Uptake Efficiency (%)	Plant P Uptake (mg)	P Leachate (mg)	Substrate P (mg)	P Uptake Efficiency (%)
N250:P25	431.6 (± 30.1)	84.2 (± 10.1) a	695.6	15.8	41.8 (± 3.4)	5.4 (± 1.2) b	25.8	15.2
N250:P5	351.4 (± 51.8)	99.2 (± 15.4) a	588.3	12.8	22.4 (± 3.7)	1.9 (± 0.3) c, d	9.9	40.7
N250:P0	309.6 (± 41.8)	106.7 (± 8.9) a	670.6	11.1	0.5 (± 2.8)	2.9 (± 0.3) d	7.2	--
N25:P25	54.9 (± 8.9)	9.7 (± 1.1) b	10.9	20.9	30.7 (± 5.6)	9.1 (± 0.8) a	48.3	11.2
N25:P5	60.9 (± 10.1)	12.7 (± 1.9) b	6.9	23.2	25.2 (± 3.0)	3.9 (± 0.7) b, c	15.3	45.9
N25:P0	80.2 (± 52.4)	22.0 (± 2.6) b	14.5	31.2	7.2 (± 2.2)	2.7 (± 0.3) d	6.5	--

Root P content declined with decreasing P rate within each N treatment. Consequently, the N/P ratio increased directly as a function of decreased P application. Higher N/P ratios were seen in the high N treatment combinations. Interestingly, there was P uptake (Table 6-3) in the zero P treatment, and total plant P increased from initial harvest, despite P not being added at anytime to the treatments.

6.3.1.3 Uptake Efficiency and Leaching

Nitrogen and P uptake efficiency (Table 6-3) reflects the fraction of applied nutrient accumulated by plants during the 12-week period in 2001. Efficiency in nutrient uptake decreased as nutrient application rate increased for both N and P (Table 6-3). Nitrogen uptake efficiency was between two and three times greater for the low N treatment compared to the high N treatments. The P uptake efficiency of low P plants increased three-fold over high P plants.

There was no interaction of treatments from N leachate ($P>0.75$) and differences in N leachate were due to N treatment alone ($P<0.01$). On average, N loss through leaching (Table 6-3) was between 5 and 10 times higher in high N treatment than in low N treatment, but N leaching was not affected by P treatment.

There was treatment interaction in P leachate ($P<0.04$). Simple treatment effects for P leachates are shown in Table 6-3. Phosphorus leachate was greatest in the 25N:P25 treatment ($P<0.01$). Nutrients not taken up by the plant were leached via water application or remained in substrate. Substrate N and P (Table 6-3) in the high N and P treatments reflect the large reservoir of unutilized nutrients, despite weekly leaching. Curiously, there remained between 20 and 25% of the applied N in the high treatment substrate and approximately 18% of the P applied in the 25N:25P treatment substrate at the end of the study.

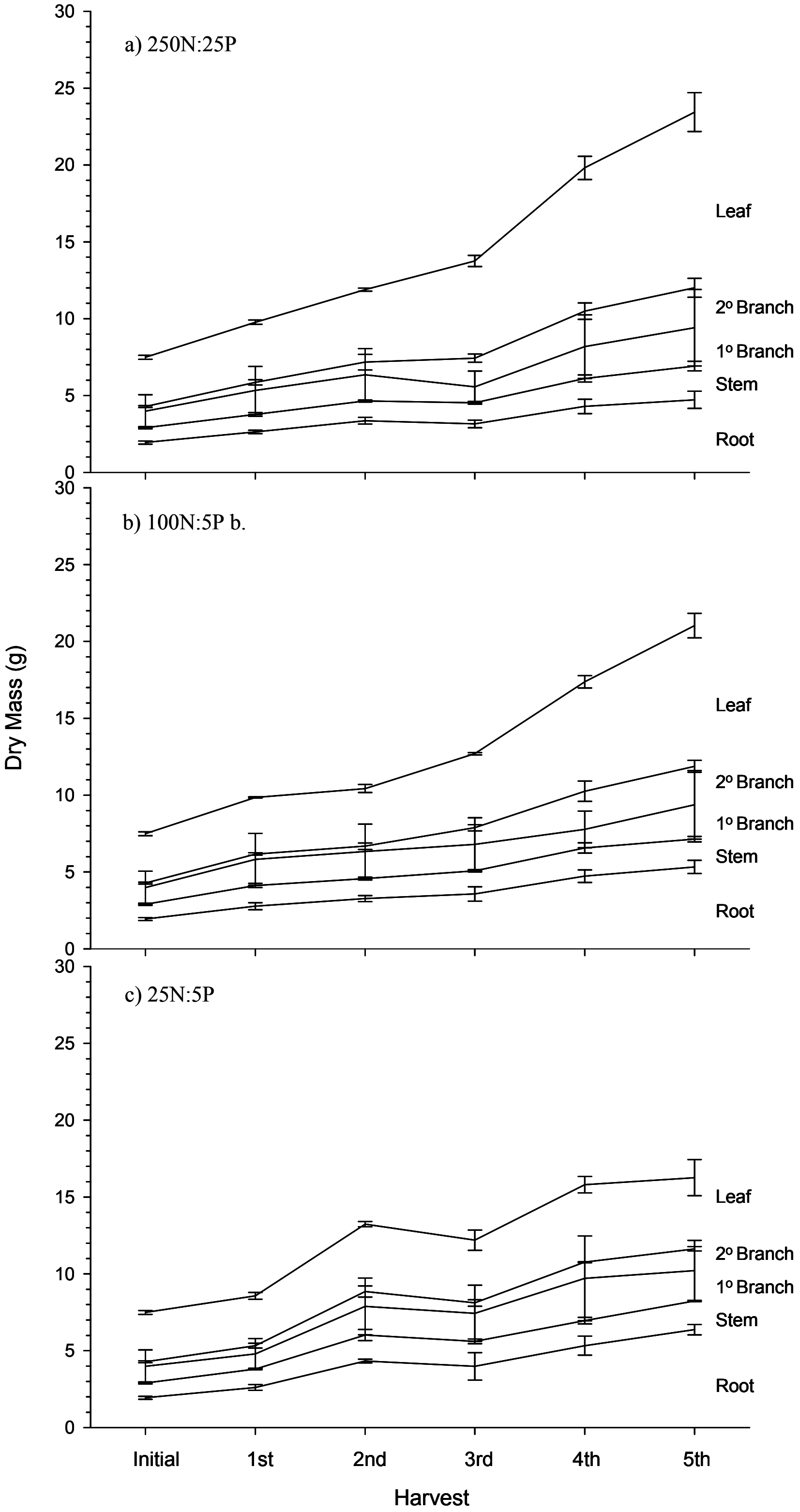
6.3.2 Spring Study 2002

6.3.2.1 Dry Mass

Figures 6-1 a, b, and c compares average azalea dry mass partitioning of the 250N:25P, 100N:5P and 25N:5P treatment combinations. Partitioning shows similar allocation of tissue dry mass between the 250N:25P and 100N:5P treatments despite the large difference between N and P rates. Dry mass partitioning graphs for all other treatments are given in Appendix C Figures C6-19 through C6-25.

Table 6-4 shows total, leaf, and root dry mass by the end of the 11-week study for all treatment combinations. There was no treatment interaction on total dry mass, leaf dry mass, and root dry mass ($P>0.80$). Differences for total dry mass between treatments were due to N treatment alone ($P<0.01$). Total dry mass was not different between azalea given 250 mg N or 100 mg N rates ($P>0.36$). Multiple mean comparisons of total dry mass show that azalea given 25 mg N per week were not different than azalea given 250N:0P and 100N:5P per week ($P>0.08$).

While total dry mass results were not clear-cut in distinguishing differences in growth, differences in leaf dry mass by treatment were more straightforward (Table 6-4). Differences in leaf dry mass were due to N treatment alone ($P<0.01$). Leaf dry mass of azalea given 250 mg N and 100 mg N per week were not significantly different from each other ($P>0.10$) but both were significantly greater than azalea given the 25 mg N per week treatments, regardless of P rate ($P<0.02$). In fact, nearly half the total dry mass in



Figures 6-1 a,b,c. Average dry mass partitioning of azalea given (a) 250N:25P, (b) 100N:5P and (c) 25N:5P in mg per week for a period of 11 weeks in the 2002 spring study. Harvests were two weeks apart. Error bars are based on n = 3.

Table 6-4. Average dry mass data for the final plant harvest after 11 weeks for 2002 Spring Uptake Study . Standard errors are in parentheses (n=3). Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment mg week^{-1}	Total Dry Mass (g)	Leaf Dry Mass (g)	Root Dry Mass (g)	Root/ Shoot Ratio
N250:P25	23.44 (± 2.34) a	11.43 (± 1.27) a	4.72 (± 0.56) b	0.25
N250:P5	22.91 (± 0.61) a b	10.84 (± 0.31) a	5.04 (± 0.21) a b	0.28
N250:P0	21.65 (± 2.26) a b c	10.19 (± 1.01) a	4.80 (± 0.62) b	0.28
N100:P25	22.49 (± 3.24) a	9.97 (± 1.54) a	5.72 (± 0.66) a b	0.34
N100:P5	21.03 (± 1.30) a b c	9.15 (± 0.80) a	5.33 (± 0.43) a b	0.34
N100:P0	23.22 (± 1.41) a	10.08 (± 0.75) a	5.82 (± 0.23) a b	0.33
N25:P25	17.72 (± 1.31) b c	5.37 (± 0.37) b	6.12 (± 0.42) a	0.53
N25:P5	16.26 (± 1.42) c	4.62 (± 1.17) b	6.37(± 0.34) a	0.64
N25:P0	17.30 (± 1.21) c	5.67 (± 0.48) b	5.81 (± 0.36) a	0.51

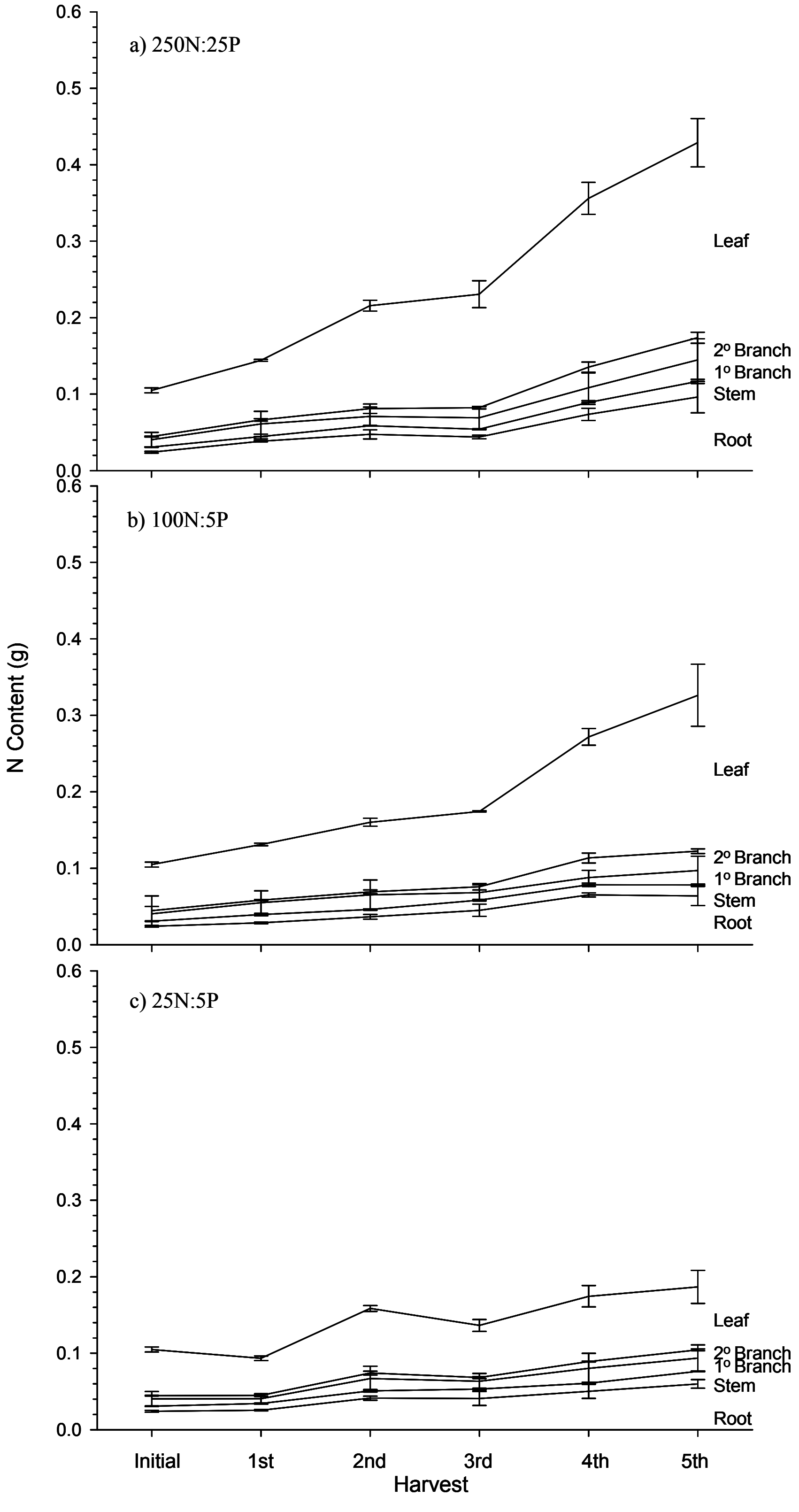
the 250 and 100 mg N treatment combinations was leaf dry mass. Average leaf dry mass of the low N (25N) was less than the other two N treatments because growth was allocated to roots.

Differences in root dry mass were due to N treatment alone ($P<0.02$). Root dry mass of azalea fertilized with 25 mg N per week was greater than root dry mass of azalea under both 250N:25P and 100N:0P treatments ($P<0.05$). Root dry mass for azalea under the 100 mg N treatments were not different from either azalea under 25 mg N treatments ($P>0.12$) or 250 mg N treatments ($P>0.10$). Also, root dry mass for azalea under 250N:5P treatment was not different from all 25 mg N treatments ($P>0.10$). Shoot dry mass (data not shown) was not significantly different between 250 mg and 100 mg N rates ($P>0.15$), and shoot dry mass between each 25 mg N treatment were not different ($P>0.41$). Root/shoot dry mass ratios of azalea given 100 mg N per day were intermediate between the 250 mg N and 25 mg N treatments, showing how carbon resources are shifted in response to N treatment.

6.3.2.2 Plant Nitrogen and Phosphorus

Figures 6-2 a, b, and c compare average azalea tissue N partitioning of the 250N:25P, 100N:5P, and 25N:25P treatment combinations. Nearly two thirds of the plant N content is contained within the leaf tissue of both 250N:25P and 100N:5P treatment combinations. Nitrogen partitioning graphs for other treatments are in Appendix C Figures C6-28 through C6-36.

Table 6-5 shows average leaf, root and total plant P in azalea per treatment. Plant N and P uptake (Table 6-6) was the difference between a baseline average (average of 15



Figures 6-2 a,b,c. Average nitrogen partitioning of azalea given (a) 250N:25P, (b) 100N:5P and (c) 25N:5P in mg per week for a period of 11 weeks in the 2002 spring study. Harvests were two weeks apart. Error bars are based on n = 3.

Table 6-5. Average tissue nutrient content as a function of dry mass and nutrient concentration Standard errors in parenthesis (n=3). Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment mg week^{-1}	**Leaf N (mg)**	**Root N (mg)**	**Total Plant N (mg per plant)**	**Leaf P (mg)**	**Root P (mg)**	**Total P (mg per plant)**	**N/P Ratio**
N250:P25	255.2 (± 31.5) a	96.1 (± 20.6) a	428.9 (± 34.1) a	28.8 (± 3.2) a	10.9 (± 2.8) a b	50.5 (± 6.8) a	8.5
N250:P5	225.2 (± 27.6) a	81.1 (± 5.3) a b	380.3 (± 19.6) a	23.3 (± 0.1) a b c	8.6 (± 0.5) b c	40.8 (± 0.9) a b	9.3
N250:P0	268.8 (± 21.8) a	77.6 (± 12.9) a b c	417.4 (± 37.6) a	18.4 (± 1.5) b c	6.3 (± 1.2) c	31.4 (± 3.6) b	13.3
N100:P25	219.2 (± 40.5) a	71.2 (± 12.5) a b c	355.3 (± 60.8) a	27.8 (± 4.9) a b	14.7 (± 2.5) a	52.7 (± 9.1) a	6.7
N100:P5	203.9 (± 16.2) a	63.7 (± 6.4) b	326.2 (± 22.1) a	21.5 (± 1.9) a b c	11.1 (± 0.2) a b	41.1 (± 2.4) a b	7.9
N100:P0	204.4 (± 44.7) a	74.1 (± 6.2) a b c	346.2 (± 44.4) a	20.7 (± 1.4) a b c	8.2 (± 0.8) b c	36.5 (± 2.9) b	9.4
N25:P25	96.1 (± 7.2) b	50.3 (± 3.0) c	188.0 (± 13.3) b	25.1(± 2.1) a b c	10.8 (± 0.8) a b	43.2 (±.3.5) a b	4.4
N25:P5	82.4 (± 21.6) b	59.8 (± 5.5) b c	186.8 (± 20.2) b	17.3 (± 4.7) b c d	13.1(± 0.2) a b	37.0 (± 5.1) b	5.0
N25:P0	82.5 (± 12.7) b	51.3 (± 3.2) c	177.9 (± 12.7) b	16.5 (± 3.1) d	9.9 (± 1.0) b c	31.9 (± 4.2) b	5.6

Table 6-6. Nutrient budget and plant nutrient content after the 11-week experimental period. Nitrogen and P uptake efficiency is the percentage of applied nutrient that was taken up after 9 applications. Plant nutrient uptake (N and P) is the accumulation of nutrient from initial to final harvest. Initial plant N content was 104.0 mg N and initial plant P content was 19.0 mg. Initial substrate N and P was 7.4 mg and 28.6 mg. Differences between plant nutrient uptake are same as Total N and P in Table 6-2. Standard errors are in parenthesis (n=5). Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment (mg week^{-1})	Plant N Uptake (mg)	N Leachate (mg)	Substrate N (mg)	N Uptake Efficiency (%)	Plant P Uptake (mg)	P Leachate (mg)	Substrate P (mg)	P Uptake Efficiency (%)
N250:P25	324.9 (± 34.1)	117.1 (± 16.5) b	762.6	14.4	31.5 (± 6.8)	8.3 (± 1.3) b	83.1	14.0
N250:P5	276.3 (± 19.6)	152.3 (± 17.6) a	620.3	12.3	21.8 (± 0.9)	2.4 (± 0.2) c	15.9	48.5
N250:P0	313.4 (± 37.6)	147.6 (± 7.9) a	897.1	13.9	12.4 (± 3.6)	2.0 (± 0.8) c	9.9	-
N100:P25	251.3 (± 60.8)	35.6 (± 7.5) c	169.2	27.9	33.7 (± 9.1)	13.8 (± 4.5) a	64.4	15.0
N100:P5	222.2 (± 22.1)	44.2 (± 2.3) c	92.9	24.7	22.1 (± 2.3)	2.7 (± 0.9) c	16.4	49.2
N100:P0	242.2 (± 44.4)	41.9 (± 8.8) c	178.0	26.9	17.6 (± 2.3)	1.5 (± 0.5) c	10.6	-
N25:P25	84.0 (± 13.3)	5.3 (± 0.8) d	8.6	37.3	24.3 (± 3.5)	16.3 (± 1.3) a	66.6	10.8
N25:P5	82.8 (± 20.2)	3.6 (± 0.8) d	6.7	36.8	18.0 (± 5.1)	5.1 (± 1.4) b c	24.1	40.1
N25:P0	73.9 (± 12.7)	3.8 (± 0.4) d	12.3	13.0	13.0 (± 4.2)	2.5(± 0.9) c	10.8	-

plants) and total plant N and P at the end of study for all treatments. An initial harvest at the beginning of the experiment averaged 104.0 mg N and 19.0 mg P per plant.

There was no treatment interaction on total plant N (P>0.95) and differences were due to N rate alone (P<0.01). Total plant N was not different between 250 mg and 100 mg per week treatments (P>0.09). Total plant N was significantly less for azaleas given 25 mg N per week than for azaleas given either 100 mg or 250 mg N per week (P<0.01).

There was no treatment interaction on leaf N (P=0.9284) and differences were due to N rate alone (P<0.01). Leaf N was not different between 250 mg and 100 mg per week treatments (P>0.11). Total plant N was significantly less in azaleas given 25 mg N per week than azaleas given either 100 mg or 250 mg N per week (P<0.01).

There was no treatment interaction on root N (P>0.63) and differences were due to N rate alone (P<0.01). Root N in azaleas given the 250N:25P treatment was greater than in azaleas given the 100N:5P treatment and all 25 mg N per week treatments (P<0.04). A greater percentage (one third) of the total plant N was allocated to roots in the 25N:25P treatments than either the 250N:25P or 100N:5P treatments.

Figures 6-3 a and b show average P partitioning in azaleas under the 250N:25P and 100N:0P (zero P) treatment. Phosphorus partitioning graphs for all other treatments are given in Appendix C, Figures C6-37 through C6-45. Average dry mass for these treatments were significantly greater than other treatments. Plants under the 250N:25P treatment accumulated nearly twice as much P as the 100N:0P treatment, yet average dry mass was not significantly different between them. Azaleas in the 250N:25P treatment stored excess P mainly in leaf and root tissues. As with N, over half of the plant P is partitioned into the leaf tissue.

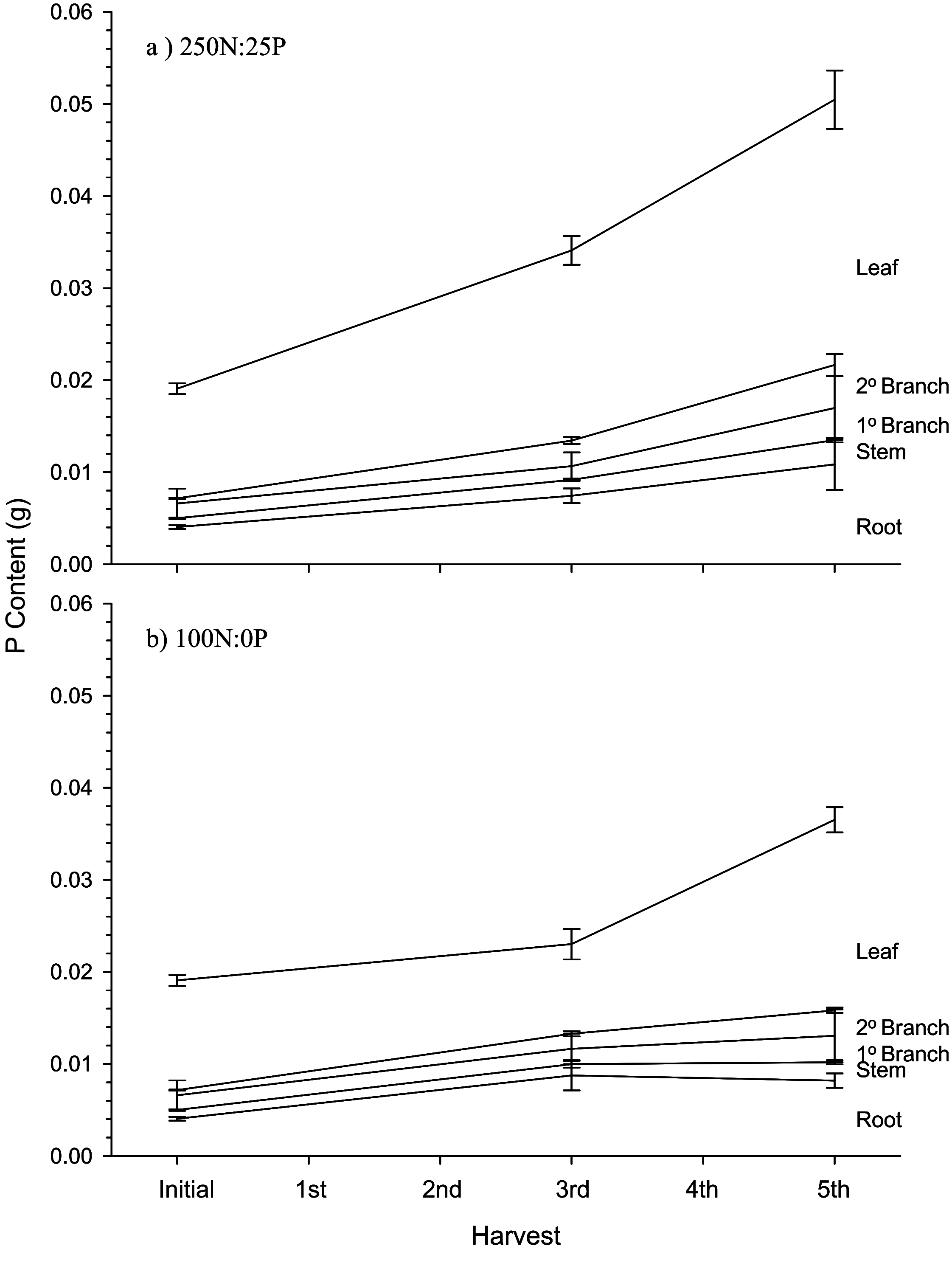


Figure 6-3 a,b, c. Average phosphorus partitioning of azalea given (a) 250 mg N and 25 mg P and (b) 100 mg N and 0 mg P per week over a period of 11 weeks in the 2002 spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

Table 6-5 shows average leaf, root and total plant P in azaleas per treatment. There was no treatment interaction on total plant P ($P>0.92$) and differences were due to P treatment alone ($P<0.01$). Total plant P was not different between azaleas given the 25 mg P and 5 mg P per week treatments ($P>0.10$) and was significantly greater than total plant P in azaleas given no P.

Table 6-5 shows average leaf, root and total plant P in azaleas per treatment. There was no treatment interaction on total plant P ($P>0.92$) and differences were due to P treatment alone ($P<0.01$). Total plant P was not different between azaleas given the 25 mg P and 5 mg P per week treatments ($P>0.10$) and was significantly greater than total plant P in azaleas given no P.

There was no treatment interaction on leaf P ($P>0.94$) and differences were due to P treatment alone ($P<0.01$). Leaf P in azaleas given the 250N:25P treatment was not different from the 250N:5P treatment, all the 100N treatments, and the 25N:25P treatment ($P>0.10$). The lowest leaf P was from azaleas under the 25N:0P treatment. There was no treatment interaction on root P ($P>0.24$) and differences were due to both N ($P<0.05$) and P treatment ($P<0.01$). Azaleas given 0 mg P per week had lower root P than azaleas given 25 mg per week in both the 250 and 100 mg N treatments ($P<0.04$). However, root P was not different between any P treatment combinations ($P>0.13$) within the 25 mg N treatment.

Phosphorus content was a function of both P and N rate. Plants given the higher P treatments accumulated more P, and at higher N rates azaleas dry mass increased, positively affecting the total P content. Roots became a sink for excess P, when N became limiting nutrient. The opposite is true for azaleas given the 250N:0P rate, which became P limited, as seen in the N/P ratio for these plants.

6.3.2.3 Leaching and Uptake Efficiency

Table 6-6 shows N and P budgets and uptake efficiencies for the second spring study. Average N uptake efficiencies in azalea given 25 mg N per week were twice as large as for azalea given 100 mg N per week and between 2.5 to 3 times as large as for azalea given 250 mg per week. The 25 mg N treatments averaged up to 40 times less loss of N through leachates as the 250 mg N per week treatments, which averaged up to 4 times greater leaching of N than the 100 mg N per week treatments. Phosphorus uptake efficiencies for azalea given the 5 mg P per week treatments were three to four times greater than that of the 25 mg P per week treatments for the N treatments, and were very similar to the first spring study. As in the first spring study, there remained a substantial amount of N and P in the high N and P treatment substrates at the end of the study.

6.4 Discussion

Nitrogen was found to be the principle nutrient promoting shoot growth, but not root growth in both studies, and intermediate fertilization rates were found to be adequate to maintain overall growth, as compared to high (recommended) fertilization rates. Total dry mass and leaf dry mass results in the first spring study suggested that N primarily promotes shoot growth, as these treatments needed no more than sufficient amounts of P to overcome a P limitation on growth (seen only in the zero P treatment). In the second spring study, a rate of 100N:5P maintained total, leaf and shoot dry mass no different from the higher fertilization rates. Despite having a zero P treatment, no differences in total dry mass were seen between any P treatment combinations for either the 250 or 100 mg N treatment. This may have been due to native P residing in the substrate (an analysis of substrate found 28.6 mg P available to each plant before the onset of the second study). From the results, this native P was sufficient to maintain adequate growth of azalea, at least for the short term.

The response of root growth was quite different, and was contradictory to the conventional view of P fertilization. The greatest root/shoot ratios were with the 25 mg per week (low) N treatments because shoot growth was severely restricted by available N. In the first study, the greatest root dry mass was with the 25N:0P treatment and the 25 mg P treatments did not show greatest root growth. While root growth was reduced without P at the 250 mg N treatment, this was not significantly different from any high N treatment or the 25N:25P treatment, again perhaps due to native P in the substrate (Handrek and Black 1994). Thus, in azalea, root mass is not improved with high P fertilization and root growth increases under conditions of low nutrient concentration, as has been shown by other authors (Zhang et al. 2002; Borch et al. 1998; Hanson and Lynch, 1998; Lynch et al., 1991). In the second study, P treatment did not seem to effect root growth, which was most likely due to the presence of plant available P in the organic substrate and probable release of substrate bound P throughout the study. Sufficient rates of both N and P (100N:5P) sustained root growth that was no different from the 25 mg N per week treatments. Comparatively larger average root mass was found in low N treatments. Fertilization recommendations commonly focus on promoting maximum shoot growth in plants. By utilizing moderate N rates optimal root/shoot ratios can be maintained, which may improve uptake efficiencies while in production and also promote greater post-planting survival rate in the landscape.

While supplying the azalea with high N and P treatments increased the plant nutrient content, greater quantities of residual substrate N and P were available for loss through leaching and perhaps other loss mechanisms. However, there was a surprisingly large quantity of residual N and P left in substrates at the end of the study, especially from the high N and P treatments. While Marconi and Nelson (1984), concluded that soiless mixes had low P adsorption capacity and that PO_4^{-3} ions could leach easily from these types of substrate, they also found that in some cases, P did not leach out in expected quantities. Citing Hanan (1981), Marconi and Nelson (1984) found that water added did not achieve 100% displacement throughout the substrate and that the applied water channeled through macropores, leaching out only portions of applied P. It is reasonable to suspect that this is what occurred in this study with both N and P. Additionally, azalea roots did not fully explore containers, leaving areas within the container untouched by root activity.

In both studies, average P leachate was greatest in 25N:P25 because N promotes growth and the applied P was not being fully utilized by the plant. In the first study, there was some P leachate from the zero P treatments. This perhaps may have been due to root turnover, or release of native P by the breakdown of the pine bark substrate. An even greater amount of available P was found in the second year substrate, in amounts enough to sustain growth. This may have been due to the fact that substrate was not well composted (as evidenced by the manganese problem). In fact, the second highest average dry mass was sampled from the 100N:0P treatment. Despite many publications pointing to the contrary, the belief that it is necessary to apply more than minimal quantities of P to promote root development seems to be common in the nursery industry. Fertilizers containing near 1:1 molar ratios of N and P claim to boost root and bloom growth. These results dispute those assertions.

Nutrient uptake efficiency was affected by the amount of nutrient applied. The plants under the highest nutrient treatments only used between 11 and 16% of the N and P in both studies. Plant uptake efficiencies for N and P were two to four times greater with lower rates of both N and P, indicating that fertilization rates were in excess of plant requirements. Azaleas and other plants are able to store excess nutrients. One advantage to excess nutrient fertilization may be that plants can utilize this excess nutrient supply in times of nutrient limitation (e.g. when first establishing roots in a new environment). Certainly, the establishment success of container plants in newly planted landscapes is a concern to the industry.

The study's efficiency results should be placed in context of loading rates. A per-plant nutrient application rate of 250 mg N per week translates into a rate of 1100 kg ha^{-1} half the standard rate cited by Chen et al. (2001) for azalea]. This assumes a 40-week production cycle and a density of 110,000 plants per hectare. If uptake efficiencies for N at this high rate average no more 16%, then 924 kg ha^{-1} can potentially lost through leachates and runoff. (1100 kg ha^{-1} x (1- 0.16). By reducing fertilization rates to 100 mg per week, uptake efficiency increases to an average of 26.5%, and under the same assumptions, only 440 kg/ha is applied per growing season. Potential N loss is reduced to 326 kg ha^{-1} (440 kg ha^{-1} x (1- 0.26), nearly a three fold decrease in N loading. Even greater reductions in P loading can be achieved by decreasing P rates to levels more attuned to actual plant requirements (22 kg P ha^{-1} vs 110 kg P ha^{-1}).

6.5 Conclusions

The results of these studies show that N influences the total growth of azalea and that P uptake is both, a function of P fertilization rate and growth, growth being governed primarily by N rate, notwithstanding other growth limitations. While insufficient quantities of both N and P increase root growth in azalea, a sufficient application rate of 100 mg N and 5 mg P per week maintained shoot and root growth at near maximal rates. While the effects of the second year's P treatments may have been confounded by native P in the substrate, the results show that very small quantities of P are needed to support growth in azalea. Many standard fertilizer formulas have N/P ratios in excess of plant P requirements. It is important to recognize that azalea is a low nutrient user, as an ericaceous perennial. Thus, these rates may represent minimal levels necessary to support general plant growth in container production.

To date, many nutrition guidelines in the literature recommend rates which over apply N to ornamentals. This study's high rate of 250 N mg per week could equate to applying 56 g of 18% N controlled release fertilizer to a liner plant throughout the first year of growth after transplanting. However, these studies suggest that maximal growth can be maintained by fertilizing with a moderate N rate, in the region of 22 g of an 18%N controlled release fertilizer. Phosphorus application should be based on N rate and P rate. Given the results of this study on azalea and based on similar high N/P ratios applied to holly (a high nutrient user) in the field study, P application should be no more than 1/10 that of the N rate. Fertilization strategy can play a role in uptake efficiency, as sufficient amounts of fertilizer applied at appropriate times during the growing period may increase the efficiency of nutrient uptake and decrease nutrient loss and loading into the environment.

Chapter Seven

Examining Issues of Water and Nutrient Supply, Uptake and Use Efficiency

7.1 Introduction

The research data presented thus far examine specific parts of the water and nutrient picture in container nursery systems. These studies took an integrated approach to examining water, nitrogen and phosphorus uptake efficiency in container plant production. It is clear that irrigation management, fertilization methods, and rates of fertilization all have interrelated effects on increasing nutrient uptake efficiency and reducing runoff in container plant production. There is great diversity in plant species grown in the ornamental nursery industry. Many varieties of ornamental plants have not been selected or bred for efficient use of nutrients, but rather for growth and flowering characteristics, and some for tolerance to difficult growing conditions in the landscape. In most cases, containerized production systems are nutrient-rich, moisture-laden environments, where ideally, all requirements for growth are met and plant growth limitations are minimized. The driving motive is to reduce production time and increase profits. Since water and fertilizer up until now have been relatively low-cost inputs into the production equation (especially compared to labor costs), there has been little incentive for efficient use of these resources. Several factors have been studied in this research, including nutrient rate, method of nutrient application and method of water application. The goal of this chapter is to examine the issues surrounding water and nutrient supply, uptake and efficiency and formulate recommendations from this research to increase plant nutrient uptake efficiency and reduce nutrient loss though runoff.

The efficiency at which plants take up, incorporate, and utilize nutrients is defined as nutrient use efficiency (NUE). Defined loosely, NUE is the amount of biomass produced per unit of nutrient (Chapin and Van Cleve, 1991). Given that definition, NUE also gives insight into the maximal efficiency of a species under nutrient limitation. In contrast, we define nutrient uptake efficiency as the fraction of applied nutrient taken up by the plant, as a proportion of that supplied. Nutrient use efficiency is influenced by plant factors such as physiological traits (e.g. high nutrient uptake and utilization) or biochemical traits (e.g. photosynthetic efficiency), and environmental factors such as nutrient availability or climatic conditions (Baligar et al., 2001). In the natural environment, plants are often restricted by one or more limiting resources and growth is often N or P limited.

If two nutrients are near the deficiency range in a system, the addition of one nutrient may temporarily increase biomass and dilute the tissue concentration of the other nutrient, causing a deficiency (Marschner, 1995). Conversely, if nutrients not in limitation are supplied, the tissue concentration of those nutrients will increase, yet growth will still be constrained by the limiting nutrient (Chapin et al., 2002). In general, plants require very similar nutrient ratios for optimal growth (Ingestad, 1971, 1982). If limitation occurs, the ratios will differ (Chapin and Van Cleve, 1991). Tissue nutrient ratios have been used to determine limitation in aquatic plants (Redfield, 1958) and in terrestrial plants (Koerselman and Mueleman, 1996). However, ratios may also reflect excess storage of an abundant nutrient rather than the limitation of another (Chapin and Van Cleve, 1991). Nutrient limitation and a tolerance for overabundance act as driving forces for physiological adaptation. Nutrient limitation is a key factor in species competition (Koerselman and Mueleman, 1996). The consequences of these adaptations are seen in the diversity of plant life via natural selection and by the short-term physiological regulation of nutrient uptake and use efficiency.

Chapin (1983) suggested several competitive adaptations for species growing in nutrient poor soil. These include slow growth, minimizing annual nutrient needs and nutrient exhaustion, efficiency in acquiring nutrients from soil, and efficient metabolism or nutrient use in producing new biomass. These adaptations are seen two on scales. For instance, on an evolutionary scale, evergreen species have adapted their physiology to suit low P turnover in poor soils by slow growth, high use efficiency, and longer retention times of leaf tissue (Chapin 1983). On a short-term basis, plants have been shown to adapt root growth based on local soil condition, nutrient availability, mycorrhizal infection (Eissenstat, 1992) or the production of root exudates (Ragothama, 1999; Gilbert et al. 1999; Marschner, 1995).

Nutrient use efficiency is an effective tool for examining nutrient availability and limitations in natural environments and explaining physiological adaptation to nutrient availability. However, since NUE may not fully explain situations where attempts are made to maximize yield or growth, (the stated goal of agriculture at present), I argue that this term (i.e. NUE) has limitations in applications to agricultural studies. Most agricultural (food) crops and certainly, most intensively grown ornamental species have not been selected or bred for high nutrient uptake or use efficiencies, nor are these plants grown in environments that would elicit high nutrient use-efficiency responses. For instance, when nutrients are abundant, as in most agronomic environments, we postulate that plant growth is genetically pre-determined to maximize shoot growth (light interception), with little need to invest in carbon-intensive root systems to scavenge for water and nutrients. Plants in these environments will have limited or confined roots systems, do not or cannot effectively explore large soil/substrate volumes; nevertheless nutrient uptake is usually luxurious and consequently, nutrient uptake efficiencies are low. Additionally, we contend that poorly timed or placed nutrient applications are not intercepted or taken up by roots, and can thus rapidly leach out of the rootzone, or are susceptible to competitive microbial use or other loss mechanisms. There certainly exists a need to breed plants for increased uptake capability or use efficiency, as Baligar et al. (2001) suggests, but better cultural management practices could possibly be as effective in increasing nutrient uptake and use efficiencies.

7.2 Improving Nutrient Use Efficiency

Baligar et al. (2001) suggest that the manipulation of plant and environmental factors along with best management practices can potentially improve plant NUE. The research data so far presented studies the effects of irrigation and fertilizer management on uptake efficiency, but has not discussed how NUE was affected by these treatments over time. The manipulation of plant growth and nutrient use efficiency by fertilization techniques is a key aspect of sound fertilization practices. Use efficiency as a concept can be used as an indicator for the use of nutrient resources. For example, Rose et al (1994) demonstrated that nutrient–use efficiency in poinsettias decreased at a high rate of N supply. Lin et al. (1996) noticed lower P tissue concentration in marigolds when fertilized with low P as compared to high P fertilization, without significant decrease in shoot growth and Lea-Cox et al., (2001b) found that short-term N use-efficiency increased in perennial citrus trees with decreased N availability.

7.2.1 Nutrient Use Efficiency as Affected by Fertilizer Rate

It is possible to influence NUE by changing fertilizer rate as seen in both azalea spring studies. In these two studies (Chapter 6), N and P rates were manipulated to ascertain the lower limits of fertilization, without compromising short-term growth. Whole plant NUE's have been calculated for each fertilizer treatment from the second spring study (2002). Table 7-1 shows azalea nitrogen NUE (N-NUE) and phosphorus NUE (P-NUE). Use efficiency in this case denotes the total amount of biomass (in grams) produced per gram of nutrient. Significant differences in N-NUE were only due to the main effects of N fertilization ($P<0.0001$). In contrast, significant differences in P-NUE were due to the main effects of both N fertilization ($P=0.0005$) and P fertilization ($P<0.0001$). It is worth noting that azalea given 100 and 250 mg N with 0 mg P per week had significantly greater P-NUE than other treatment combinations, as plant P was diluted by biomass accumulation. This further supports the fact that N is chiefly responsible for promoting vegetative growth.

Figure 7-1 shows N-NUE of all azalea under 5 mg P per week (data in Table 7-1). The fitted curve ($r=0.95$ at $P<0.001$) shows that when higher amounts of fertilizer are applied, azalea produce less biomass for each unit of nutrient, hence, nutrient use efficiency declined. These results are generally supported in the literature (Lea-Cox et al., 2001b). For instance, azalea given 25 mg N per week had significantly greater N-NUE than azalea given either 250 or 100 mg N per week treatments. The point of inflection in

Table 7-1. Average azalea NUE for N and P (2002 spring study). NUE is g biomass divided by g nutrient. Standard errors based on n=3. Lower case letters indicate significant differences (LSD at P=0.05) between treatments.

Treatment mg week^{-1}	Total Dry Mass (g)	Total N (mg per plant)	N–NUE Mass g/g	Total P (mg per plant)	P -NUE Mass g/g
N250:P25	23.44 (± 2.34)	428.9 (± 34.1)	54.6 (± 2.9) c	50.5 (± 6.8)	469.3 (± 21.1) c d
N250:P5	22.91 (± 0.61)	380.3 (± 19.6)	60.6 (± 4.1) b c	40.8 (± 0.9)	561.5 (± 6.6) b
N250:P0	21.65 (± 2.26)	417.4 (± 37.6)	51.8 (± 2.2) c	31.4 (± 3.6)	692.5 (± 16.9) a
N100:P25	22.49 (± 3.24	355.3 (± 60.8)	63.9 (± 3.2) b c	52.7 (± 9.1)	432.5 (± 20.5) d
N100:P5	21.03 (± 1.30)	326.2 (± 22.1)	64.6 (± 1.5) b c	41.1 (± 2.4)	511.7 (± 11.2) b c
N100:P0	23.22 (± 1.41)	346.2 (± 44.4)	68.9 (± 8.2) b	36.5 (± 2.9)	639.7 (± 35.4) a
N25:P25	17.72 (± 1.31)	188.0 (± 13.3)	94.2 (± 2.0) a	43.2 (±.3.5)	410.3 (± 3.2) d
N25:P5	16.26 (± 1.42)	186.8 (± 20.2)	87.5 (± 2.2) a	37.0 (± 5.1)	447.0 (± 28.4) c d
N25:P0	17.30 (± 1.21)	177.9 (± 12.7)	98.1 (± 9.2) a	31.9 (± 4.2)	553.8 (± 52.1) b

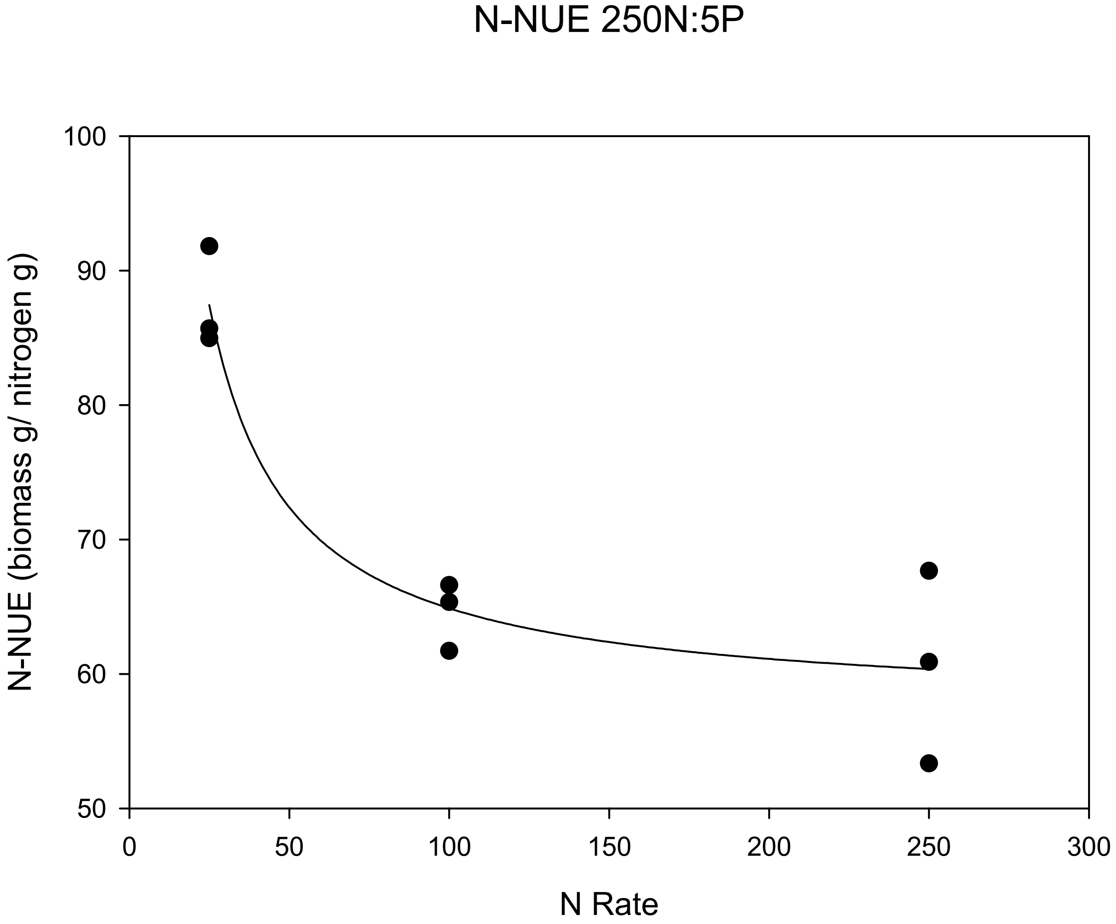


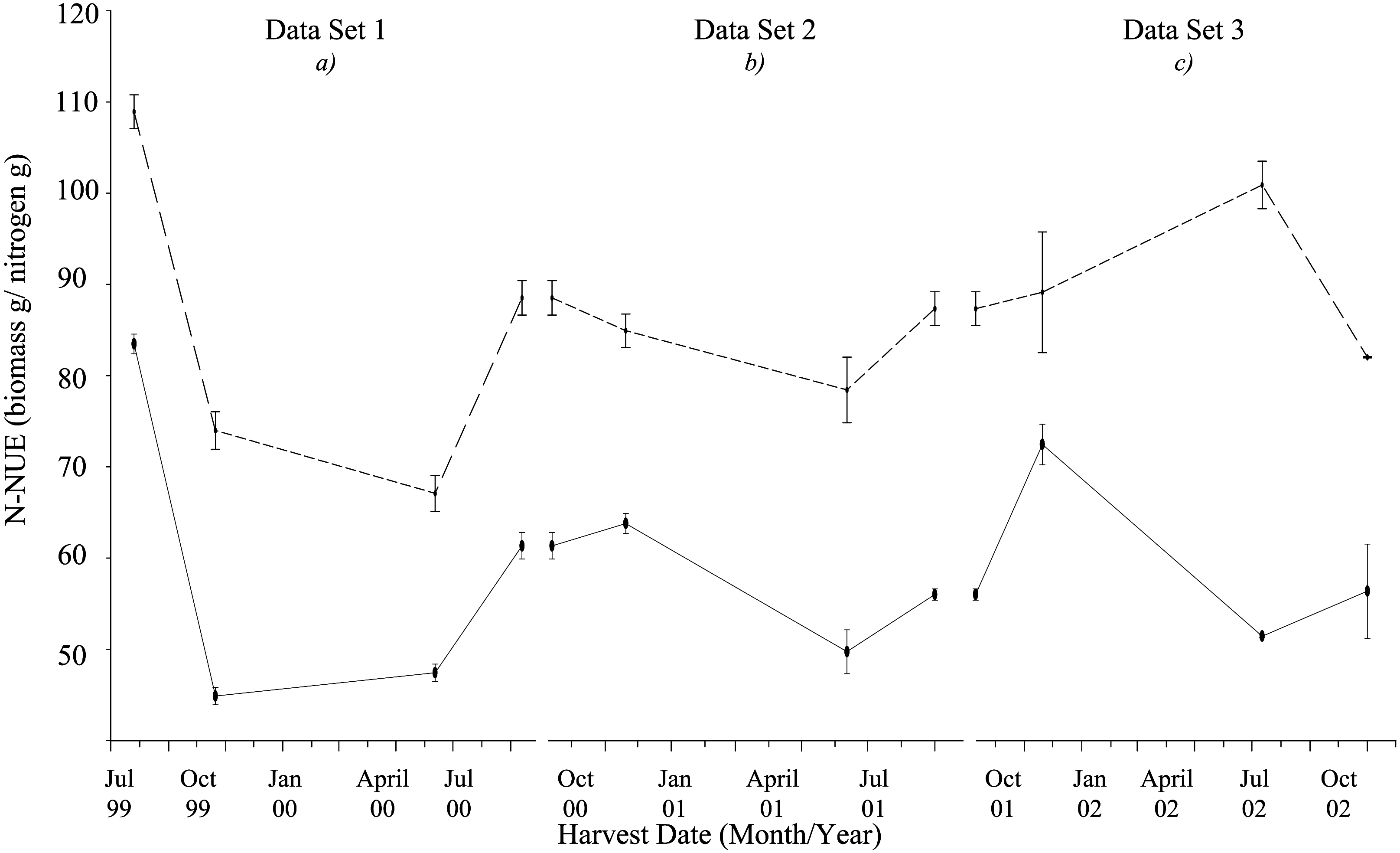
Figure 7-1. Nitrogen NUE for azalea given all N treatments and 5 mg P per week (2002 spring study). The data was best fit with an inverse first-order polynomial curve with the equation $y = 57.4 + 751.8 /x$, $r^2 = 0.90$.

this graph (i.e. the point at which the most biomass (g) was produced per gram N, i.e., the most efficient NUE) was approximately 65 mg N per week. This perhaps indicates that azalea growth in this specific study and at this stage of growth would not be limited by N above this average weekly N supply (rate). However, while NUE shows the efficiency of nutrient use, it does not necessarily take into account all the changing factors that may affect growth over time. While improving use efficiency through limiting nutrients is effective, this method would be not be economically feasible for a nursery operation, if growth and/or yield was significantly compromised by nutrient limitation.

7.3 A Comparison of Studies

The long-term field experiments examined several aspects of fertilization and irrigation application efficiency over three separate seasons. Efficiency comparisons may be made between certain field study treatments and similarly aged plants from the spring study treatments. Azalea under drip irrigation received 12.17 g N and 1.41 g P over the first 14 months with approximately 42 growing weeks (July through November 1999 and March through August 2000) in that time. Thus, the average weekly fertilization rate would approximate 290 mg N and 34 mg P per week, which was quite similar to the second spring study's high weekly N and P rate (250N:25P). Additionally, fertilizer was applied directly (by hand) to azalea in this spring study not unlike with drip irrigation. Nitrogen uptake during the spring studies for azalea under the 250N:25P treatment averaged 31 mg N per week. In comparison, azalea under drip irrigation averaged a N uptake of 20 mg per week during the first 12 weeks of data set 1 (Sept. 1999 to Nov 1999), which increased to 95 mg per week the following spring and slowed to an average of 63 mg per week during the summer of 2000. Tyler et al. (1996b) found *Cotoneaster* in 3.8 l containers took up approximately 70 mg N per week at 27% uptake efficiency at a rate of 250 mg per week within a 100-day study from June to September. The increase in uptake rate in spring may have been due to azalea roots exploring virtually the whole container volume (11.7 l) by this time. Nitrogen and P uptake efficiencies between azalea in the spring greenhouse studies at 250N:25P and azalea under drip irrigation in data set 1 were remarkably similar (see Tables 4-1, 5-1, 6-3 and 6-6). So, given the uptake rates and efficiencies of the field and spring studies, the 250 mg N and 25mg P nutrient application rates were almost assuredly above those required to satisfy the growth requirements of azalea, at least during the first few months of the study. From the spring study results, it appears 100mg N and 5 mg P treatments were in all likelihood sufficient to maintain maximal growth rates of azalea. Nutrient uptake efficiencies were significantly affected by the rate of N and P supply, increasing on average from 12% to 28% and 37% at N additions of 250, 100 and 25 mg N per week, respectively. Similarly, P uptake efficiency increased from 15% to nearly 50%, comparing the 25 and 5mg P per week rates. These results are significant when you consider that 100mg N per week translates to five, 500ml irrigations at 40 mg N l^{-1} over the week, which may be up to a ten-fold reduction in N applications for many commercial growing operations. Similarly, 5 mg P per week translates to a concentration of 2 mg P l-1 in the same irrigation volume, a 15 to 20-fold reduction in P applications for many growing operations. Even though azalea is known to be a low nutrient-use species, Ristvey et al. (2001) showed that holly (a supposedly high nutrient-use species) had no greater N and P uptake than azalea during the first year of production. Nevertheless, as roots explore the remainder of the container volume and as demand for nutrients increase with plant growth, increased rates would more than likely be needed after the first season. For instance, maximal nutrient uptake in azalea under cyclic drip irrigation averaged 220 mg week and occurred during the first fall season of data set 3. Incidentally, this high uptake rate was accompanied by an uptake efficiency of 40%. The following spring, summer and fall, the rate of N uptake decreased together with uptake efficiencies indicating periodicity of nutrient uptake during the growing season. This also may have been due to releasing the limitation of constrained rooting volume after increasing pot size before the onset of data set 3.

Figures 7-2 a, b, and c show whole plant and leaf N-NUE for azalea under drip irrigation with cyclic timing for data sets 1, 2 and 3. To interpret the figure, note that a decrease in NUE shows greater nutrient uptake and slower growth per unit of N. An increase in NUE shows greater growth and slower nutrient uptake per unit N. No change in NUE denotes a balance of plant growth and nutrient uptake. After the initial harvest, there is a general upward trend in NUE until the penultimate harvest. This shows the long-term trend of an increase in woody (perennial) biomass, which increases NUE because it contains less N. Leaf NUE, a measurement typically used to indicate plant nutrient status (Chapin and Van Cleve, 1991) tracks whole plant NUE patterns for the first two data sets. The initial harvest in July of 1999 (Fig 7-2 a) shows whole plant and leaf N-NUE at a very high level, as plants were probably nitrogen deficient at this time. Nitrogen use efficiency rapidly decreases during the first 3 months showing luxurious N uptake with little growth. By the end of data set 1, N-NUE increased to levels resembling that of azalea given 25 mg N per week in the spring studies. This may have been due to a combination of rapid



Figures 7-2 a, b, and c. Mean nitrogen use efficiency of whole azalea plants (dashed line) and leaf (solid line) under drip irrigation and cyclic timing for data sets 1 (July 1999 to Sept. 2000), 2 (Sept. 2000 to Sept 2001) and 3 (Sept. 2001 to Nov2002). Standard error bars based on n=8 for data set 1 and 2, n=2 for data set 3.

growth and exhaustion of the CRF fertilizer, even though there was supplemental soluble N fertilization applied at 90 mg a week from August to the end of the data set in September 2000. It is also possible that the June pruning removed tissue with a high concentration of N. Note that the NUE data does not address growth or yield directly. The increasing N-NUE value may be due to the difference in biomass as compared to the relatively young azalea liners used in the spring studies. Of note however, is that similar patterns for N-NUE in data sets 1 and 2 show a strong periodicity between nutrient uptake and plant growth. Spring and fall decreases in N-NUE suggest periods of N uptake while summer N-NUE increases suggest biomass growth. In data set 3 (Fig. 7-2 c) however, whole plant N-NUE does not follow this pattern even though leaf N-NUE does. The upward slope denotes increased biomass to N ratio. The cause could be related a response to constant fertilization, but is more likely due to a June pruning which removed tissue containing the greatest concentration of N, increasing N-NUE. A rapid decline in N-NUE from July to Nov. 2002 shows increased N-uptake in contrast to the previous data sets. Lastly, this semi-deciduous azalea has partial leaf loss and N is retranslocated out of leaf tissue into roots in response to shorter periods of light and cold weather dormancy. Nitrogen NUE were compared between azalea under cyclic timed drip irrigation and azalea under cyclic timed overhead irrigation to evaluate differences irrigation may have had on N-NUE (see Appendix B Figure B7-1). Azalea N-NUE from the two treatments were comparable, especially with the first two data sets.

7.4 Predicting Rate and Timing of Fertilization from Efficiency Data

Efficiency in nutrient uptake and use in azalea and other plants (Rose et al., 1994; Tyler et al.,1996b; Lea-Cox et al., 2001b) are in part affected by rates of application. Additional factors affecting uptake efficiency are associated with irrigation management, cultural practices (such as pruning) and other loss mechanisms like microbial competition. With knowledge of the cumulative effects of these factors, we should be able to more efficiently gauge fertilization rates to containerized plants. Our studies and most others in the literature have found that N uptake efficiencies average no more than 35% per year in containerized ornamental production, given current methods of application and at minimal rates. Yeager (1996) reported uptake efficiencies of up to 55% in Yaupon holly, but as a southeastern US native species, which competes well in sandy soils, it may be naturally efficient in N uptake. Recent studies reported N uptake efficiencies ranging from 8 to 31% in holly and viburnum (Ivy et al., 2002), and in cotoneaster (Groves et al., 1998; Tyler et al. 1996b) depending on rate and timing of fertilization. Our studies show N uptake efficiencies of 35% in azalea under TDR timed drip irrigation and 37% in azalea given limiting N rates (25 mg N· week^{-1}). However, these treatments are either not practical or best-case management scenarios, which are unlikely to be utilized as the general practice in container nursery operations. Where industry standard application methods were used in our studies, i.e., where both soluble and CRF were applied at rates greater than or equal to100 mg per week with overhead irrigation, N uptake efficiencies in azalea were at best between 20 and 28%.

Azalea in the long-term study under drip irrigation accumulated 9.89 grams of N in a 3-year growth cycle (data sets 1, 2, and 3) of 112 growing weeks. The total amount of N taken up increased from the previous data set (see Tables 4-1, 2, and 3) and the weekly rate of N uptake in azalea under drip averaged 50, 100 and 112 mg in each successive data set. This was an average rate, as during the first part of data set 1 (August to November 1999) and these plants did not take up more than 20 mg a week. However, the rate of uptake rate increased with plant growth to a maximum of 220 mg N per week and an uptake efficiency of 40% in the fall of 2001 (data set 3). We therefore conclude that for azalea and high nutrient-use woody perennials (such as holly), that a rate equating to 100 mg per week during the first season would be more than adequate to maintain maximal growth rates. After the first season, higher rates would obviously be needed to satisfy increasing plant growth requirements. Growth requirements for azalea would dictate that N fertilizer rates should probably increase to between 200 and 250 mg N per week during the second year. This incidentally, is a common recommended rate for 6 to 9 month CRF (The Scotts Company, Maysville, OH.)

Most importantly, the implications of adjusting fertilization rates and increasing uptake efficiency have large consequences for potential loading rates (loss) to the environment. For example, at a rate of 250 mg per week and 16% uptake efficiency, the loading rate at a nominal 110,000 (12 l) container plants per ha is 250 mg x 40 weeks x 110,000 = 1,100 kg N ha^{-1} yr^{-1} (1000 lbs N /acre/yr). Thus, at 16% uptake efficiency, the potential loss would be 924 kg N ha^{-1}. At 100mg N per week and at 26.5% uptake efficiency, this potential loss would be reduced to 323 kg ha^{-1} [i.e. 100mg x 40 weeks x 110,000 = 440 kg N; 440 kg ha^{-1} x (1- 0.26)], a reduction of more than 65% in N loading to the environment. Even greater reductions in P loading can be achieved under the same scenario, by decreasing P rates to levels more attuned to actual plant requirements (22 kg P ha^{-1} vs. 110 kg P ha^{-1}).

7.5 Increasing Efficiency through Management Practices

With present irrigation practices and fertilization rates, N uptake efficiencies in many container nursery production situations appear to be between 10 and 28% at best. At these efficiencies, N and P fertilization rates are excessive from an environmental viewpoint. I contend that if optimal growth is to be maintained and environmental needs be met, uptake efficiency must be increased. Several factors other than rate and irrigation method affect the efficiency of N and P uptake including irrigation management, cultural practices and other loss mechanisms like microbial competition. It is likely that further increases in uptake efficiency and reductions of nutrient loss could be attained if additional management practices are adopted.

Irrigation is the most important aspect of controlling nutrient runoff and in many respects, has important implications for nutrient uptake efficiency. While drip irrigation significantly decreased total runoff in the long-term studies particularly when soluble fertilizer was used, the management of drip systems with small container sizes is daunting.

With increased sole use of CRF's for supplying nutrients in the container nursery industry, drip irrigation may become less of a concern factor to reduce total nutrient losses. Since overhead irrigation is the most widely used method of irrigation by nurseries throughout the US, increasing interception efficiency for water conservation purposes will likely become the more important issue. Although TDR did not effectively increase uptake efficiency in either azalea or holly, it did prove effective in both reducing water use and nutrient runoff with both overhead and drip irrigation systems, as water applications were more exactly matched to actual plant water requirements. Seasonal growth patterns are exhibited in many species and timing nutrient rates with seasonal uptake is also needed to improve uptake efficiency.

7.6 Conclusion

This research presented an integrated study of container nursery management practices, to investigate the efficiencies of plant nutrient uptake and potential nutrient loss as influenced by irrigation water management. Recommendations on fertilizer rate are given to provide practical guidance, reduce nutrient inputs, increase plant uptake efficiencies and reduce loading rates to the environment. Sensing substrate water potentials using TDR effectively reduced water use and runoff. The success of this type of irrigation sensing technology warrants further research into less expensive and wireless forms of this technology.

This research has shown that plant nutrient uptake efficiency can be manipulated by a variety of factors, and nutrient loss from runoff can be significantly reduced, if relatively modest changes in fertilization practices are adopted. The relatively high rates at which N and P fertilizers are applied to container ornamentals in general exceed the requirements of azalea and holly, resulting in very low nutrient uptake efficiencies. Furthermore, poor irrigation management, pruning, and microbial competition for N results in the need to increase nutrient application to replace these losses. Lastly, it has been shown that NUE can be used as a tool to determine nutrient status in plants, but care must be given when interpreting growth or yield from NUE information in intensive agricultural scenarios.

Chapter Eight

Summary

8.1 Introduction

Water quality remains as a dominant issue within the Chesapeake Bay watershed and nutrient loading from point and non-point sources continues to undermine the progressive recovery of this ecosystem. The agronomic industry has taken many innovative steps toward reducing nutrient inputs, using a knowledge base that spans several decades. Until recently, few data existed to assist the ornamental plant industry to increase the efficiency of nutrient application, and none have examined water and nutrient uptake efficiency issues in an integrated fashion. Specifically, these research studies examined water, nitrogen and phosphorus application, uptake, partitioning, loss and efficiency of azalea and holly in container-nursery plant production, to understand the long-term dynamics and to develop best management practices to increase nutrient efficiency and reduce nutrient runoff.

8.2 Summary of Research Results

Management factors have an interrelated effect on increasing nutrient uptake efficiency and reducing runoff in container plant production. Irrigation water application and management plays a dominant role in reducing nutrient runoff from these production systems. Methods for delivering the correct amount of water based on plant needs have yet to be fully utilized in nursery settings. Drip irrigation was shown to be more efficient in water application, to have less runoff, and in some cases, greater irrigation use efficiencies (IUE), yet is impractical for most container-nursery operations. Therefore, improving overhead irrigation management by increasing interception efficiency will have a positive effect on reducing potential runoff and may improve IUE. The use of plant-driven irrigation scheduling technology such as TDR was shown to be effective in reducing irrigation water applications and particularly in reducing runoff volumes from overhead irrigation systems. The success of this type of substrate-sensing technology warrants further research into less expensive and wireless forms of this technology.

This research is first in the ornamental literature that has simultaneously documented N and P dynamics in a containerized nursery by integrating application, leaching, and uptake data into a single study. The results showed that in many cases N and P uptake efficiency and runoff is negatively affected by overhead irrigation, especially if soluble nutrients are applied via fertigation. Since the use of overhead irrigation remains the least problematic and most economic method of irrigation at present, several management options can be employed to increase the efficiency of nutrient application and reduce runoff. The results of these studies suggest that the use of controlled-release fertilizers compared to soluble fertilizer sources may help minimize the negative environmental impacts of overhead irrigation. Additionally the use of plant driven irrigation technology (TDR) decreased total overhead volumes and soluble nutrient runoff by half.

The results of these experiments suggest that seasonal timing of fertilizers may increase N and P uptake efficiency. Evidence from reduced runoff and fall growth rates indicated that fall fertilization of azalea and holly was equally efficient as spring and summer fertilization. This is also the first study of its kind to examine the affects of pruning on nutrient use and document the impact on total N and P reserves. Large quantities of N and P were removed seasonally from plants. This nutrient removal almost certainly has negative impacts on potential growth, increasing the time to sale and reducing profit margins.

Intensive Spring study results show that N influences the total growth of azalea and that P uptake is both a function of P fertilization rate and growth, governed by N rate. Higher fertilization rates increase plant nutrient uptake but do little to increase growth. These studies suggest that effective growth can be maintained by fertilizing with a more moderate N rate. Phosphorus application rates should be based on a more equitable N:P ratio. Many standard fertilizer formulas have N/P ratios in excess of plant P requirements and P application for long-term vegetative growth should be no more than 1/10 that of the N rate for most woody ornamentals. Finally, fertilization strategy can play a role in uptake efficiency, as sufficient amounts of fertilizer applied at appropriate times during the growing period may increase the efficiency of nutrient uptake and decrease nutrient loss and loading into the environment.

The application of nutrient use efficiency (NUE) gave insight into seasonal fluctuations of nutrient use in azalea. Nutrient use-efficiency is a valuable tool in determining nutrient status in plants, but long-term dynamics indicate that care must be given when interpreting growth or yield from NUE information, especially in water and nutrient-rich environments.

At best, N uptake efficiencies average no more than 28% in a given growing season utilizing typical management practices such as overhead irrigation with an adequate fertilization rate. These efficiencies can be much less with lower plant densities (to maximize canopy development) and high fertilization rates. Novel management strategies in the area of irrigation, fertilization, and cultural practices suggested within this research can be adopted to improve upon these low efficiencies and reduce nutrient pollution in our watersheds.

Appendix A

Table A2-1. Target soluble fertilization regime by Data set. In data set 2 and 3, two drip stakes were placed in containers, doubling the volume/min received in data set 1.

Data Set	Dates	Target ppm	Cycles per day (cyclic irrigation only)	Minutes per Cycle Drip/Overhead	Irrigation Start times	Fertilizing Schedule
		N/P				
1	Aug 99 to Sept 99	150 / 1.5	1	20 / 20	11.00 am	3 weekly
	Sept 99 to Nov 99	75 / 1.5	2	20 / 20	8:00/11:00 am	2 weekly
	May 00 to Aug 00	150 / 1.5	2	15 / 30	8:00/11:00 am	2 weekly
	Aug 00 to Sept 00	75 / 1.5	2	15 / 30	8:00/11:00 am	2 weekly
2	Sept 00 to Nov 00	100 / 1.5	2	15 / 30	5:00 / 10:00 am	2 weekly
	May 01 to June 01	250 / 2.5	2	15 / 30	5:00 / 10:00 am	2 weekly
	June 01 to July 01	200 / 2.5	3	15 / 30	5:00 / 8:00 11:00 am	2 weekly
	July 01 to Sept 01	75 / 2.5	3	15 / 30	5:00 / 8:00 11:00 am	continuous
3	Sept 01 to Nov 01	50 / 1.5	3	10 / 30	5:00 / 10:00 am 1:00 pm	continuous
	May 02 to June 02	100 / 4.5	3	10 / 30	5:00 / 10:00 am 1:00 pm	continuous
	June 02 to Nov 02	50 / 4.5	3	10 / 30	5:00 / 10:00 am 1:00 pm	continuous

Table A2-2. Ratio of N, P, K and Fe in soluble fertilizer from Wye Field Studies.

Fertilizer	N %	P %	K %	Fe
NH_4NO_3	34.00	0	0	0
KNO_3	13.75	0	45.00	0
APP	11.00	* 14.84	0	0
[§]Sprint	0	0	0	10

Table A2-3. Data set 1 fertilizer concentrate formulations in 70l container for a 1:200 injection.

N/P ppm	**150/1.5**	**75/1.5**
Fertilizer	g	g
NH_4NO_3	5760	2880
KNO_3	757.5	378.8
APP (mls)	70	70
[§]Sprint	40	40
[‡] STEM	90	90

Table A2-4. Data set 2 fertilizer concentrate formulations in 70L container for a 1:200 injection.

N/P ppm	**100/2**	**250/2**	**200/2**	**75/2**
Fertilizer (g)	g	g	g	G
NH_4NO_3	3840	9600	7680	2880
KNO_3	505	1010	1010	378.8
APP (mls)	161	161	161	161
[§]Sprint	40	40	40	40
[‡] STEM	90	90	90	90

Table A2-5. Data set 3 fertilizer concentrate formulations in 70L container for a 1:200 injection.

N/P ppm	**100/1.5**	**100/4.5**	**50/4.5**
Fertilizer (g)	g	g	g
NH_4NO_3	3840	3840	1920
KNO_3	505	505	252.5
APP (mls)	161	404	404
[§]Sprint	40	40	40
[‡] STEM	90	90	90

[§]Sprint – chelated iron
[‡] STEM - Soluble Trace Elements

Table A2-6. Soluble fertilization recipe for Spring Study 2001 for 6 N:P rates. An 8 liter concentrate was made and hand applied onto azalea at 250 ml aliquots.

	Rate					
Fertilizer	250:25 g	250:5 g	250:0 g	25:25 g	25:5 G	25:0 g
NH4NO3	20.58	20.58	20.58	2.29	2.29	2.29
KNO3	5.78	5.78	5.78	0.00	0.00	0.00
KH2PO4	3.52	0.70	0.00	3.52	0.70	0.00
K2SO4	0.00	1.80	2.25	4.98	6.78	7.23

Table A2-7. Soluble fertilization recipe for Spring Study 2002 for 6 N:P rates. A 9 liter concentrate was made and hand applied onto azalea at 300 ml aliquots two times a week.

	Rate								
Fertilizer	250:25 g	250:5 g	250:0 g	100:25 g	100:5 g	100:0 g	25:25 g	25:5 g	25:0 g
NH4NO3	9.64	9.64	9.64	4.29	4.29	4.29	1.07	1.07	1.07
KNO3	2.71	2.71	2.71	0.00	0.00	0.00	0.00	0.00	0.00
KH2PO4	1.65	0.33	0.00	1.65	0.33	0.00	1.65	0.33	0.00
K2SO4	0.00	0.85	1.06	2.33	3.18	3.39	2.33	3.18	3.39

Calculation A2-1. Conversion of bulk substrate CRF incorporation rate to N and P content in containers at start of data set 1.

Hardwood substrate (Holly)
1.39 kg m^{-3} Osmocote 19-5-9 = 4.94 g N per pot
70 pots = 0.57 g P per pot

Pine Bark substrate (Azalea)
1.04 kg m^{-3} Osmocote 19-5-9 = 3.70 g N per pot
70 pots = 0.42 g P per pot

Calculation A3-1. Example conversion of rainfall totals into rain water received per container in data set 1, 2 and 3.

Rainfall total for data set 1 = 121.1 cm
Plot area = 700488.9 cm^2

1. Convert to liters per plot

   121.1 cm x 700500 cm^2=
   84408912.45 cm^3 =
   84830.6 l

2. Convert to liters per container

   $\frac{84830.6\ \mathrm{l}}{448\ \mathrm{containers}}$ = 189.4 l per container

Rainfall total for data set 2 = 99.2 cm
Plot area = 700488.9 cm^2

1. Convert to liters per plot

   99.2 cm x 700500 cm^2=
   69489600 cm^3 =
   69489.6 l

2. Convert to liters per container

   $\frac{69489.6\ \mathrm{l}}{224\ \mathrm{containers}}$ = 310.1 per container

Rainfall total for data set 3 = 56.2 cm
Plot area = 700488.9 cm^2

1. Convert to liters per plot

   56.2 cm x 700500 cm^2=
   39368100 cm^3 =
   39368.1 l

2. Convert to liters per container

   $\frac{39368.1\ \mathrm{l}}{140\ \mathrm{containers}}$ = 281.4 per container

Calculation A3-2. Theoretical interception efficiency for data sets 1 and 2 based on container density of the production area occupied by containers receiving double irrigation coverage (where irrigation spray overlaps) and single irrigation coverage.

Production area = 7.9 x 8.8 = 69.5 m^2
Double irrigation coverage area = 4.9 x 7.3 = 35.8 m^2
Single irrigation coverage area = 69.5 – 35.8 = 33.7 m^2

Data set 1

Container surface area = 20.5 m^2

Data set 2

Container surface area = 10.3 m^2

Interception Efficiency (IE):

$$\frac{\text{Container surface area}}{\text{Double coverage area} + \left(\frac{\text{single coverage area}}{2}\right)}$$

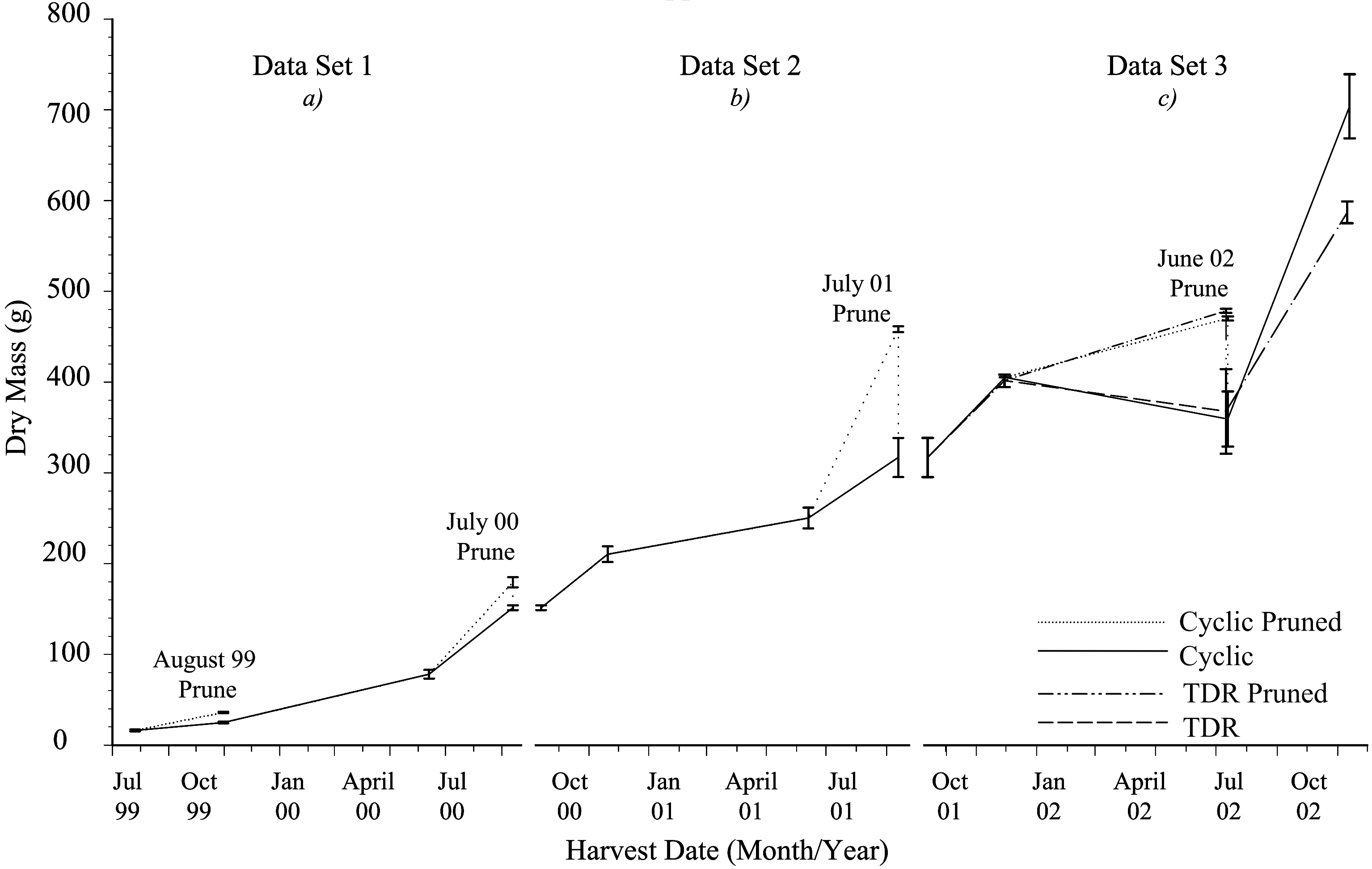
For data set 1

$$\frac{20.5\ m^2}{35.8\ m^2 + \left(\underline{33.7\ m^2}\right)} \times 100 = 38.8\ \%$$

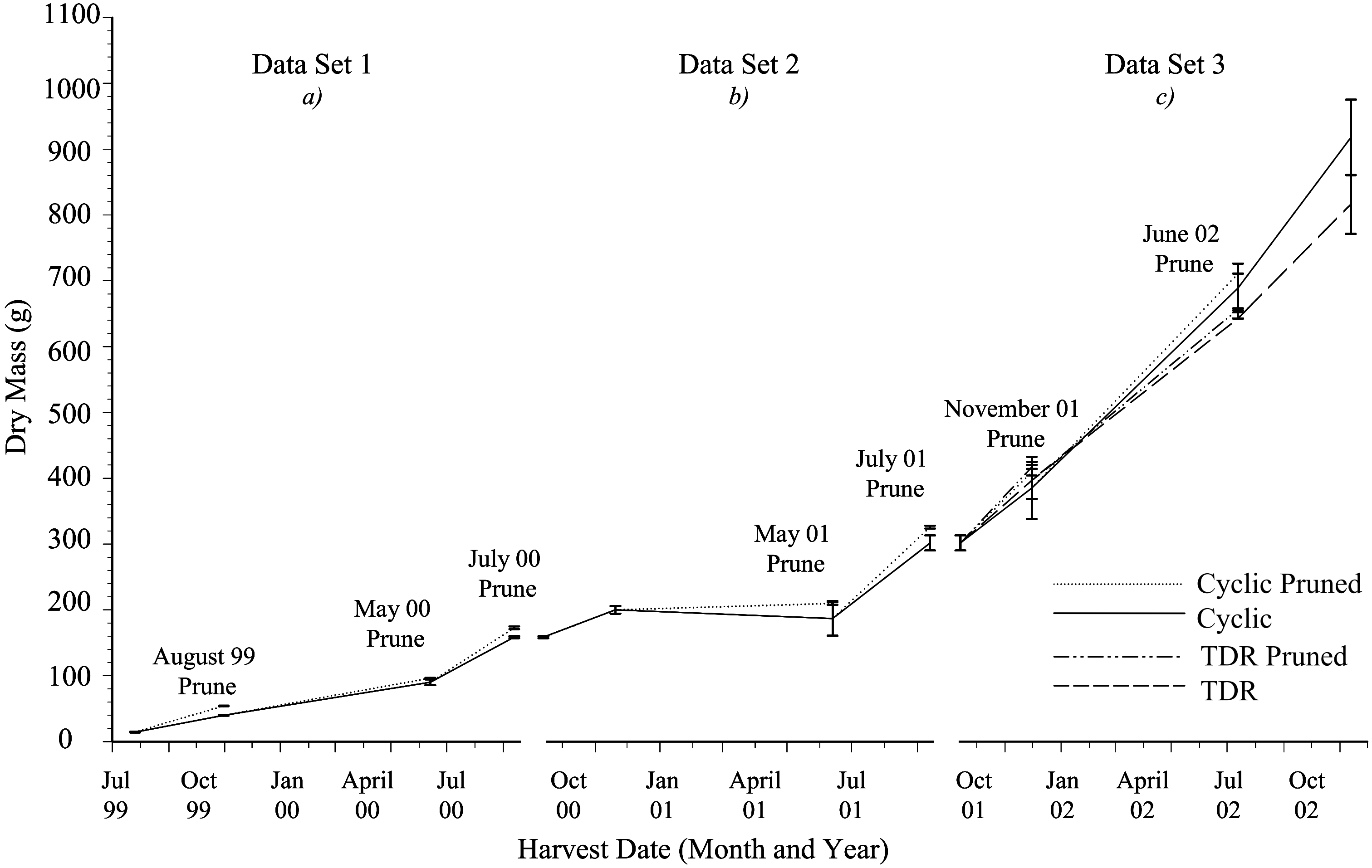
For data set 2

$$\frac{10.3\ m^2}{35.8\ m^2 + \left(\underline{33.7\ m^2}\right)} \times 100 = 19.4\%$$

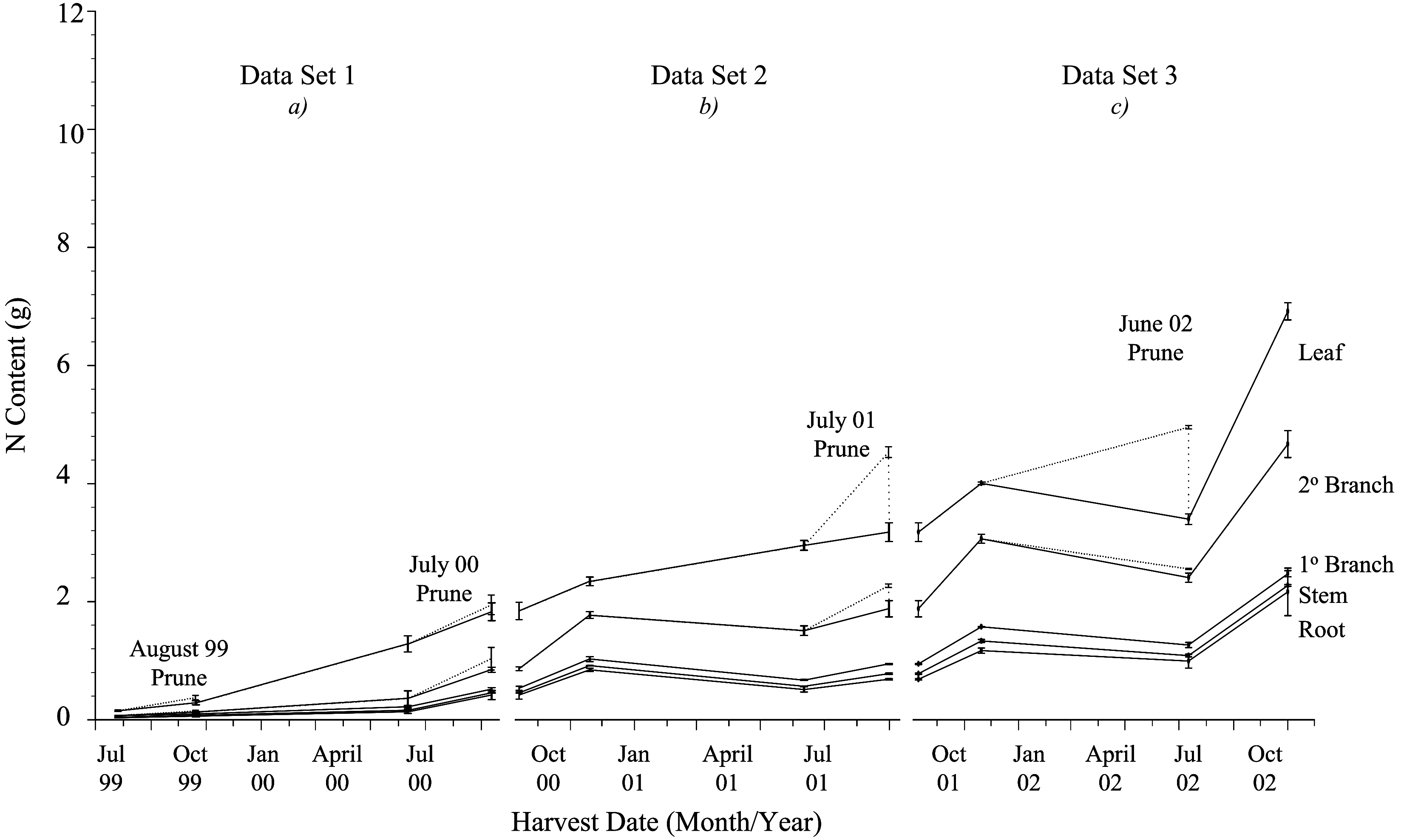
Appendix B



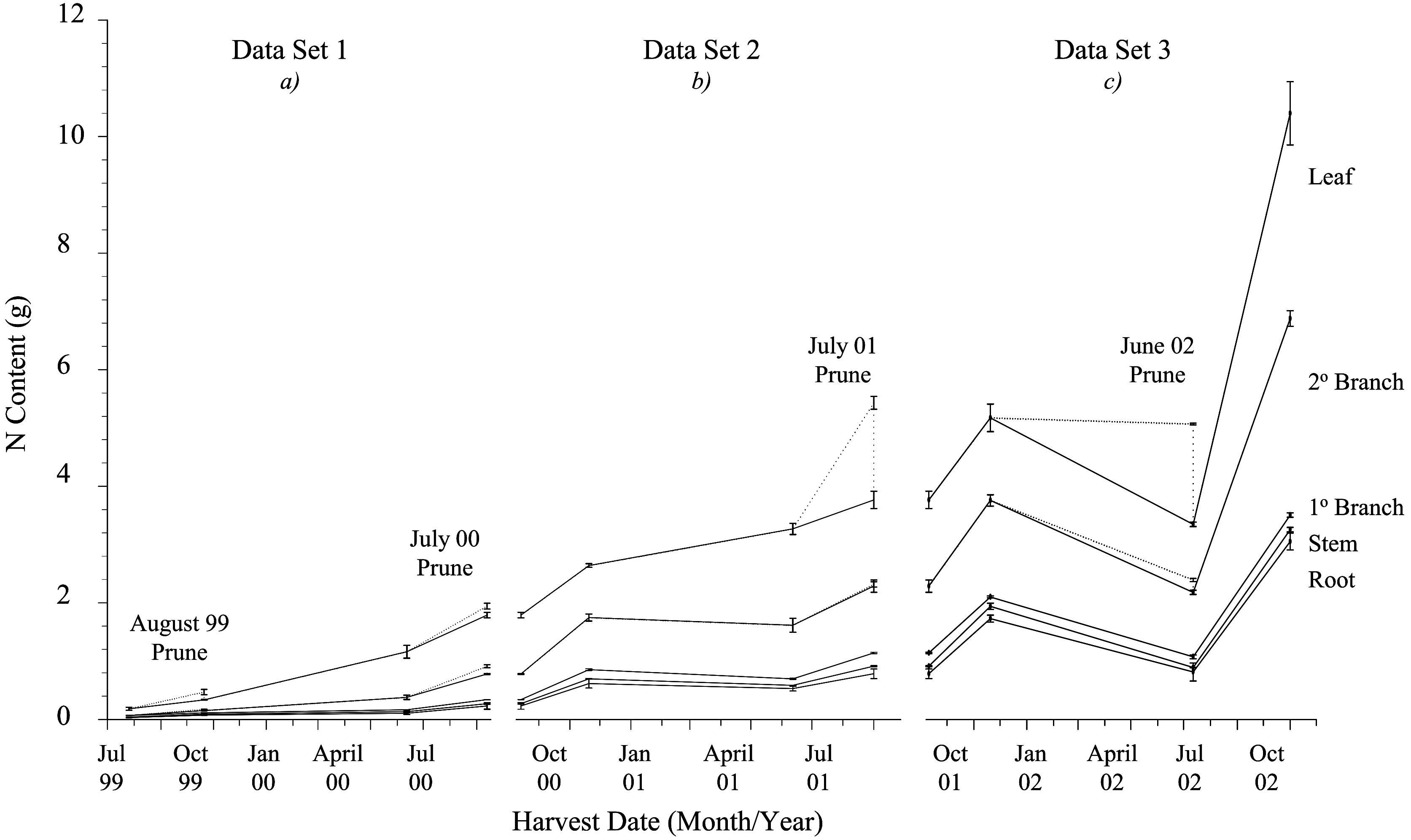
Figures B4-1 a, b, c. Mean cumulative dry mass of azalea under overhead irrigation for data sets 1, 2, and 3. FigureB4-1 c shows dry mass for both cyclic (solid line) and TDR (dashed line) irrigation scheduling treatments. Dry mass pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



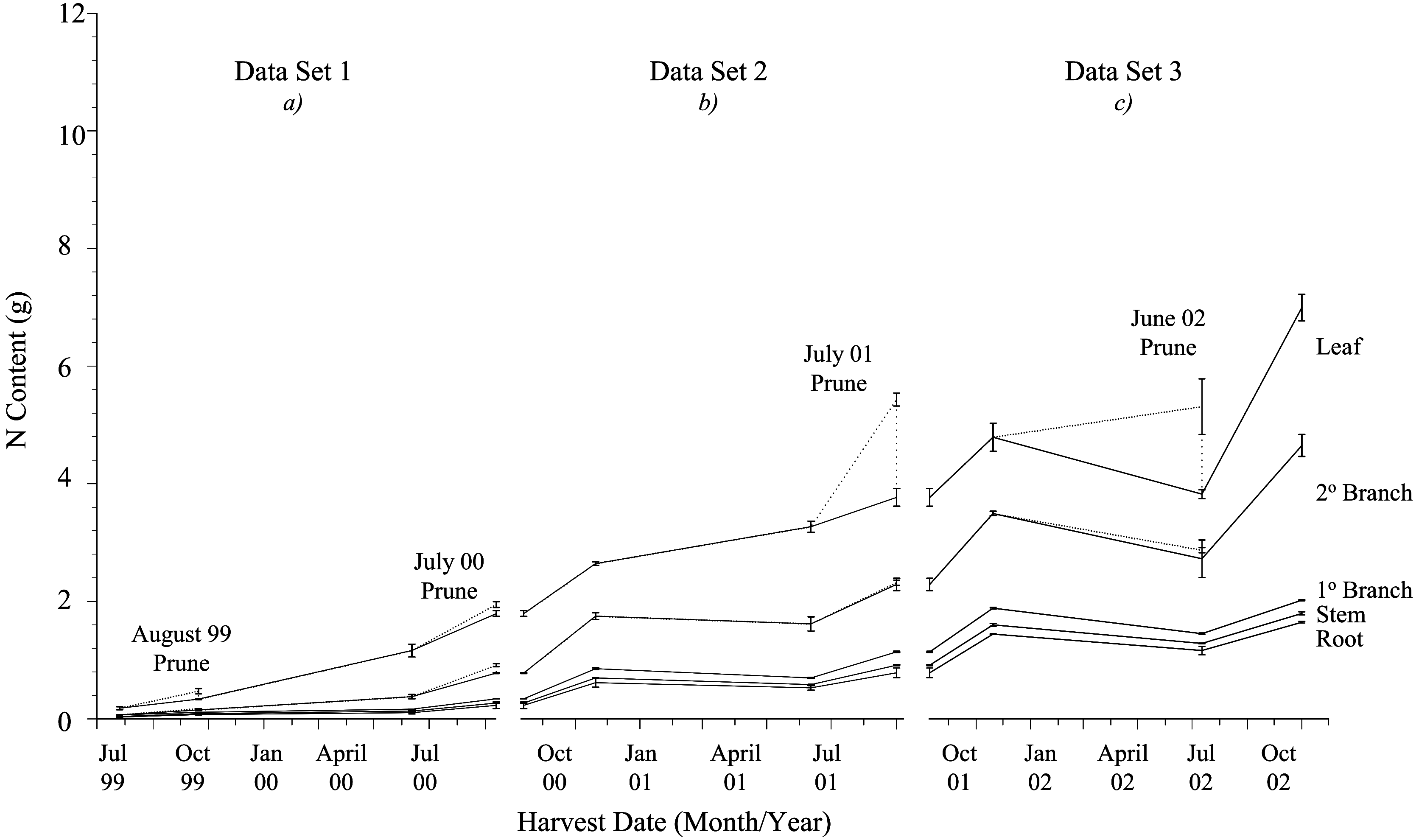
Figures B4-2 a, b, c. Mean cumulative dry mass of holly under drip irrigation for data sets 1, 2, and 3. Figure B4-2 c shows dry mass for both cyclic (solid line) and TDR (dashed line) irrigation scheduling treatments. Dry mass pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



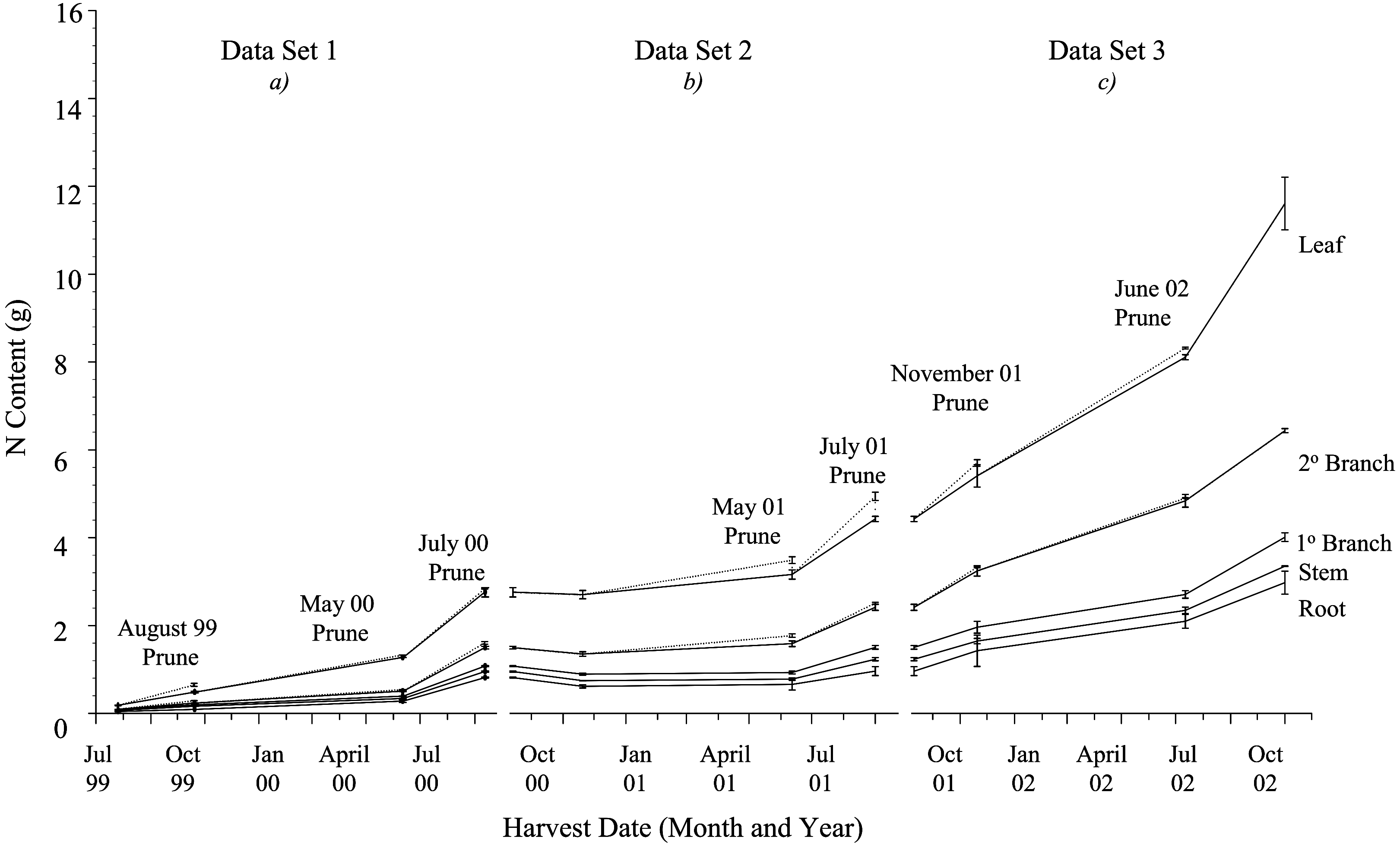
Figures B4-3 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of azalea plants under drip irrigation with TDR scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



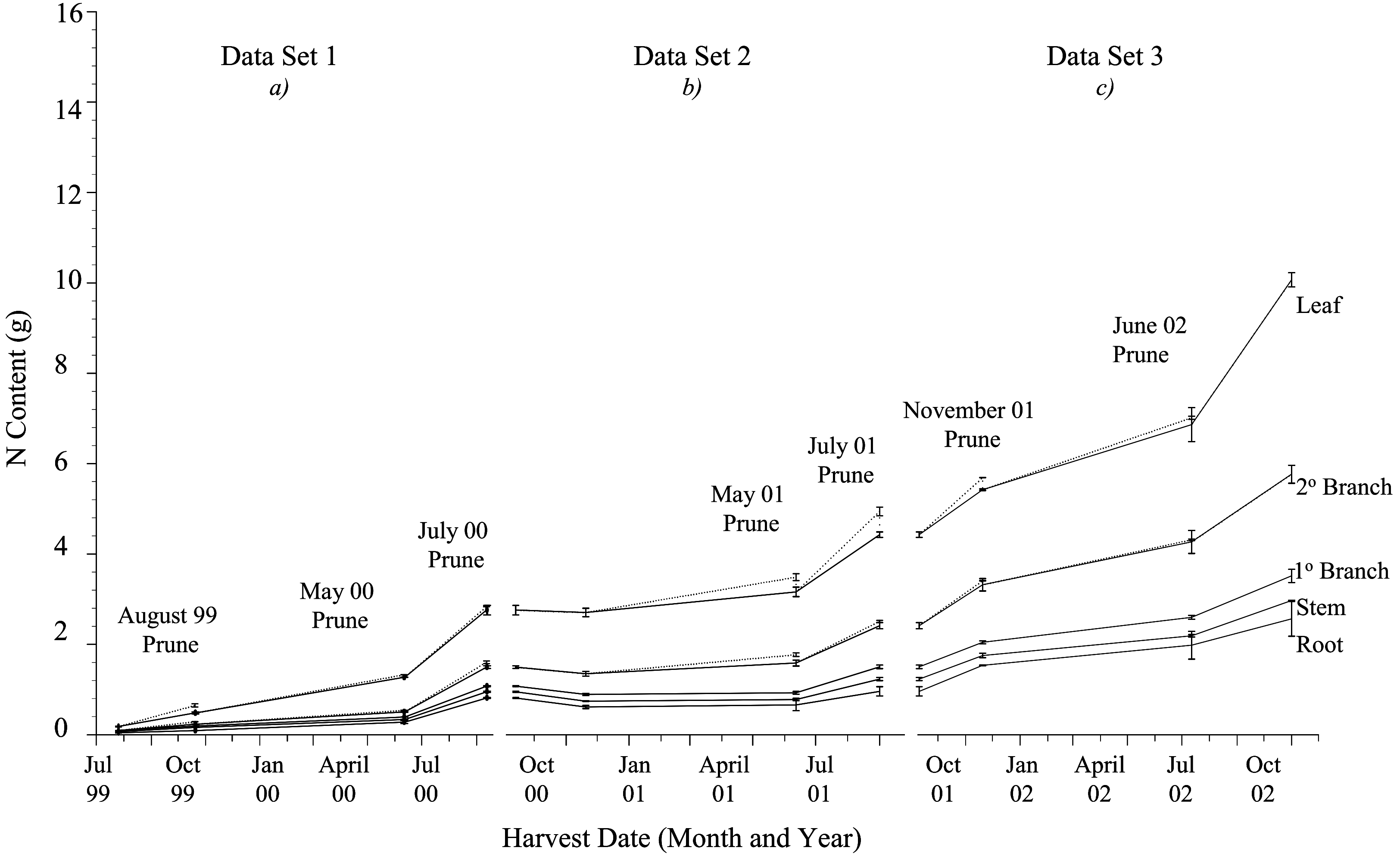
Figures B4-4 a, b, c. Mean cumulative N content of root, stem, 1^o branch, 2^o branch and leaf of azalea plants under overhead irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



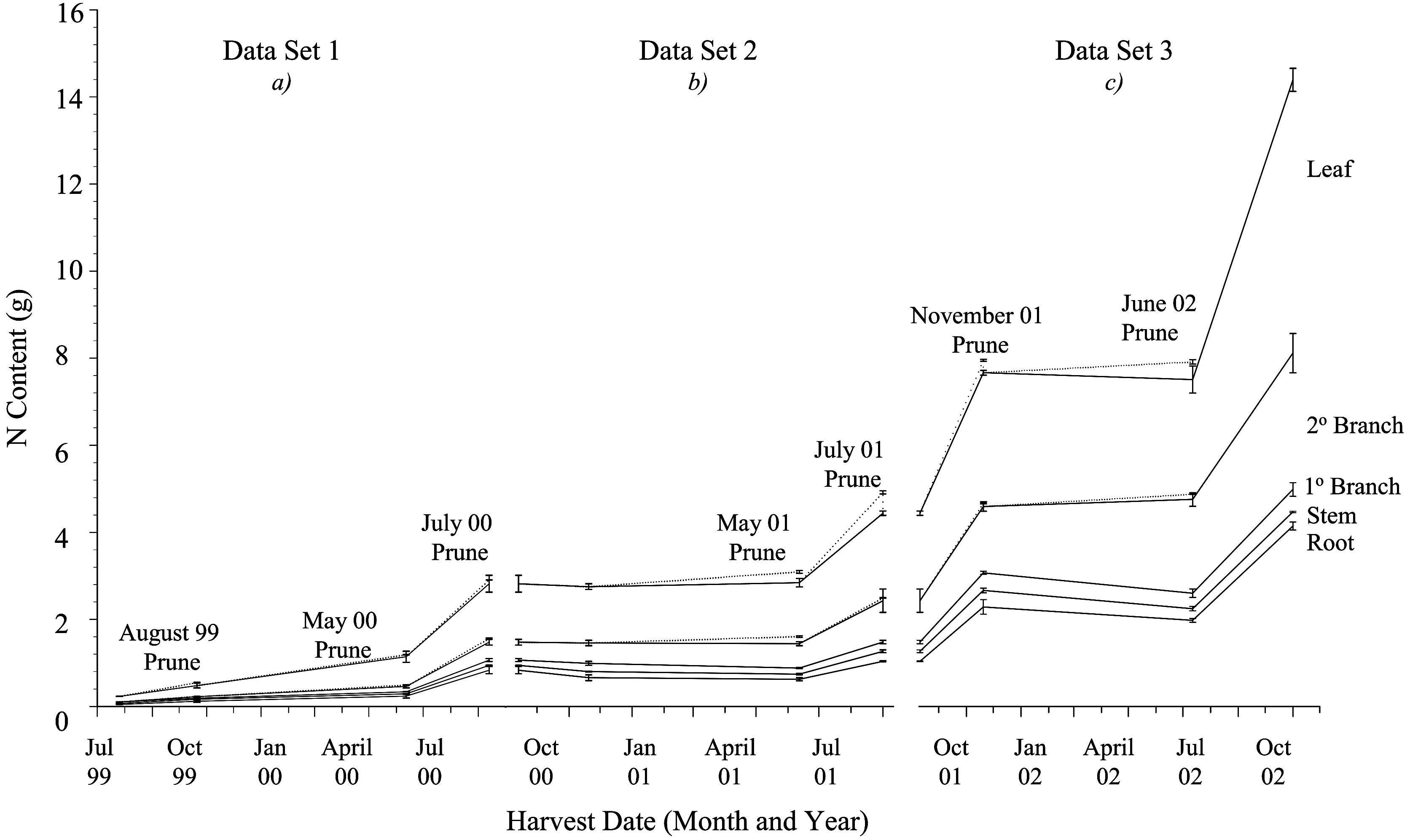
Figures B4-5 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of azalea plants under overhead irrigation with TDR scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures B4-6 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of holly plants under drip irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures B4-7 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of holly plants under drip irrigation with TDR scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.



Figures B4-8 a, b, c. Mean cumulative N content of root, stem, 1° branch, 2° branch and leaf of holly plants under overhead irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue N content in grams. Nitrogen pruned shown as dotted lines above solid lines shows amount removed on pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

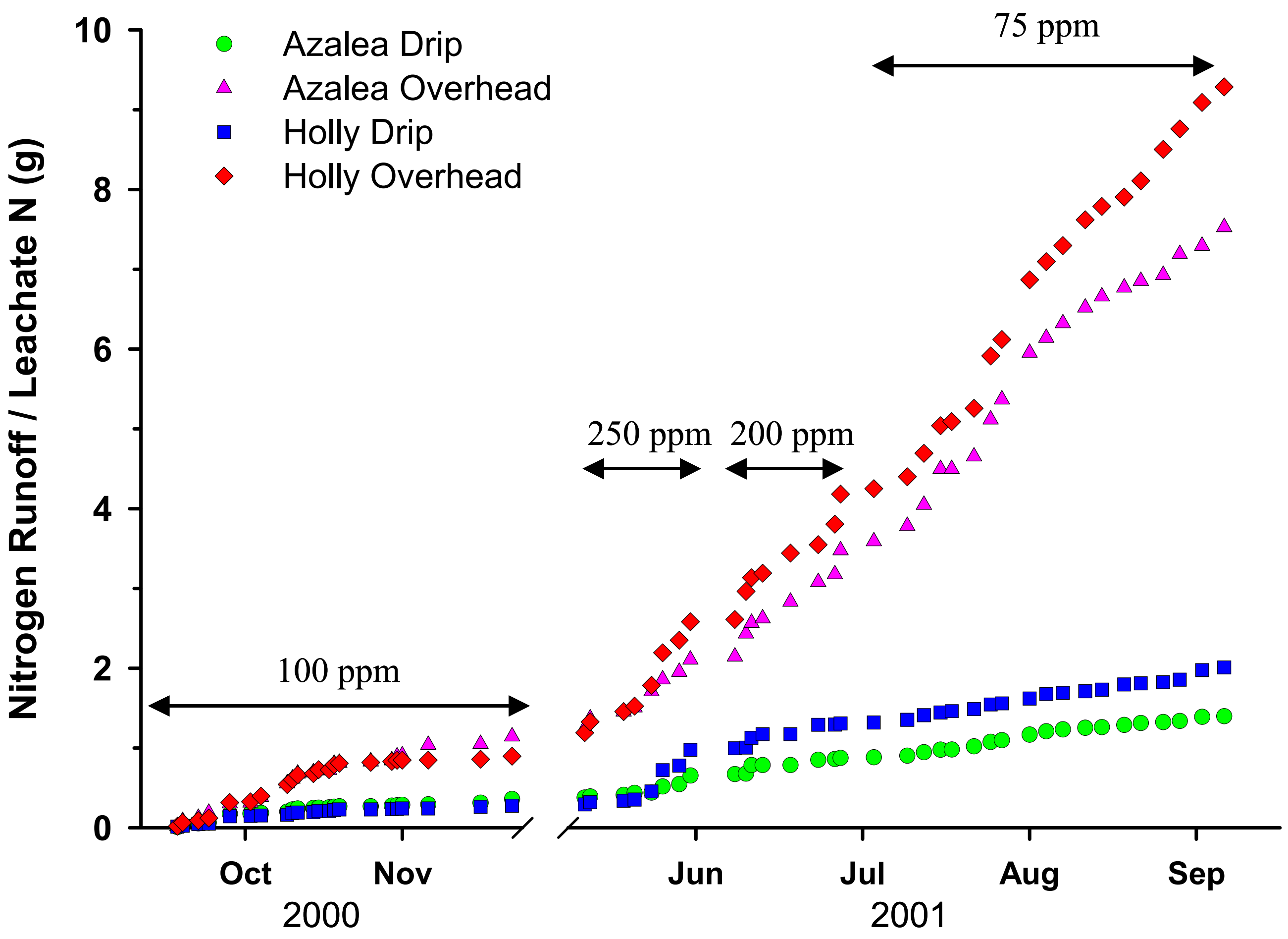


Figure B4-9. Mean cumulative runoff of N from drip and overhead cyclic irrigation on a per plant basis over a fourteen week period between September 2000 and September 2001, data set 2. Four different soluble rates were applied. Averages based on n=4.

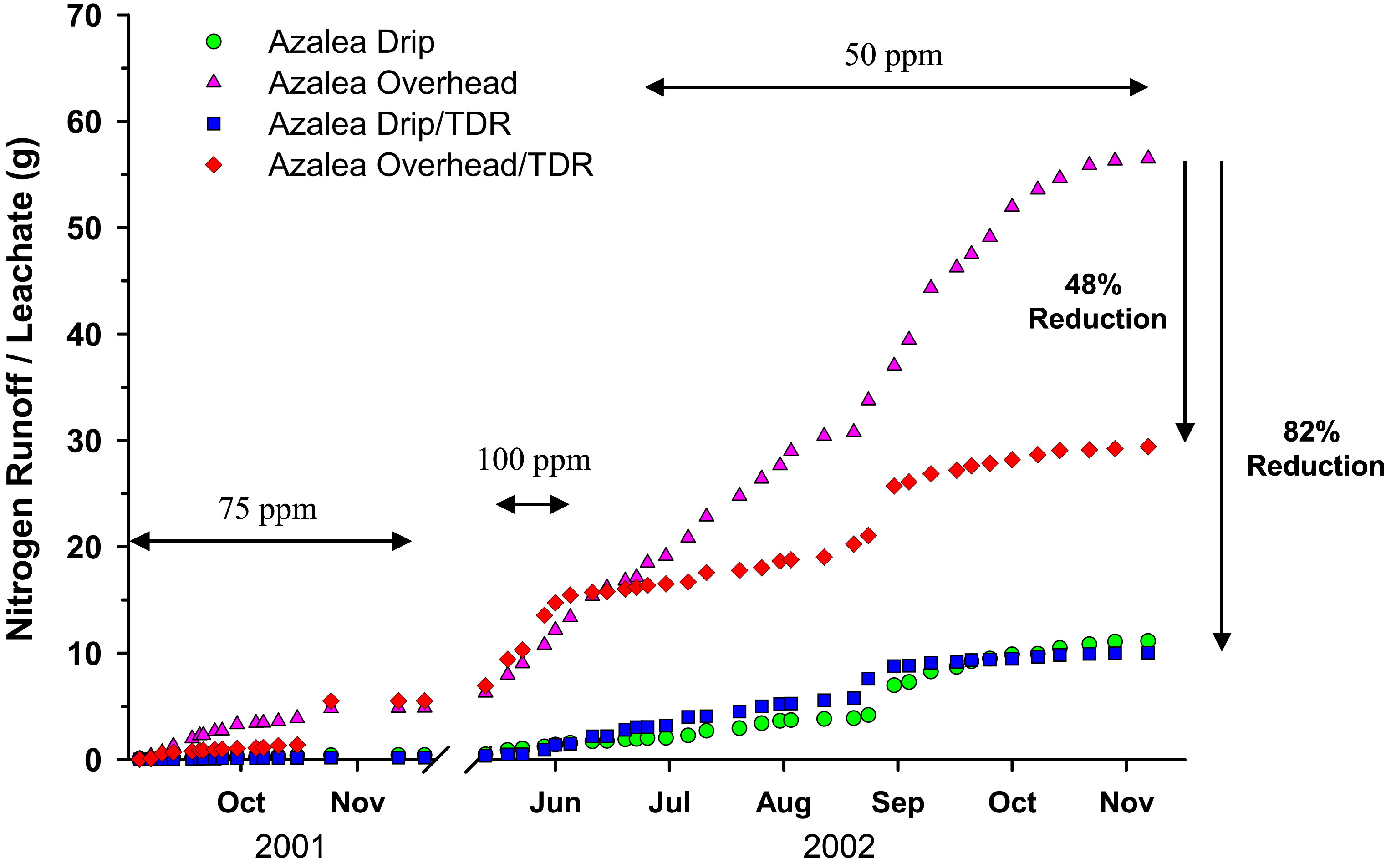


Figure B4-10. Mean cumulative runoff of N from azalea under cyclic and TDR controlled drip and overhead irrigation on a per plant basis over a fourteen week period between September 2001 and November 2002, data set 3. Three different soluble rates were applied as shown. Averages based on n=2.

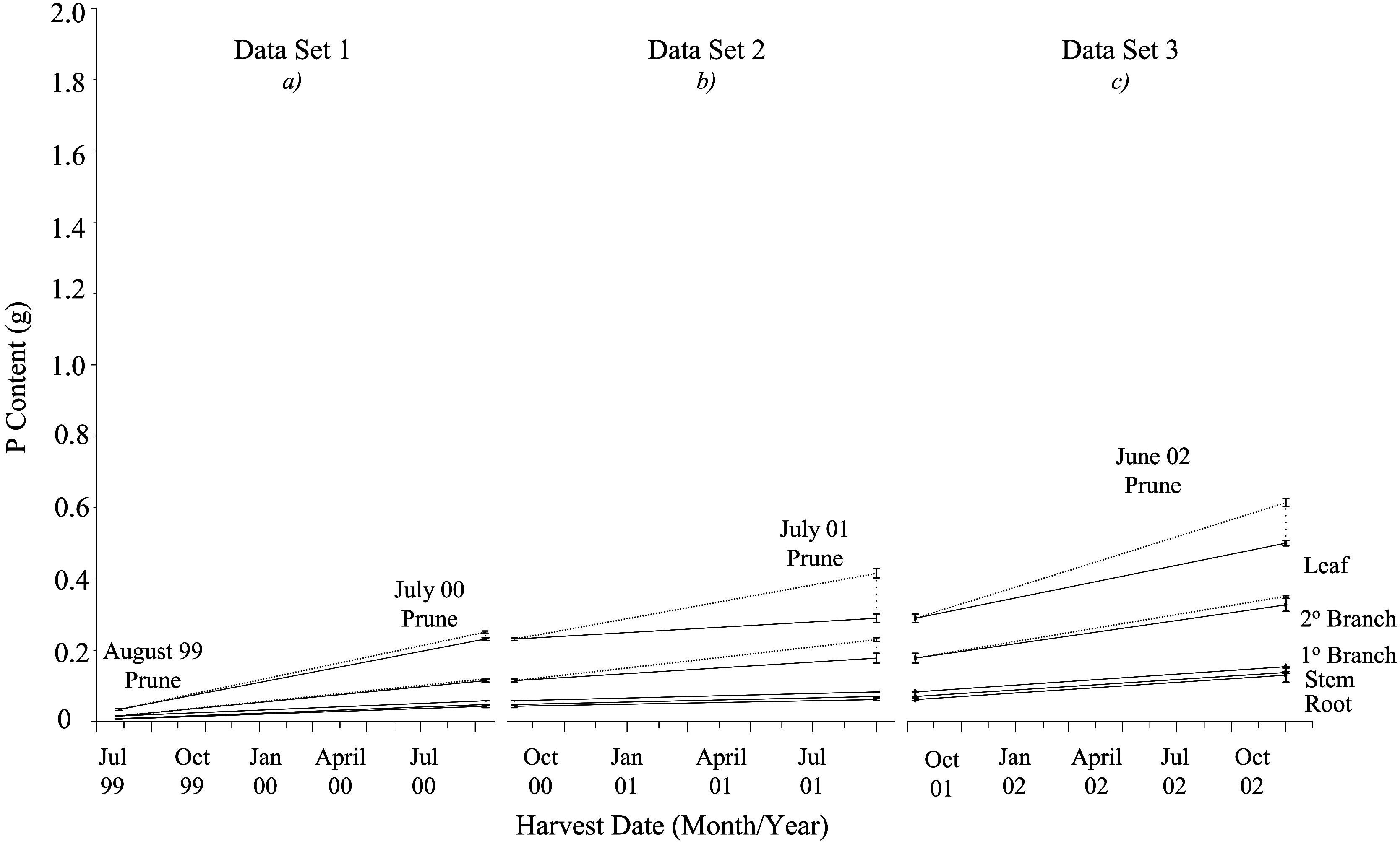


Figure B5-1 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of azalea plants under drip irrigation with cyclic scheduling for data sets 1 and 2, and TDR scheduling for data set 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

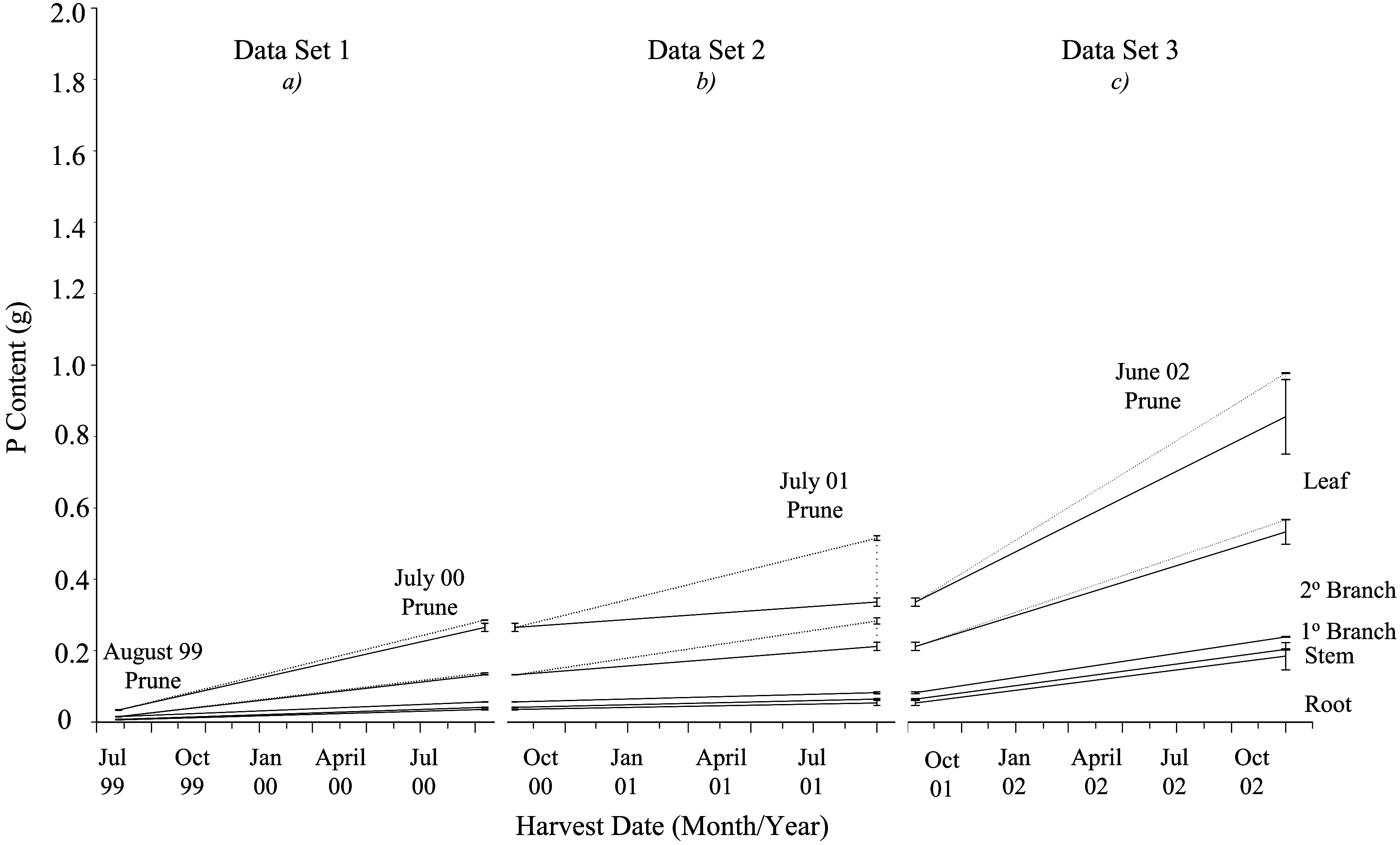


Figure B5-2 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of azalea plants under overhead irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

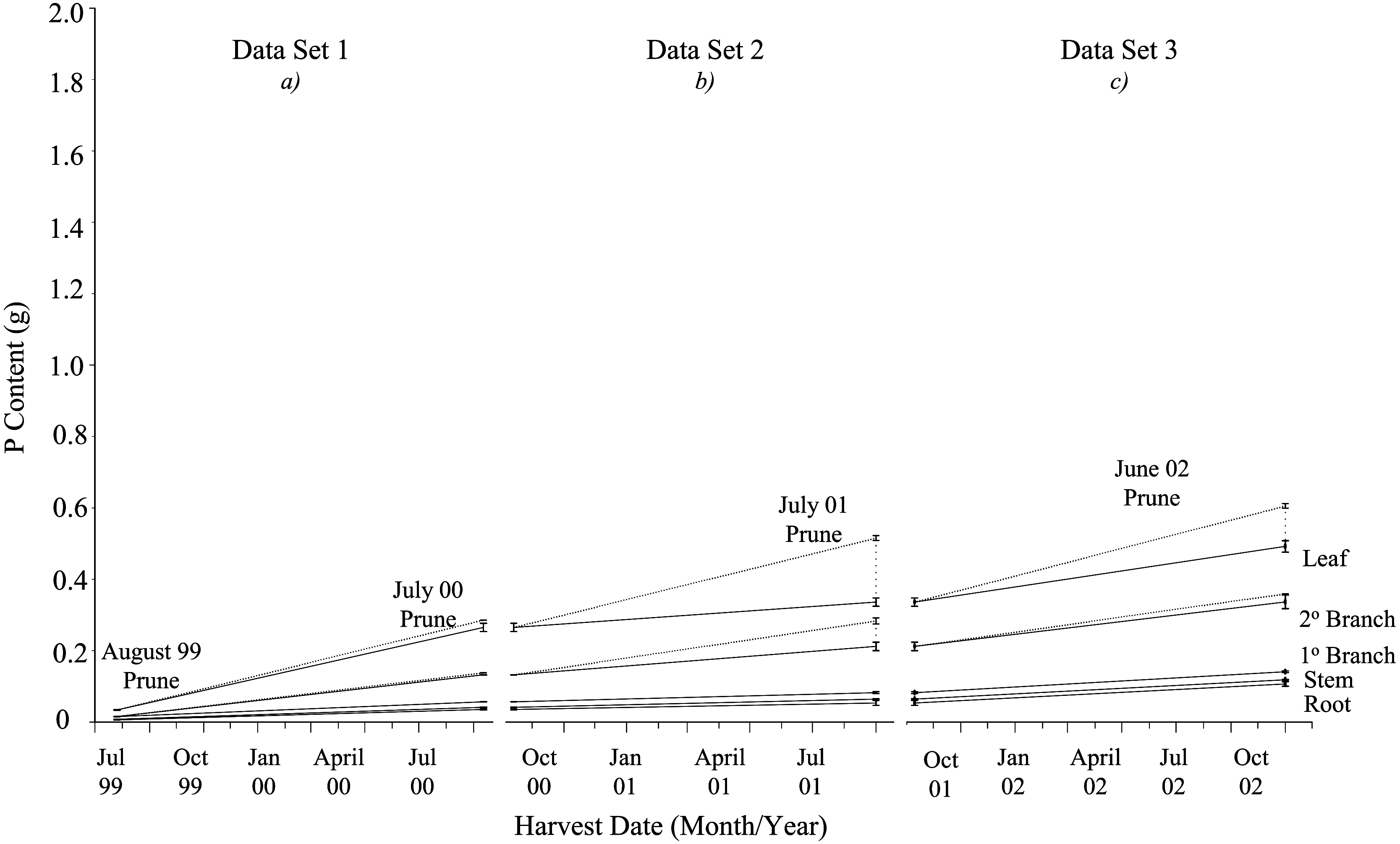


Figure B5-3 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of azalea plants under overhead irrigation with cyclic scheduling for data sets1 and 2, and TDR scheduling for data set 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

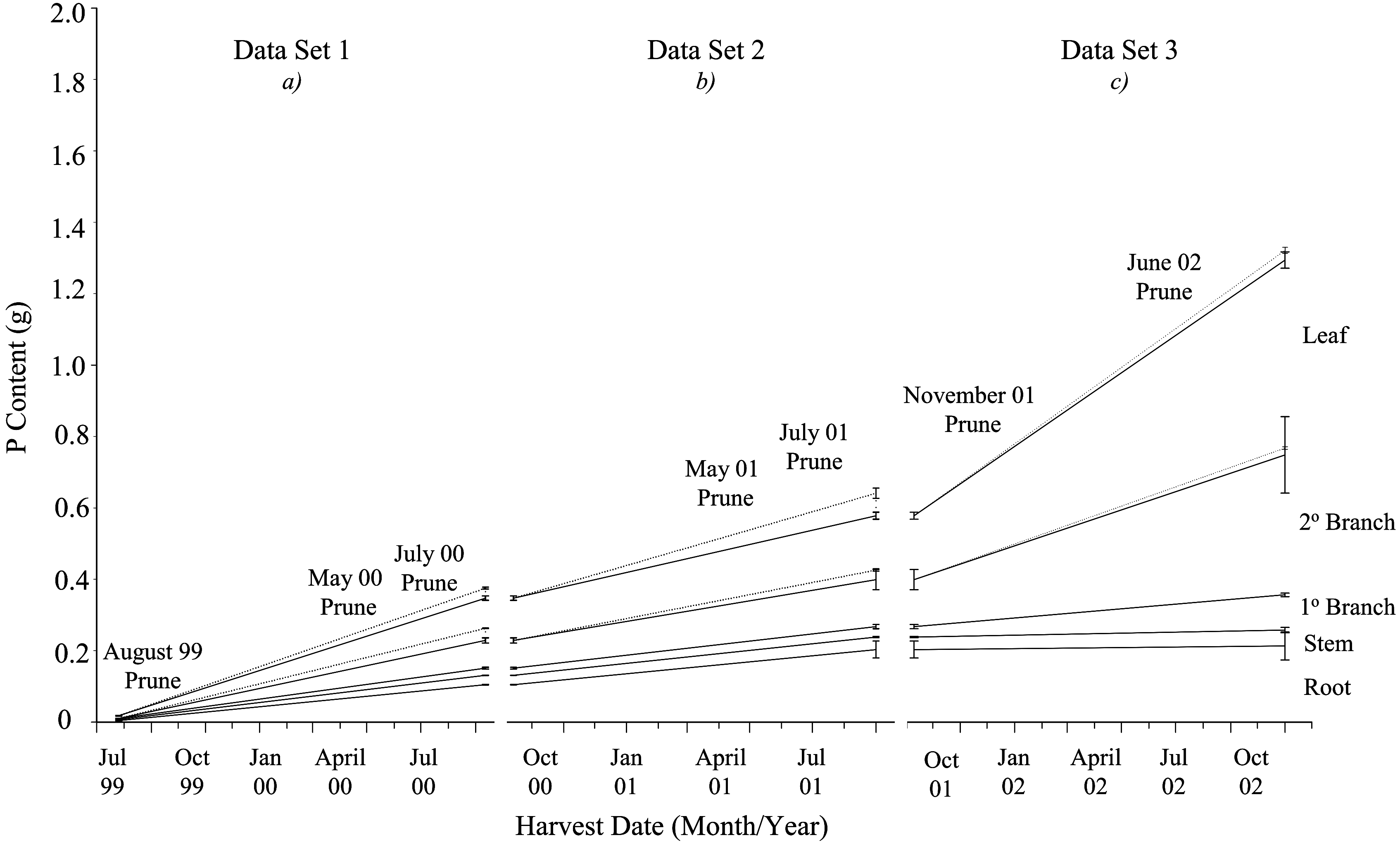


Figure B5-4 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of holly plants under drip irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

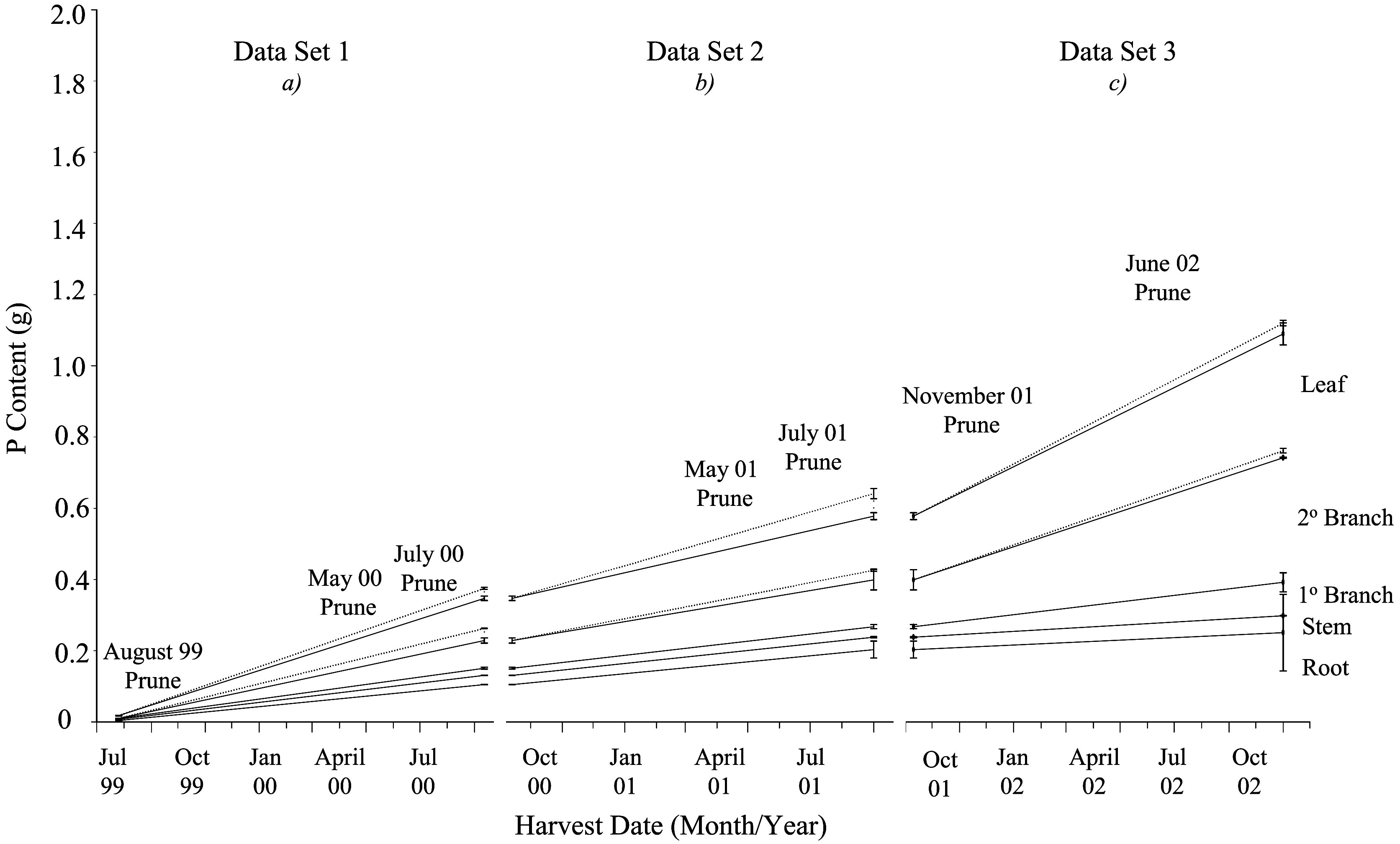


Figure B5-5 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of holly plants under drip irrigation with cyclic scheduling for data sets 1 and 2, and TDR scheduling for data set 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

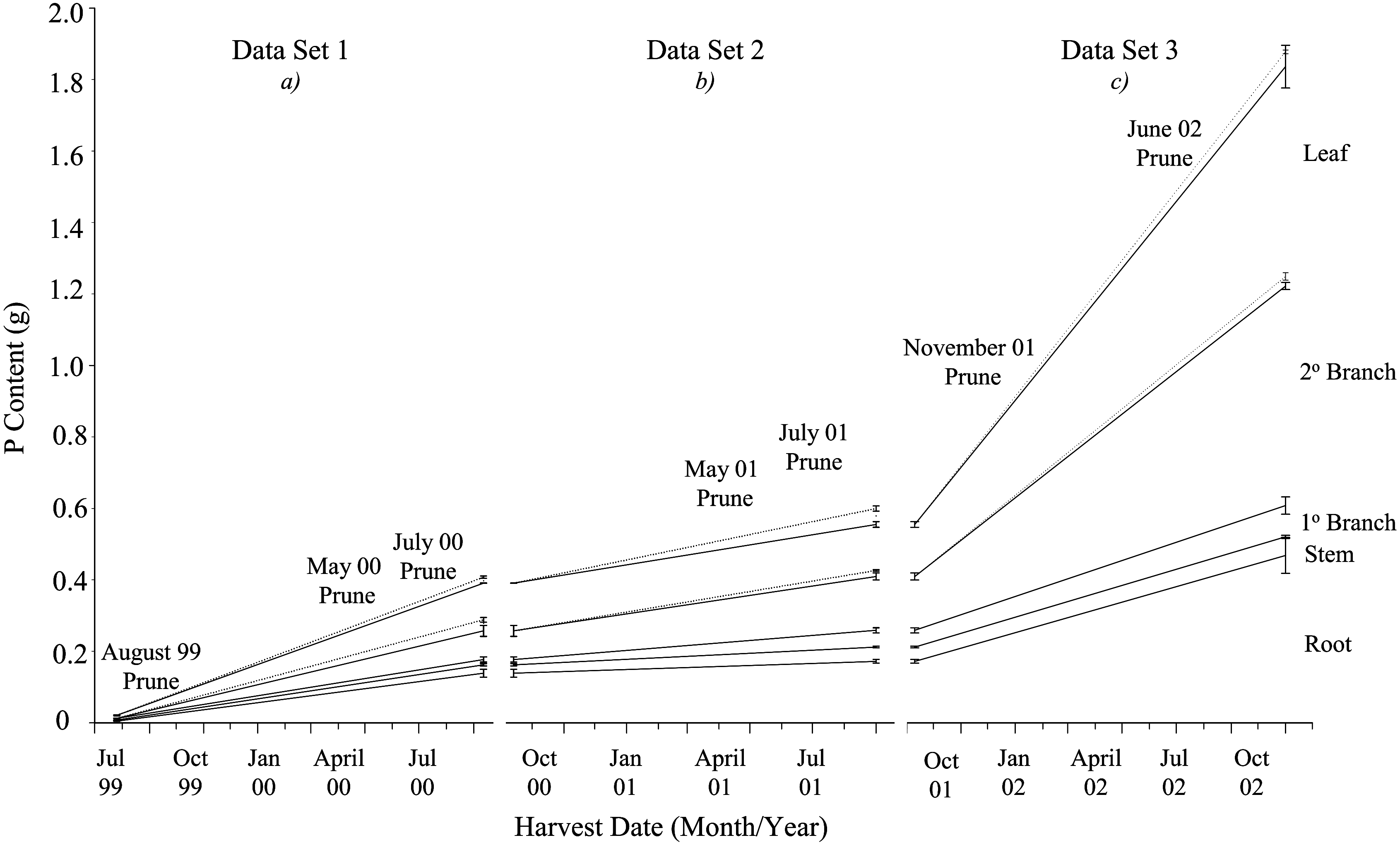


Figure B5-6 a, b, c. Mean cumulative P content of root, stem, 1° branch, 2° branch and leaf of holly plants under overhead irrigation with cyclic scheduling for data sets 1, 2, and 3. Area under each line represents tissue P content in grams. Phosphorus pruned shown as dotted lines above solid lines. Pruning dates labeled in figures. Standard error bars based on n=2 in data set 1, n=4 in data set 2, and n=2 in data set 3.

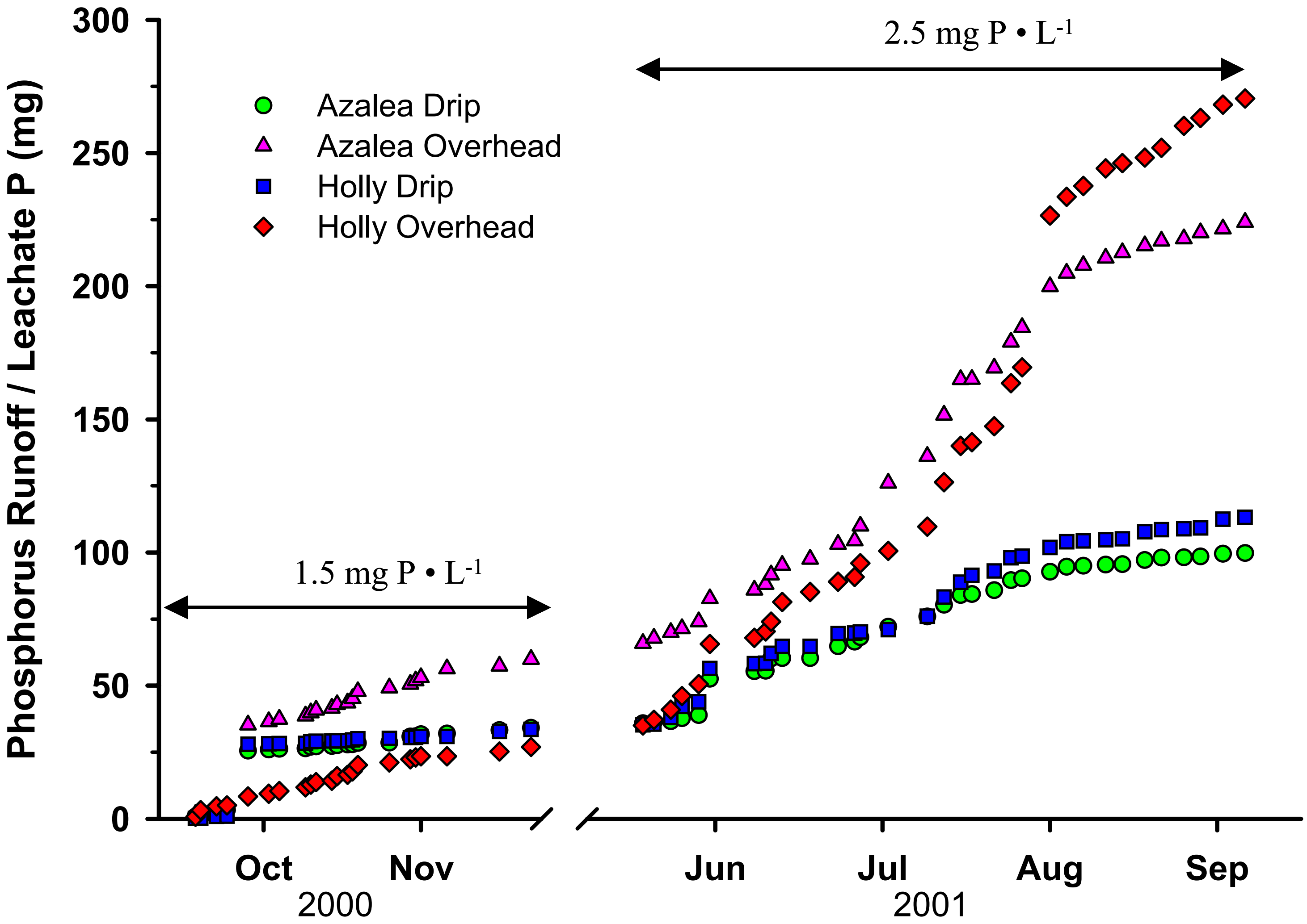


Figure B5-7. Mean cumulative runoff of P from drip and overhead cyclic irrigation on a per plant basis over a 12 month period between September 2000 and September 2001, data set 2. Two different soluble rates were applied. Averages based on n=4.

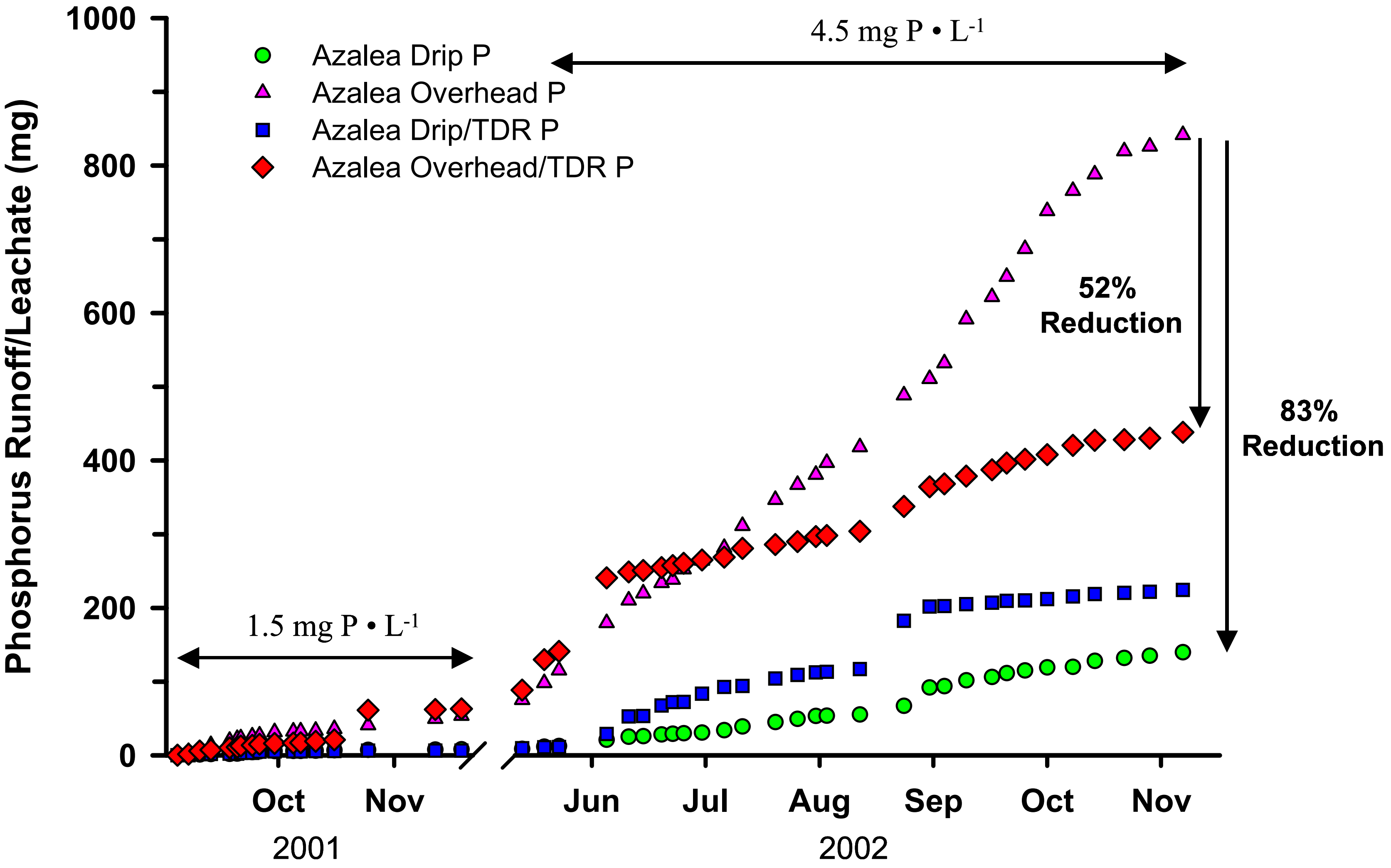


Figure B5-8. Mean cumulative runoff of P from azalea under cyclic and TDR controlled drip and overhead irrigation on a per plant basis over a fourteen month period between September 2001 and November 2002, data set 3. Two different soluble rates were applied as shown Averages based on n=2.

Appendix C

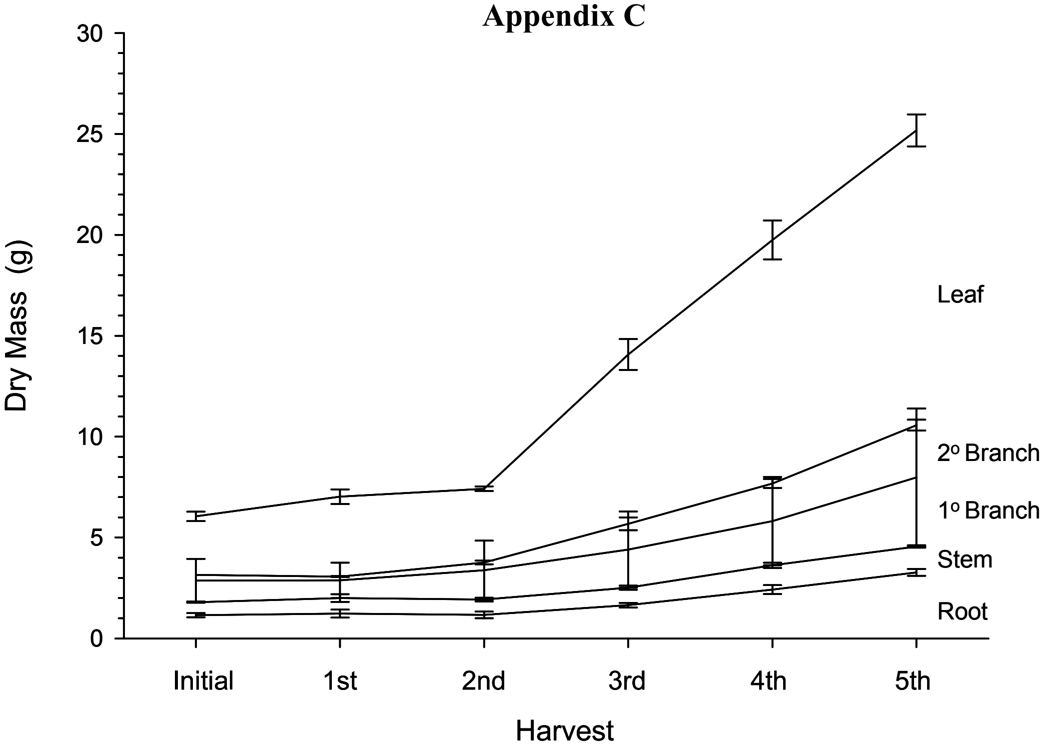


Figure C6-1. Average dry mass partitioning of azalea given 250 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

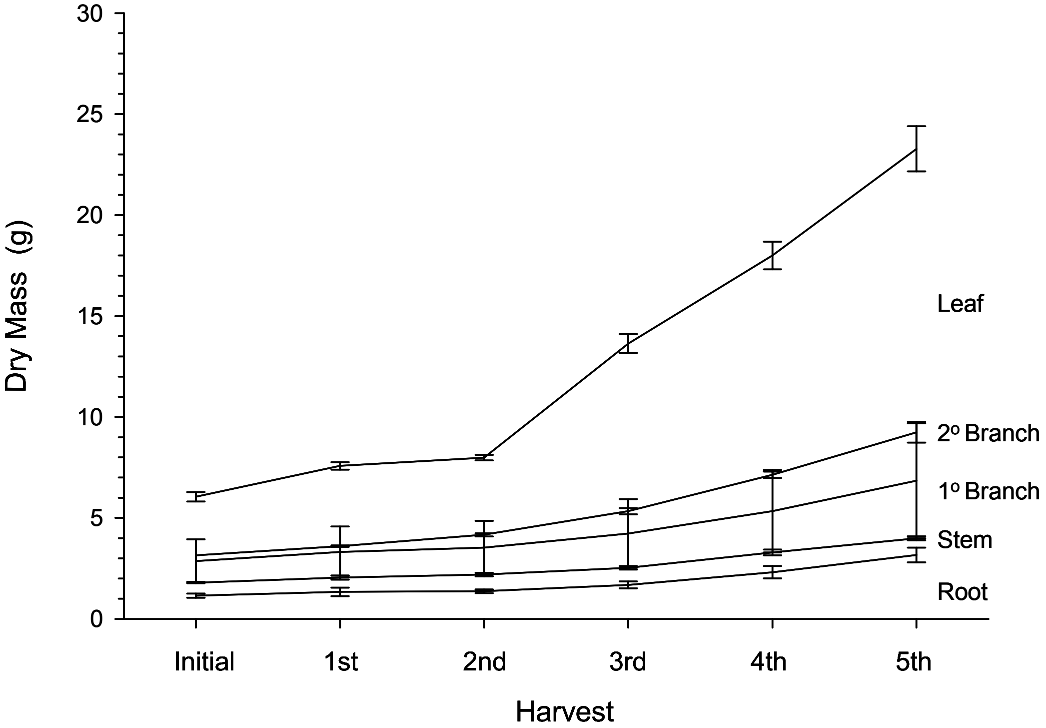


Figure C6-2. Average dry mass partitioning of azalea given 250 mg N and 5 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

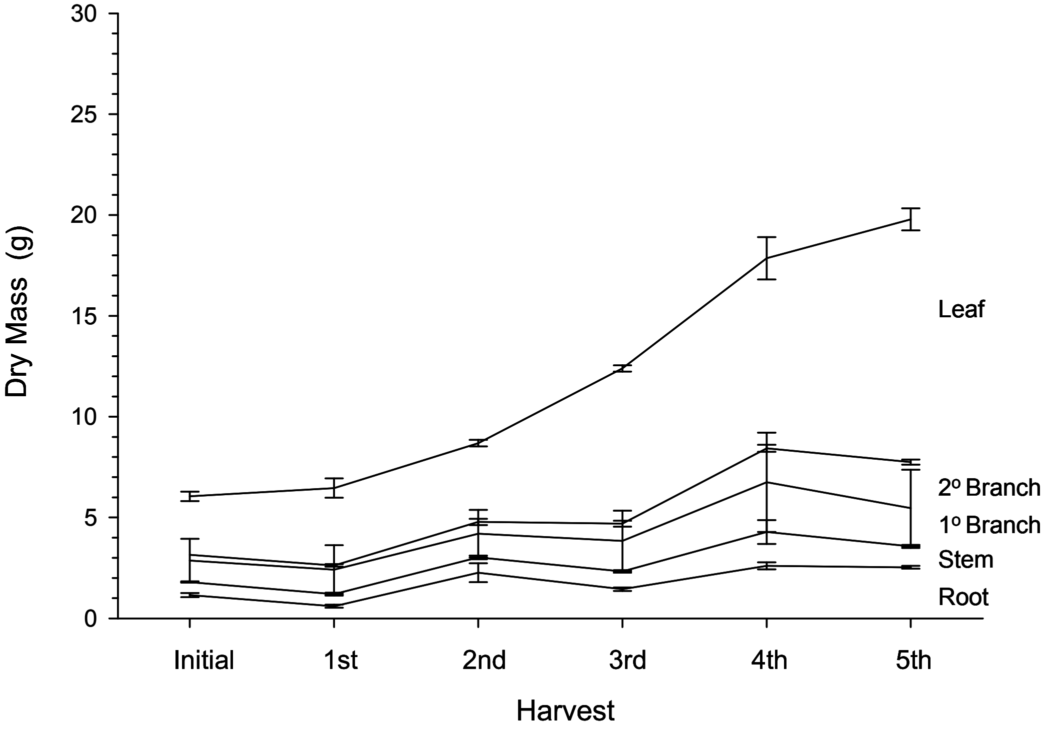


Figure C6-3. Average dry mass partitioning of azalea given 250 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

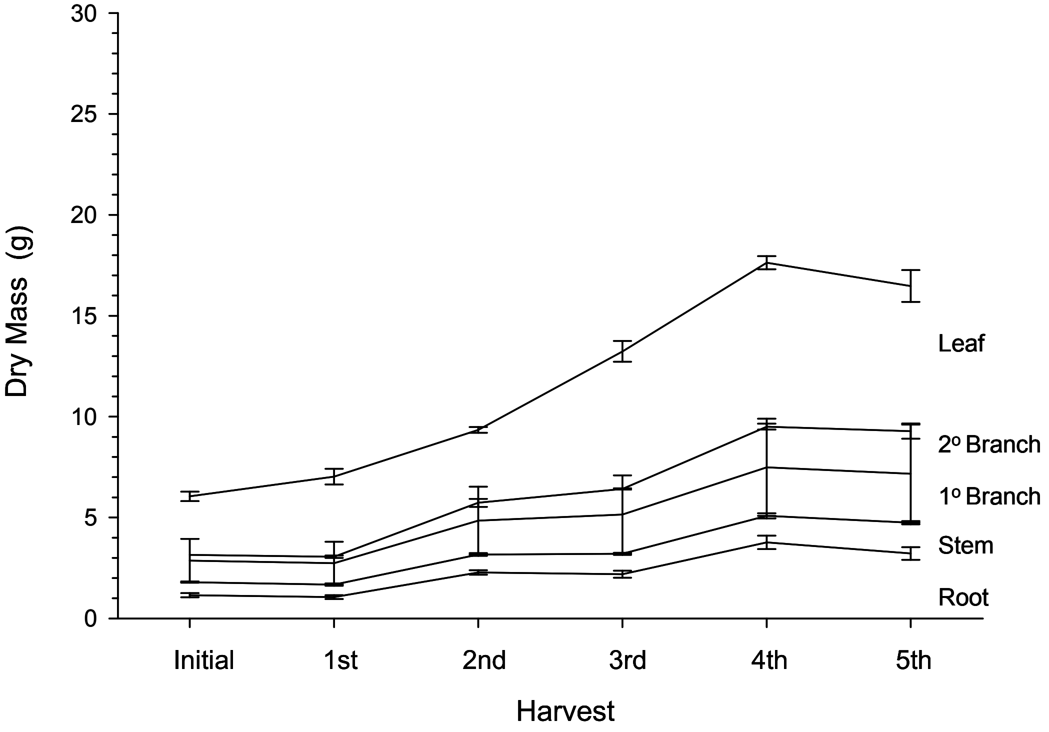


Figure C6-4. Average dry mass partitioning of azalea given 25 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

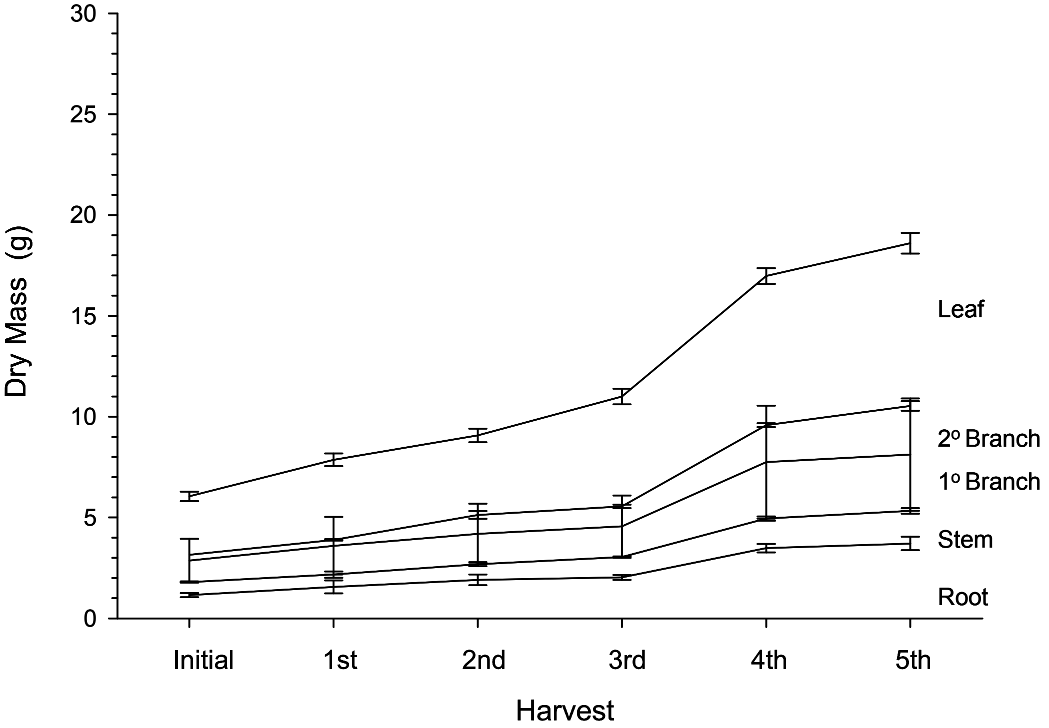


Figure C6-5. Average dry mass partitioning of azalea given 25 mg N and 5 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 3.

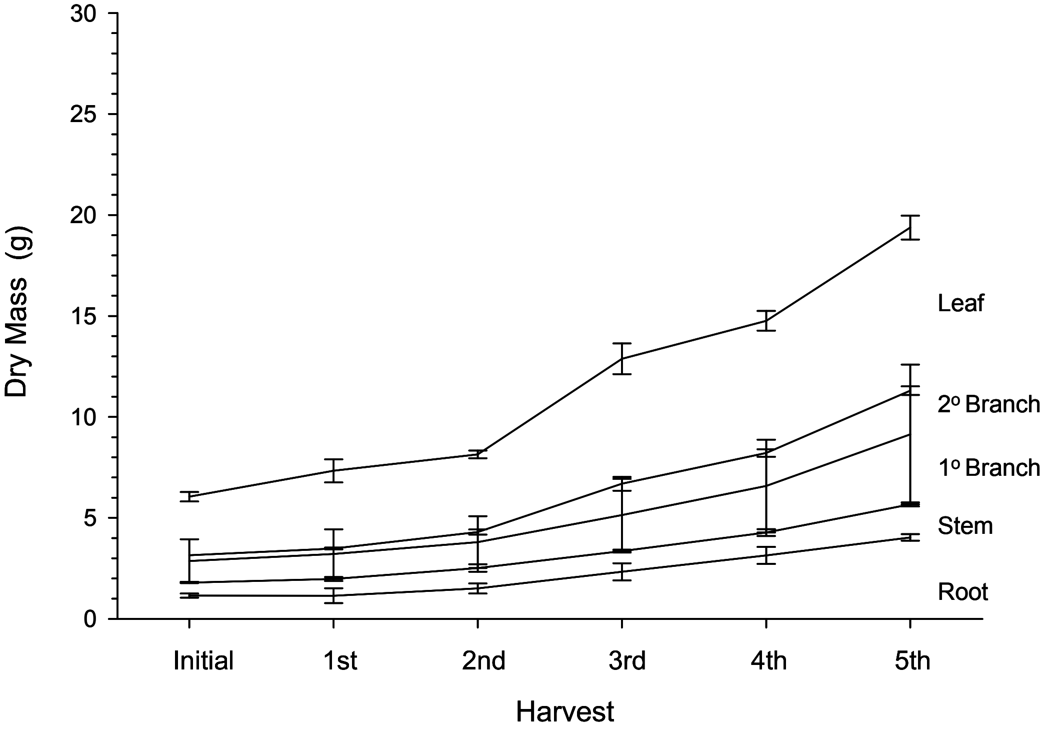


Figure C6-6. Average dry mass partitioning of azalea given 25 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

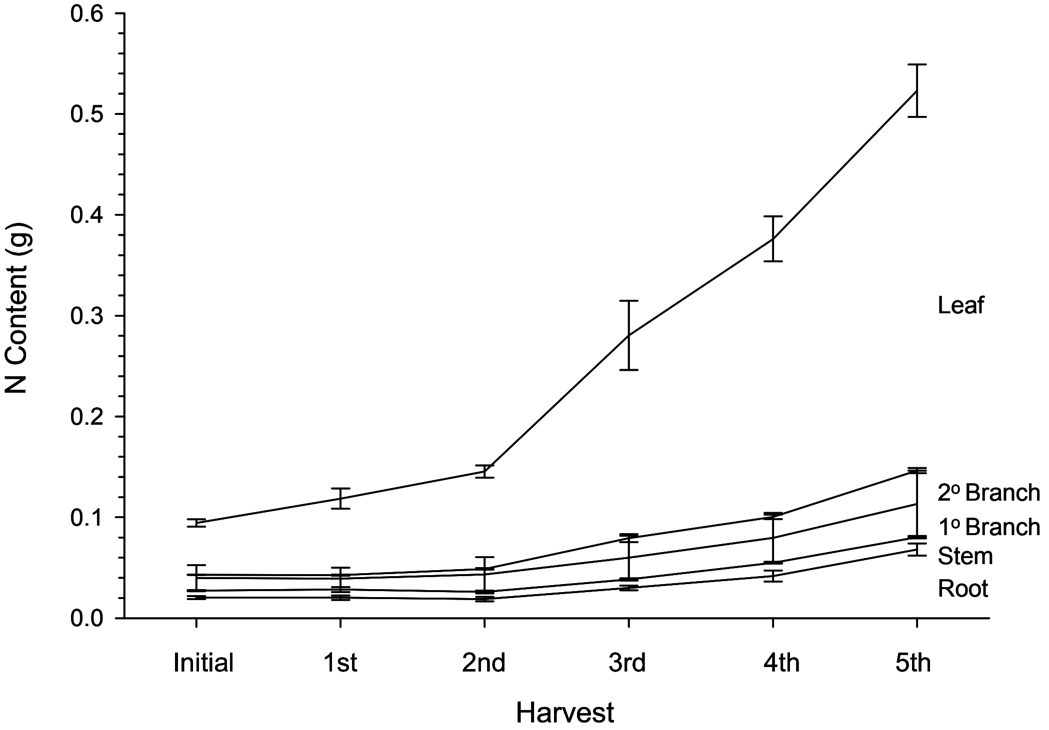


Figure C6-7. Average nitrogen partitioning of azalea given 250 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 3.

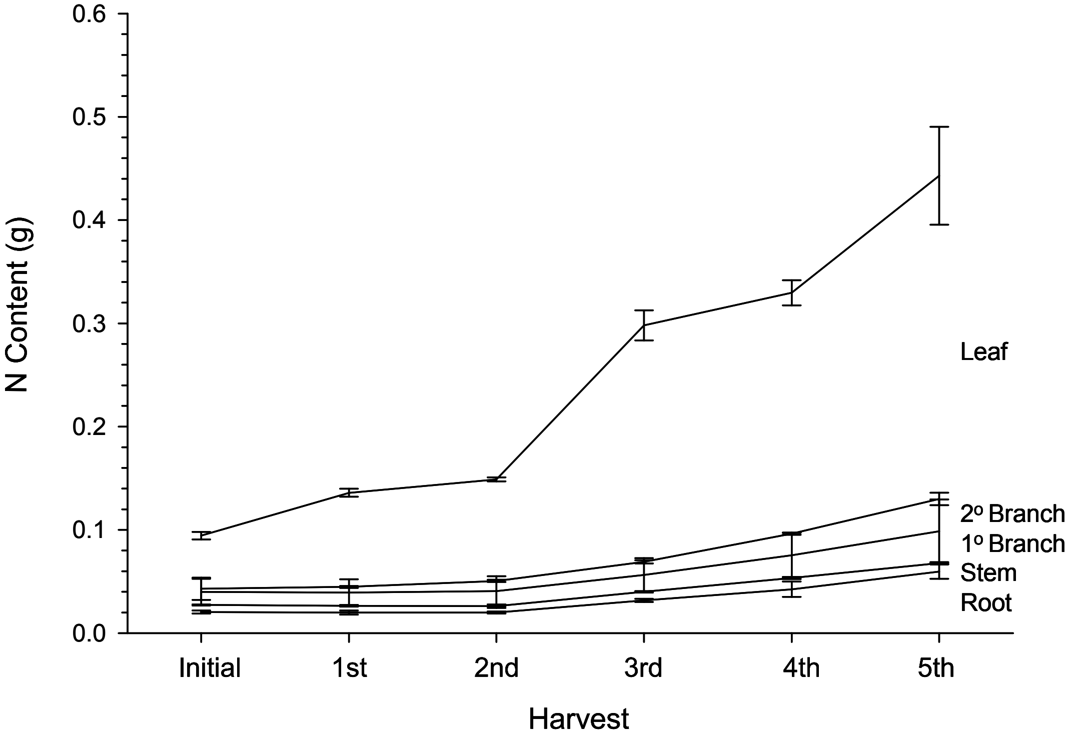


Figure C6-8. Average nitrogen partitioning of azalea given 250 mg N and 5 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

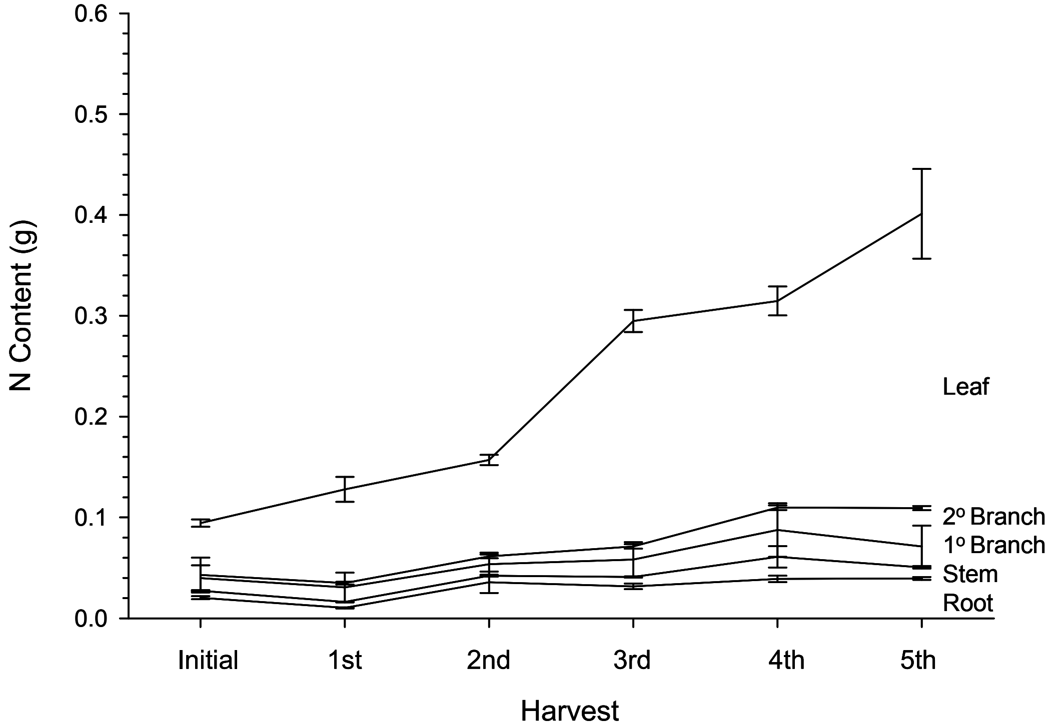


Figure C6-9. Average nitrogen partitioning of azalea given 250 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

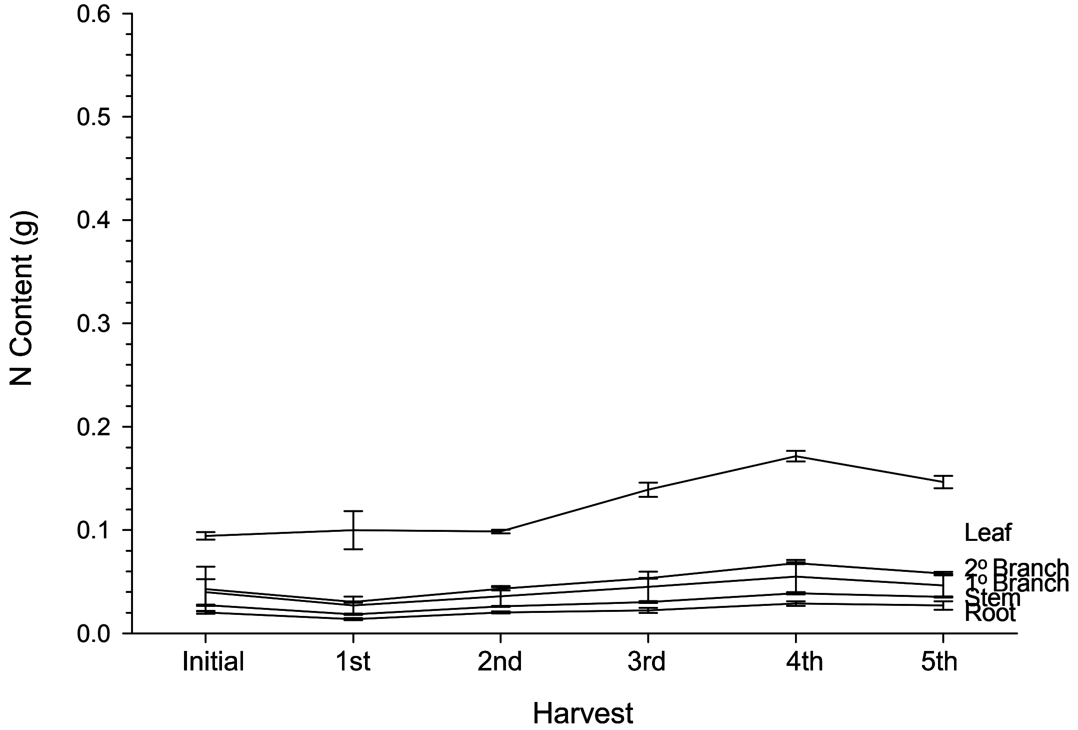


Figure C6-10. Average nitrogen partitioning of azalea given 25 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

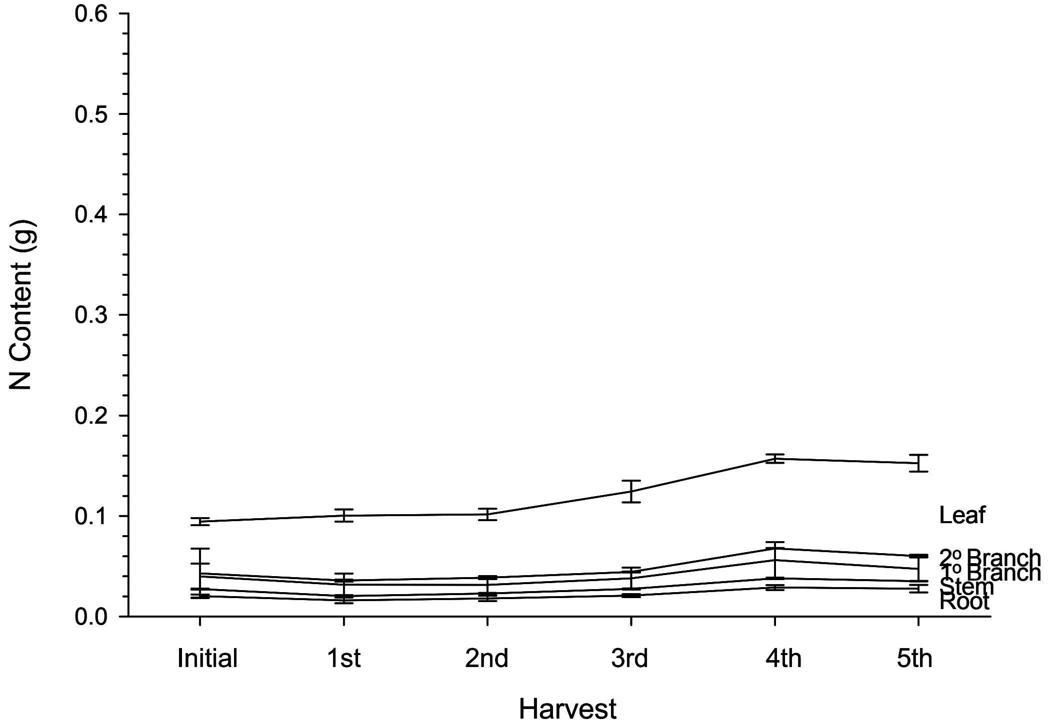


Figure C6-11. Average nitrogen partitioning of azalea given 25 mg N and 5 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

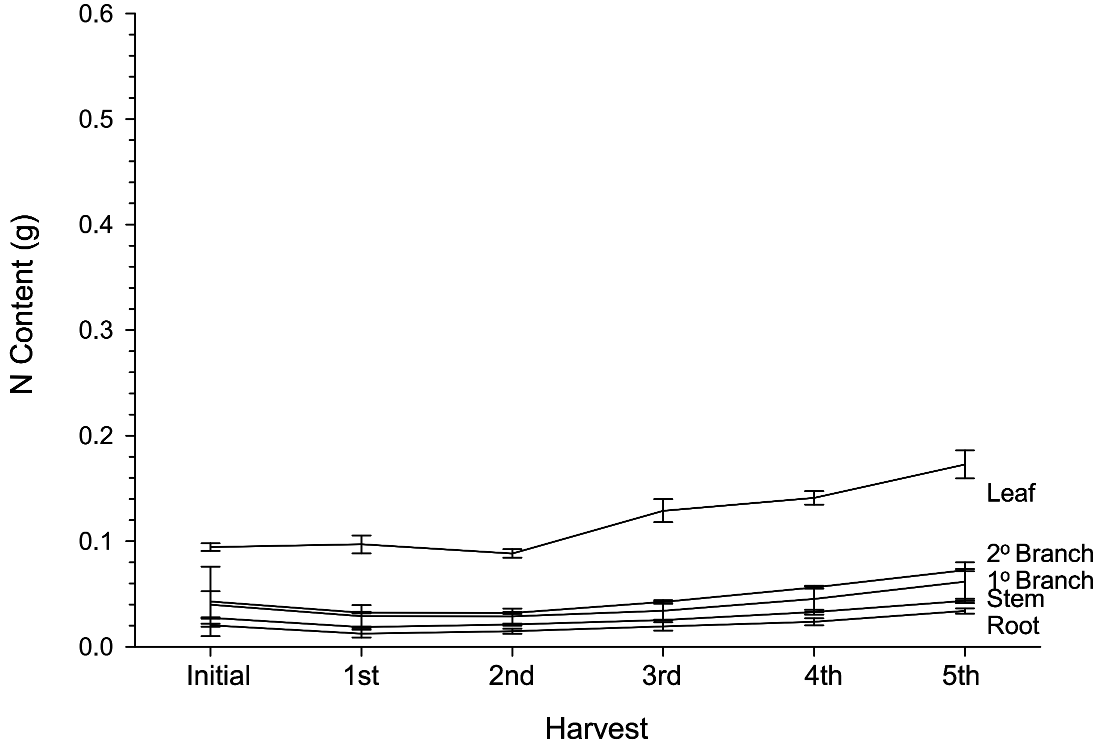


Figure C6-12. Average nitrogen partitioning of azalea given 25 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Harvests were two weeks apart. Error bars are based on n = 5.

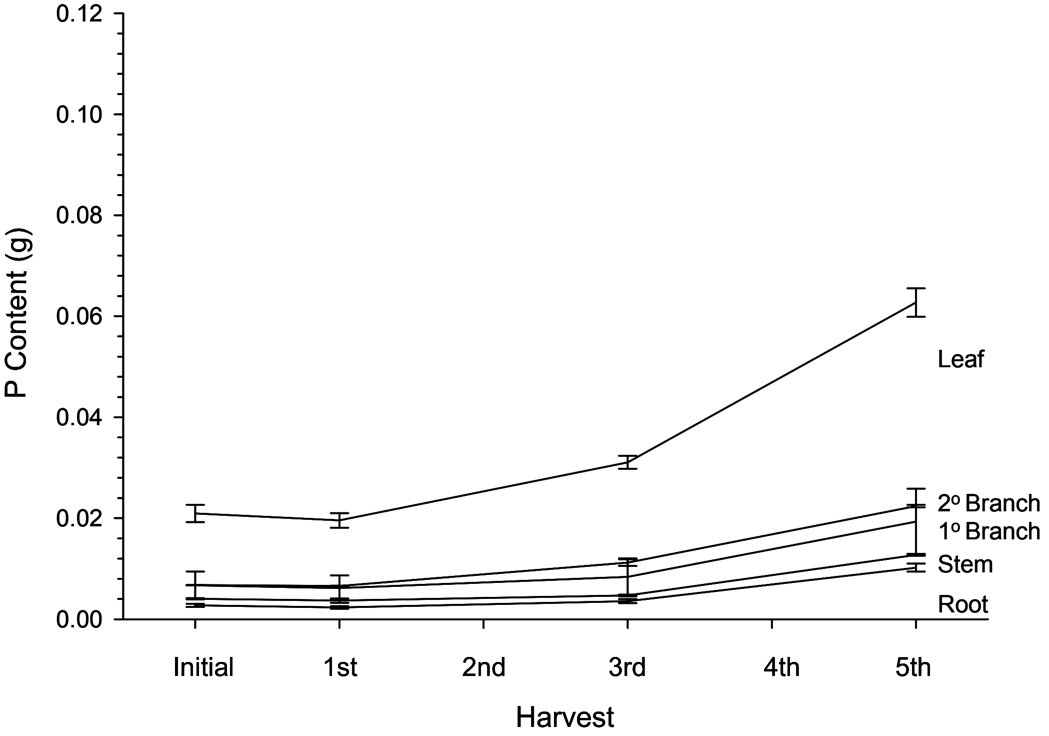


Figure C6-13. Average phosphorus partitioning of azalea given 250 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 5.

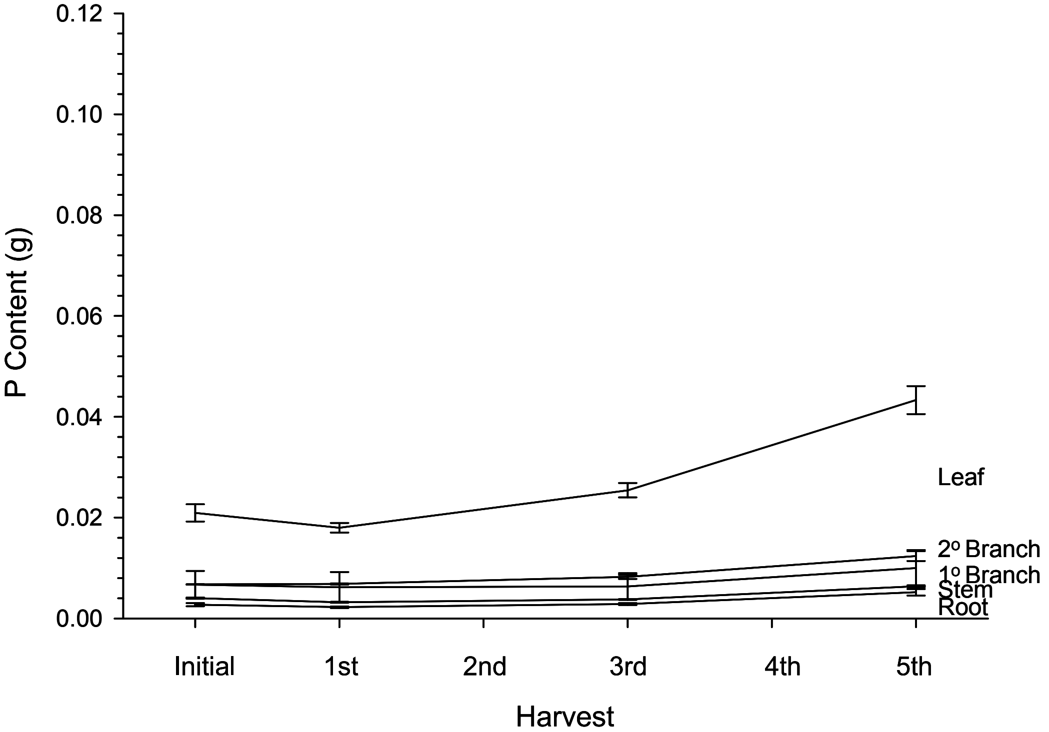


Figure C6-14. Average phosphorus partitioning of azalea given 250 mg N and 5 mg P per week over a period of 12 weeks in the first spring study Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 5.

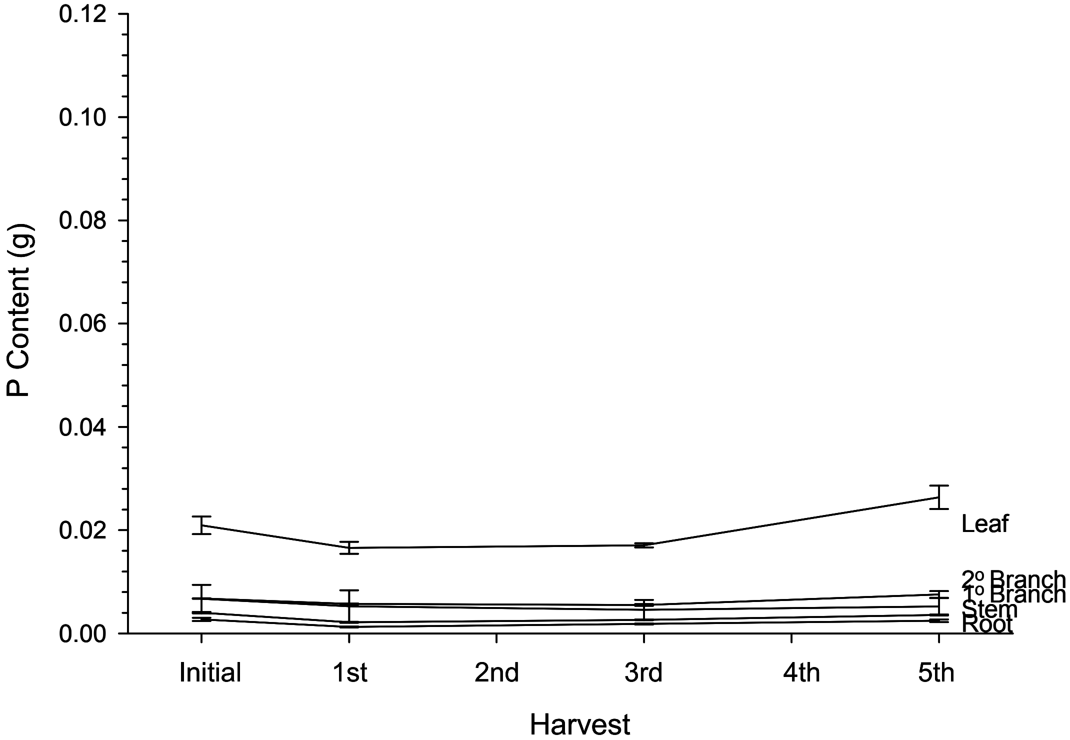


Figure C6-15. Average phosphorus partitioning of azalea given 250 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 3.

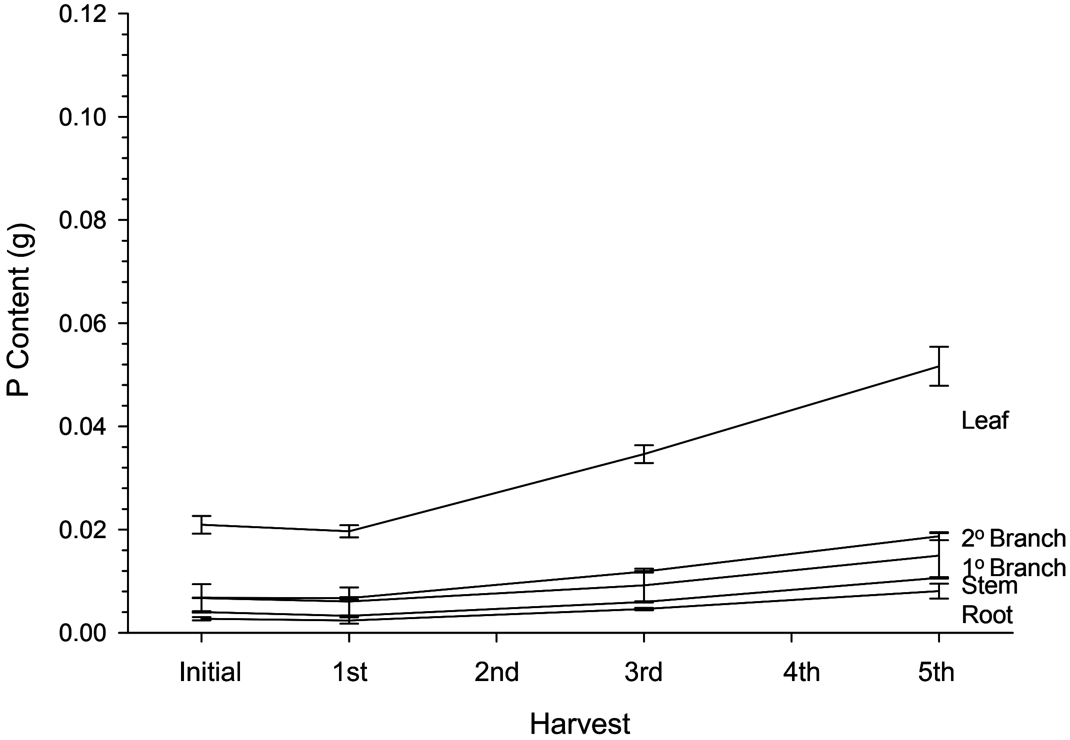


Figure C6-16. Average phosphorus partitioning of azalea given 25 mg N and 25 mg P per week over a period of 12 weeks in the first spring study. Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 5.

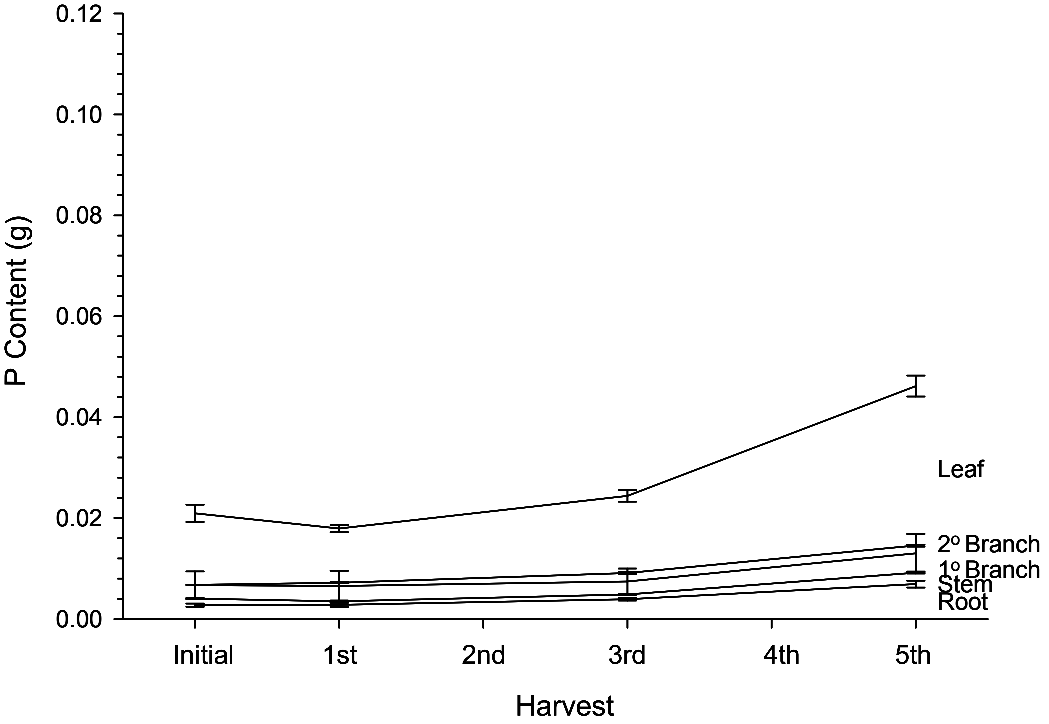


Figure C6-17. Average phosphorus partitioning of azalea given 25 mg N and 5 mg P per week over a period of 12 weeks in the first spring study. Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 5.

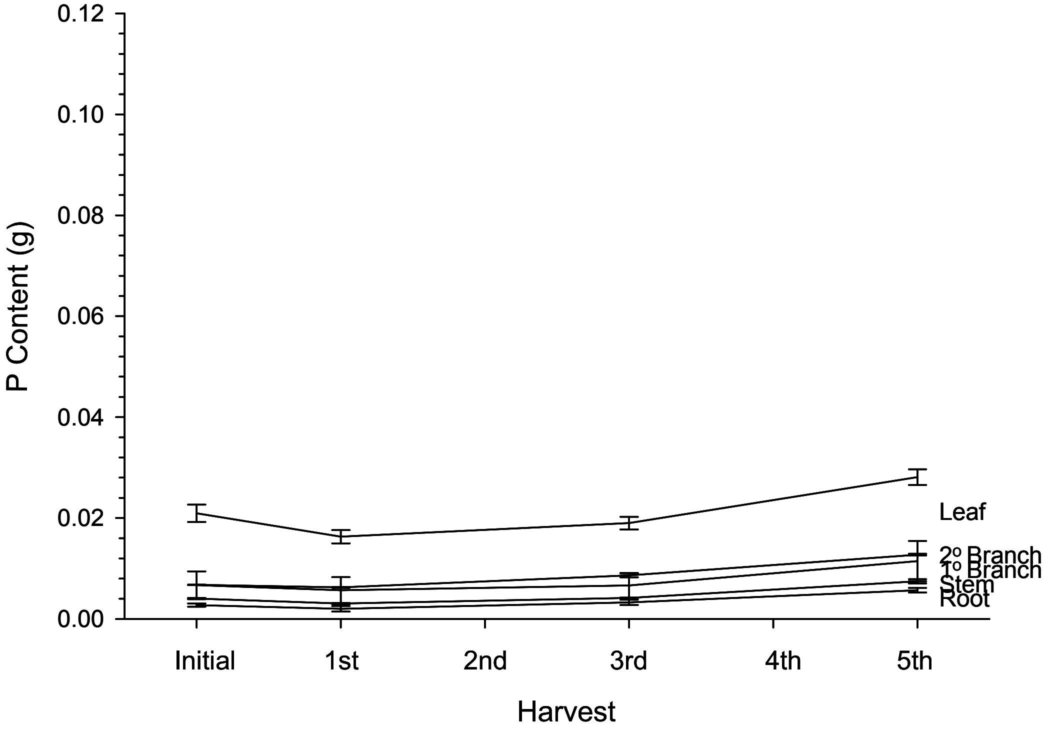


Figure C6-18. Average phosphorus partitioning of azalea given 25 mg N and 0 mg P per week over a period of 12 weeks in the first spring study. Tissue P analysis included initial, first, third and last harvests. Error bars are based on n = 5.

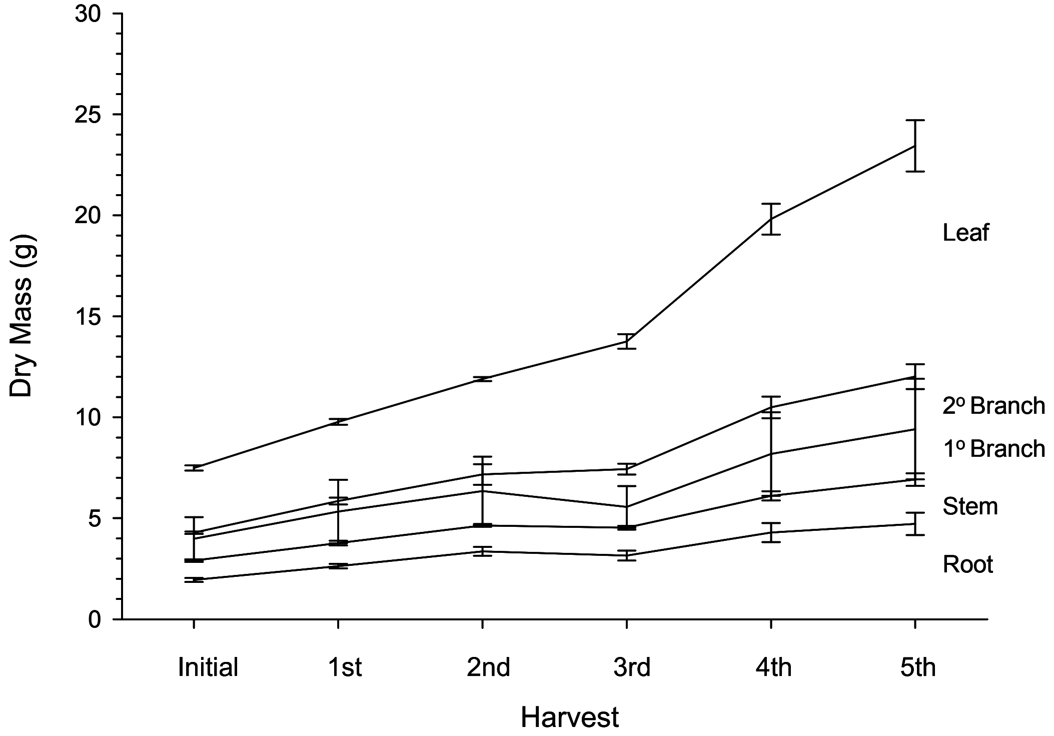


Figure C6-19. Average dry mass partitioning of azalea given 250 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

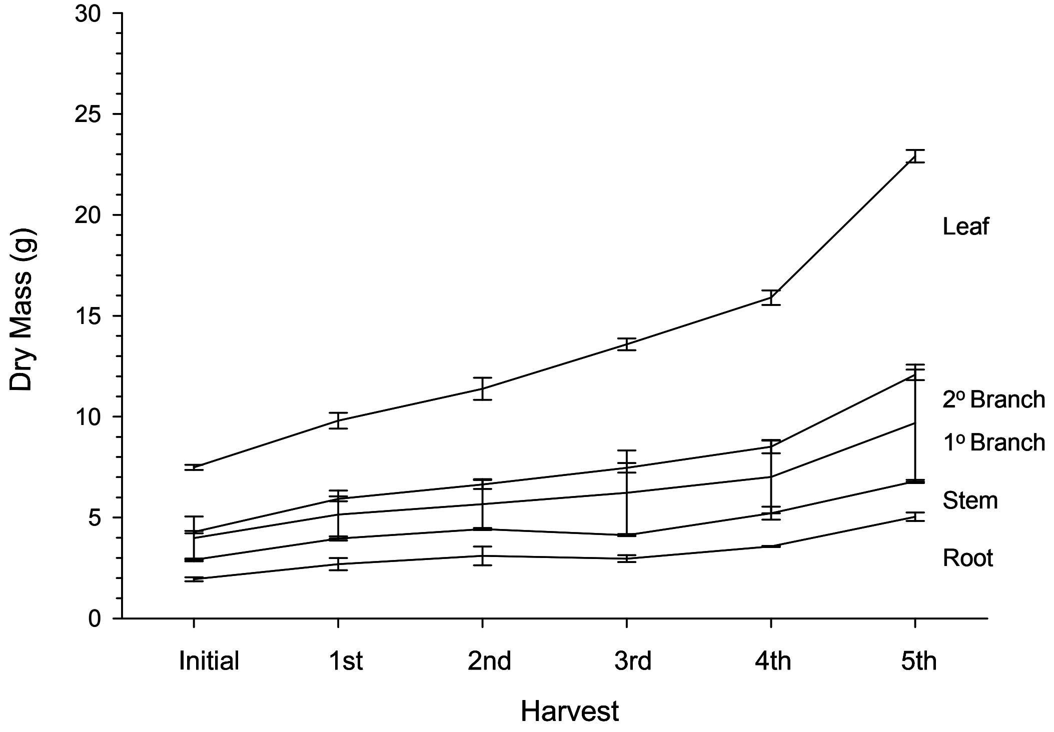


Figure C6-20. Average dry mass partitioning of azalea given 250 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

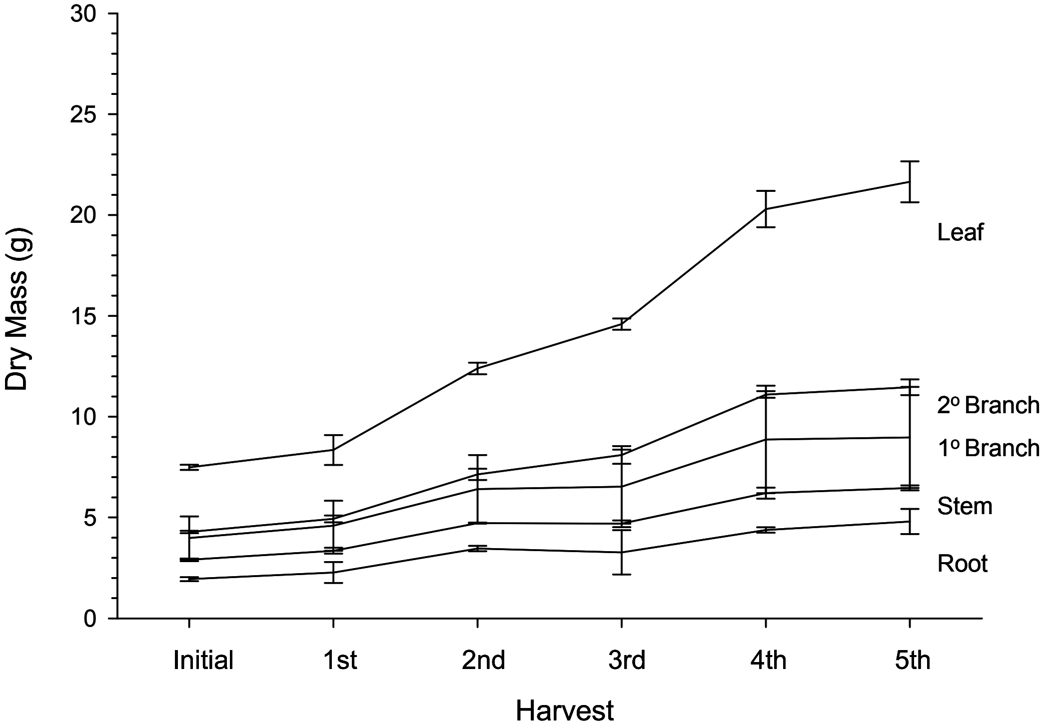


Figure C6-21. Average dry mass partitioning of azalea given 250 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

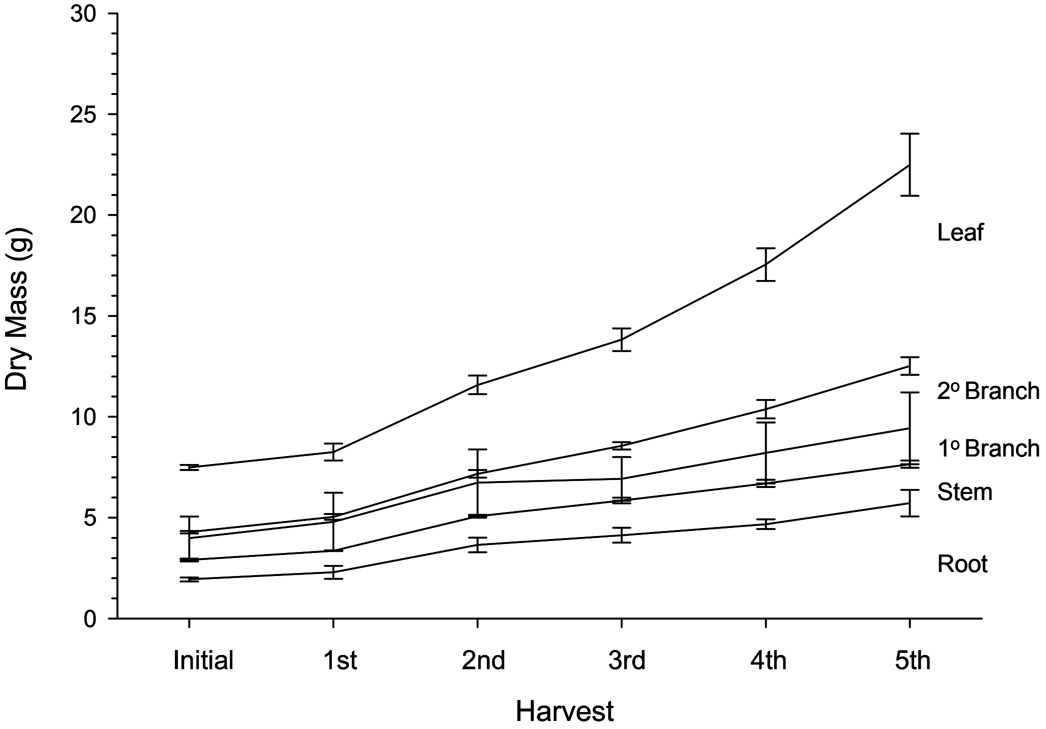


Figure C6-22. Average dry mass partitioning of azalea given 100 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

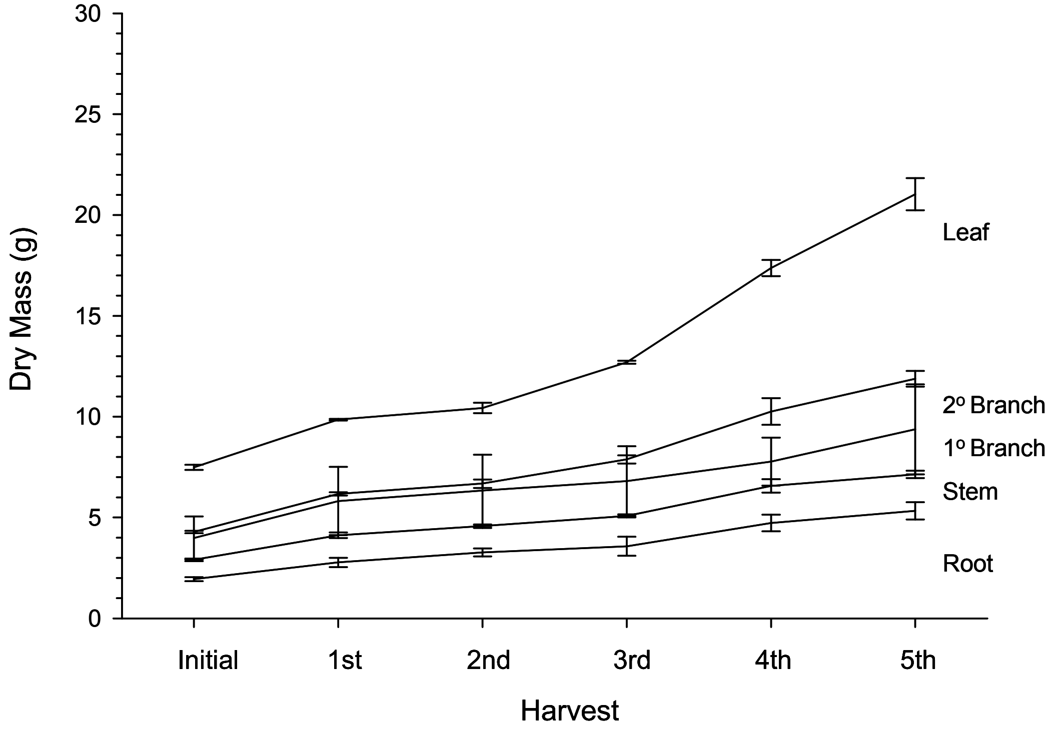


Figure C6-23. Average dry mass partitioning of azalea given 100 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

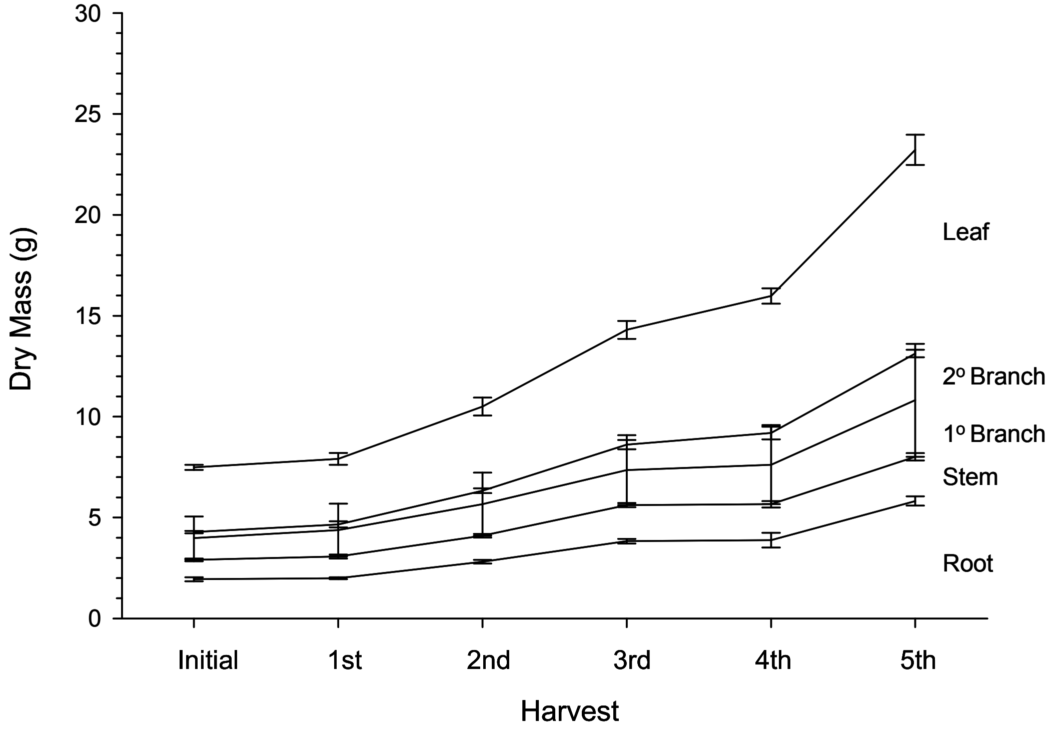


Figure C6-24. Average dry mass partitioning of azalea given 100 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

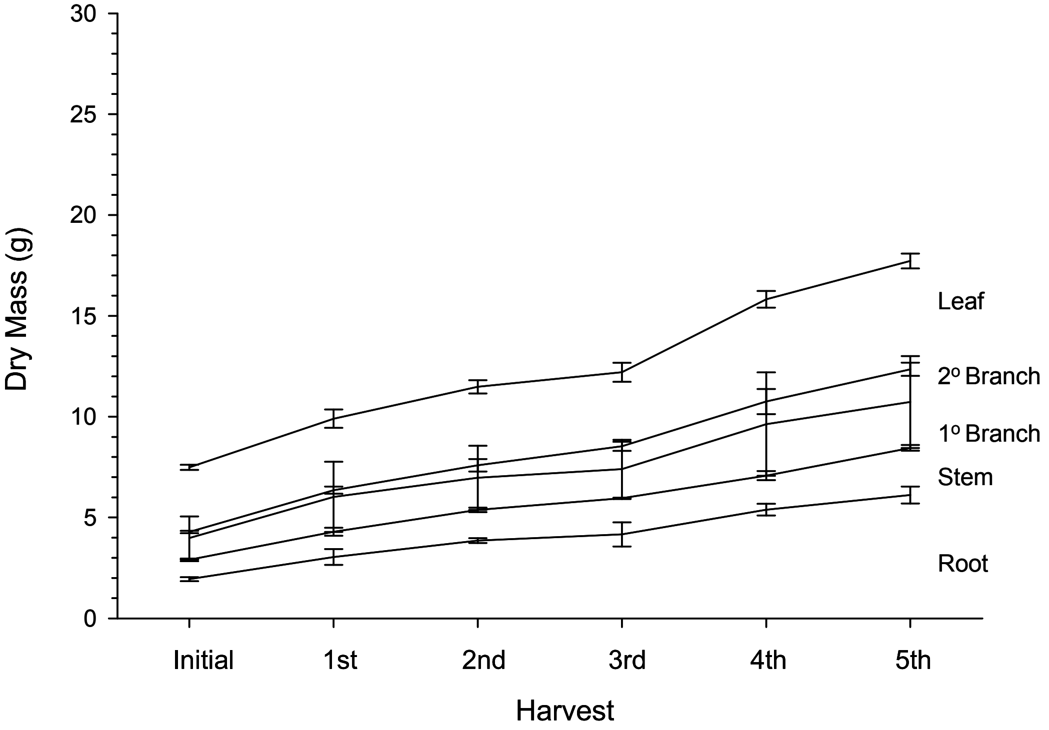


Figure C6-25. Average dry mass partitioning of azalea given 25 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

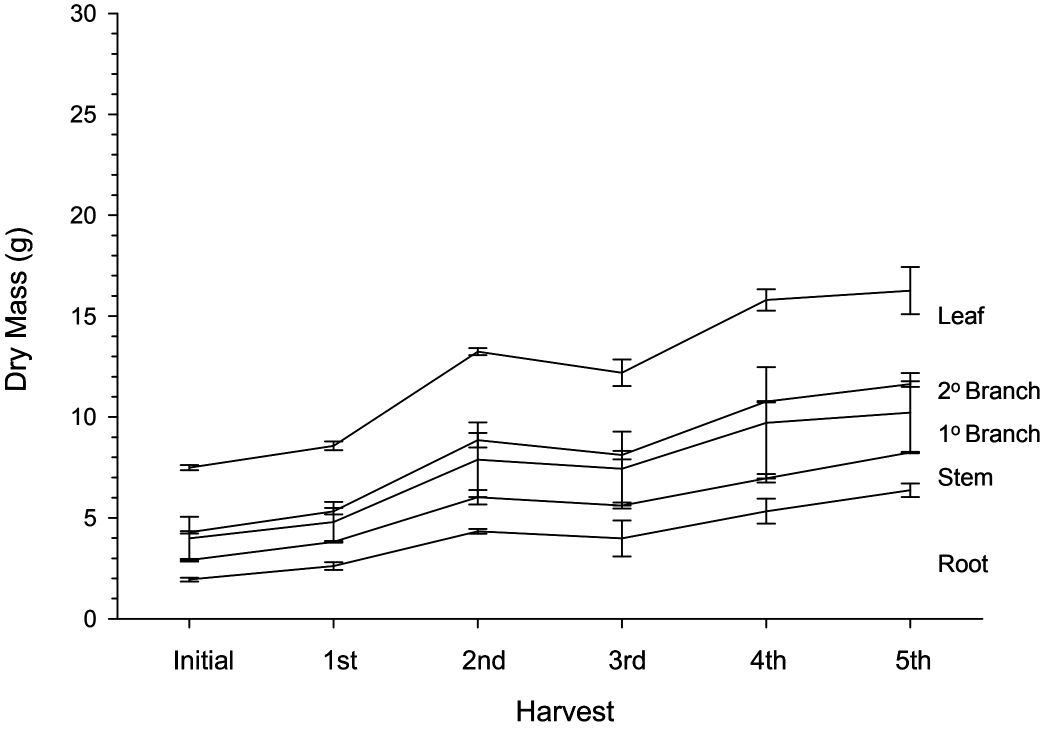


Figure C6-26. Average dry mass partitioning of azalea given 25 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

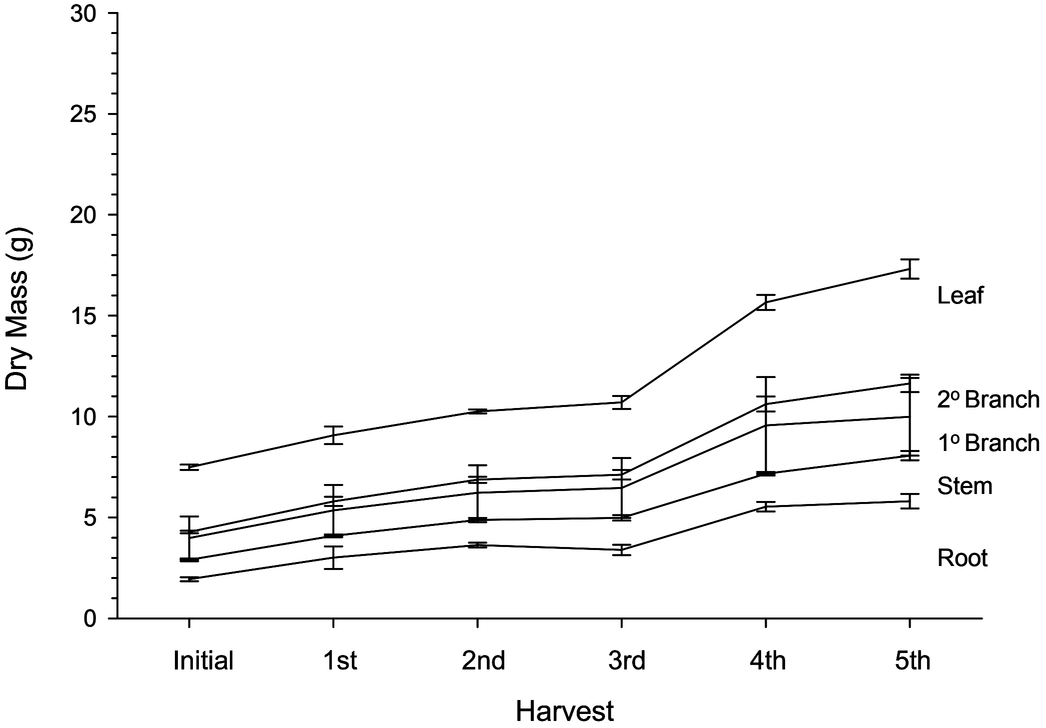


Figure C6-27. Average dry mass partitioning of azalea given 25 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

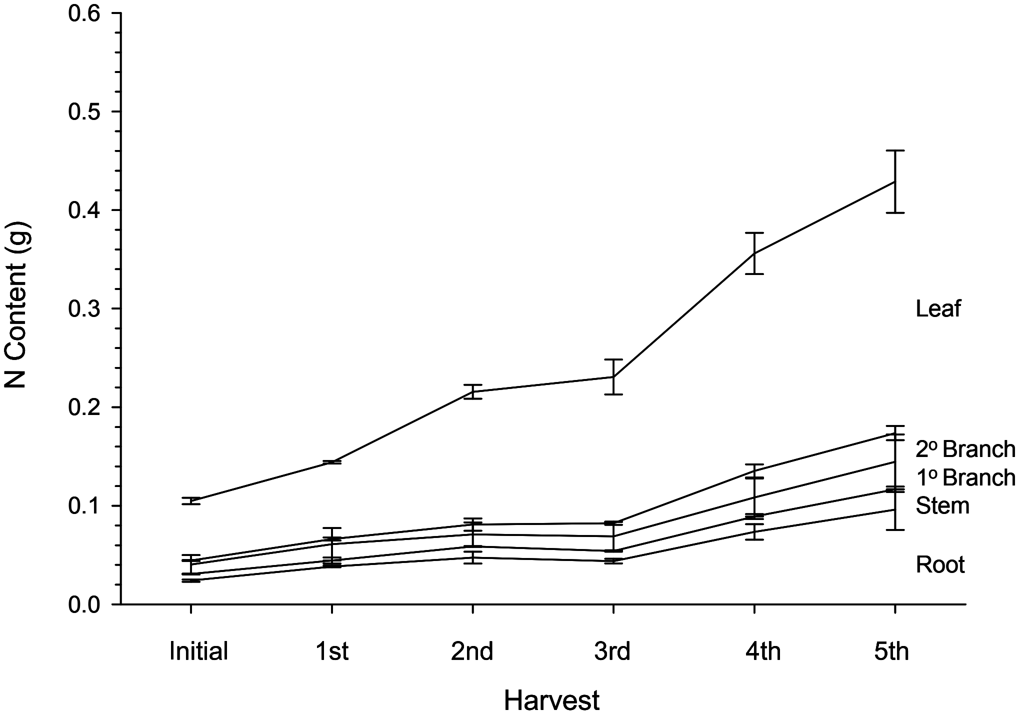


Figure C6-28. Average nitrogen partitioning in azalea given 250 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

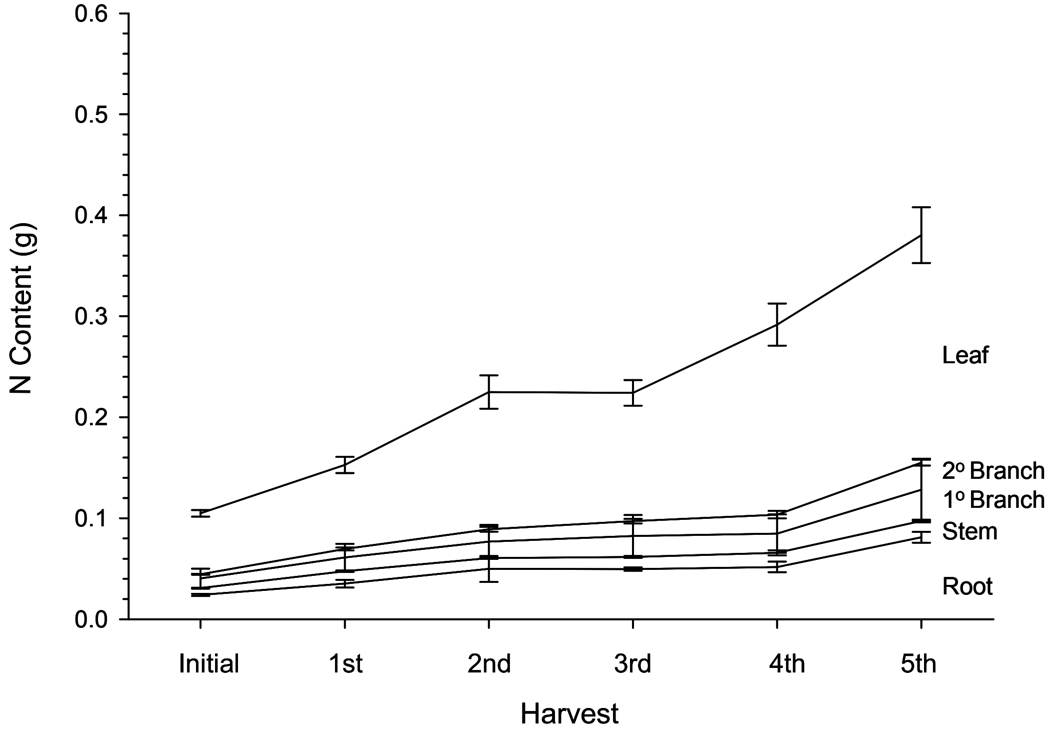


Figure C6-29. Average nitrogen partitioning of azalea given 250 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

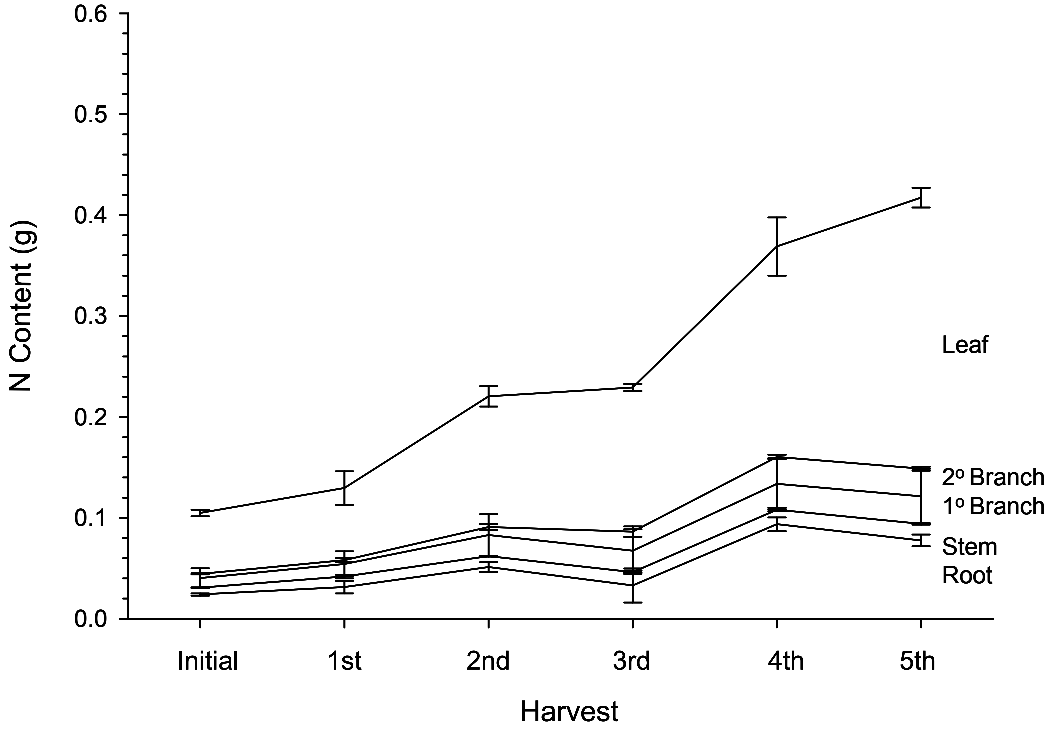


Figure C6-30. Average nitrogen partitioning of azalea given 250 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

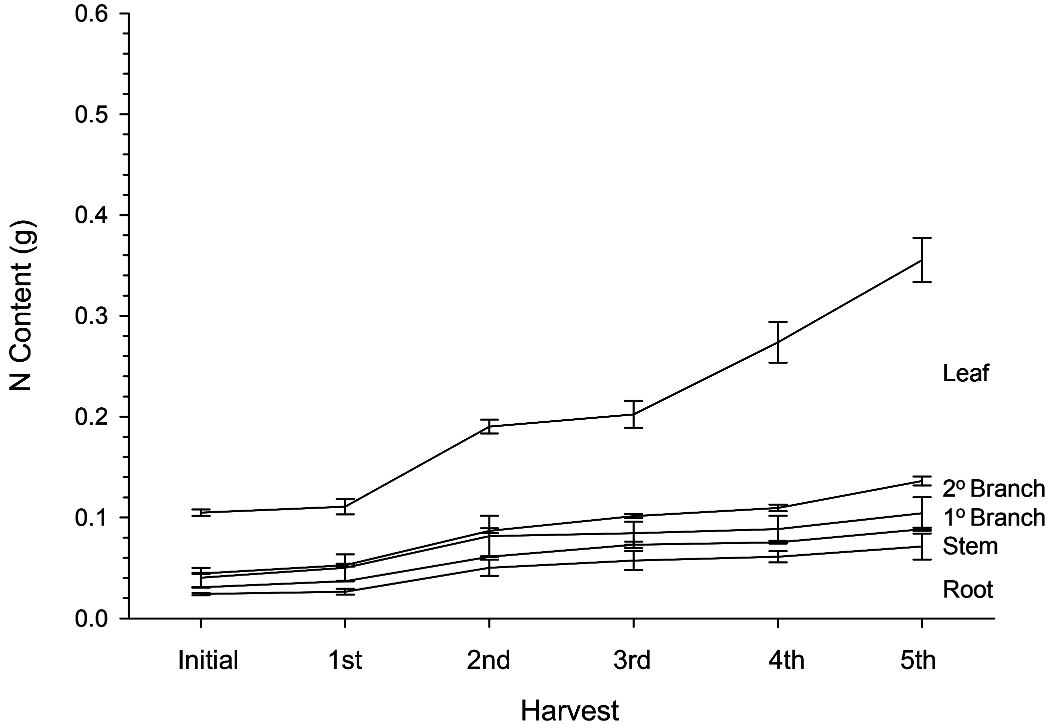


Figure C6-31. Average nitrogen partitioning of azalea given 100 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

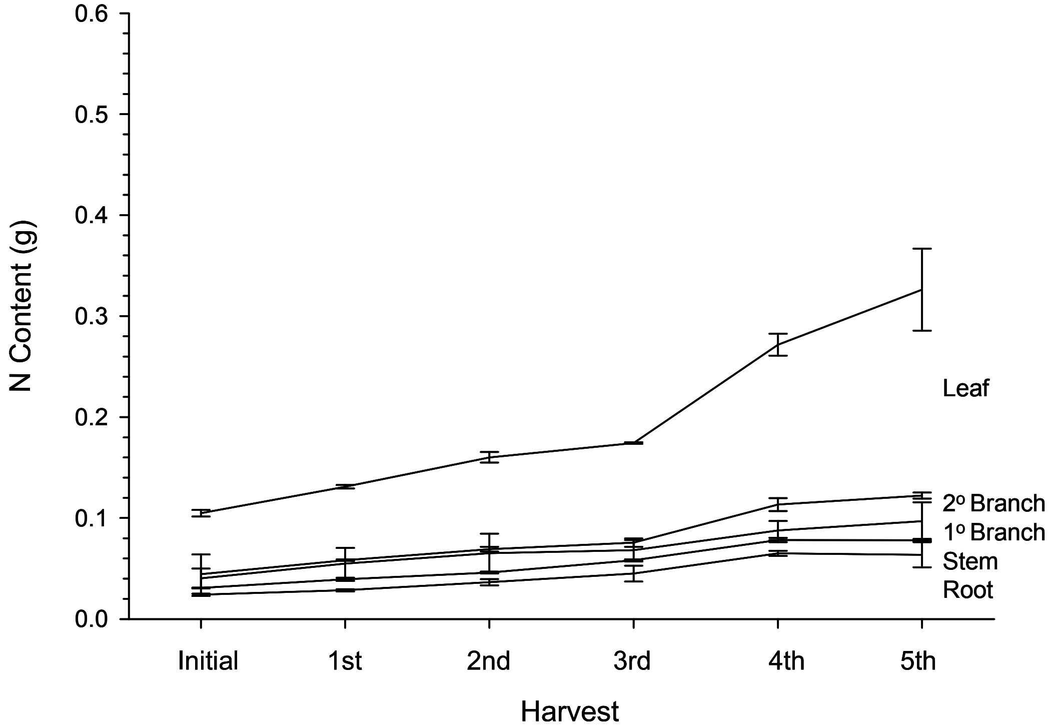


Figure C6-32. Average nitrogen partitioning of azalea given 100 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

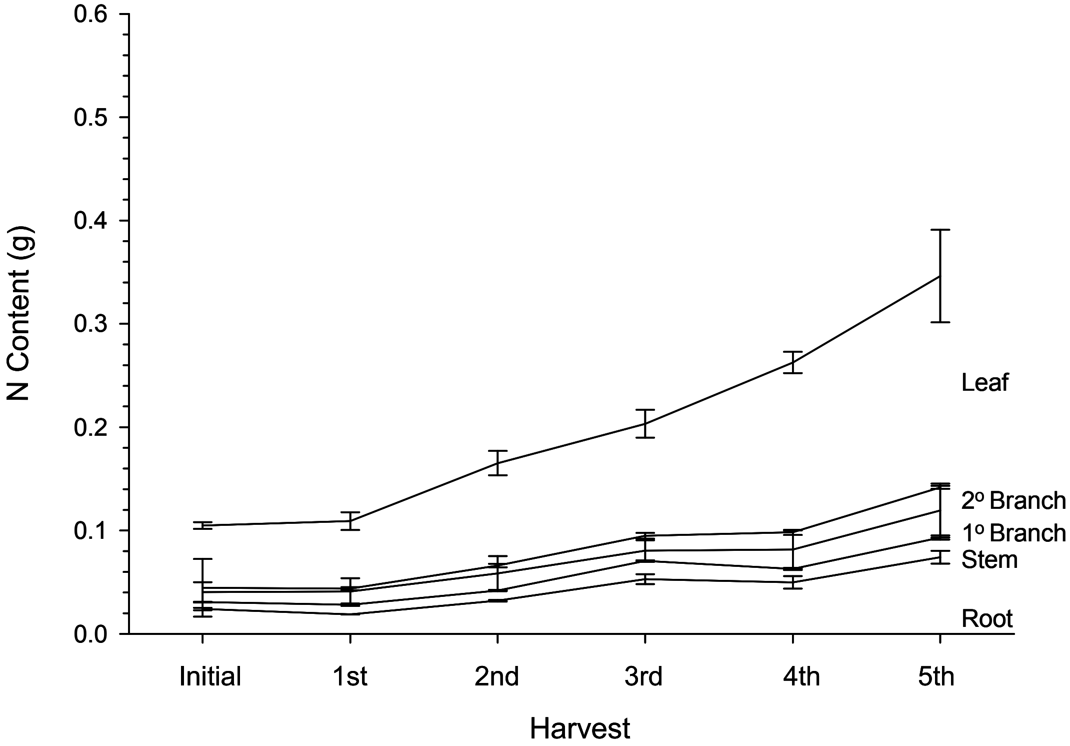


Figure C6-33. Average nitrogen partitioning of azalea given 100 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

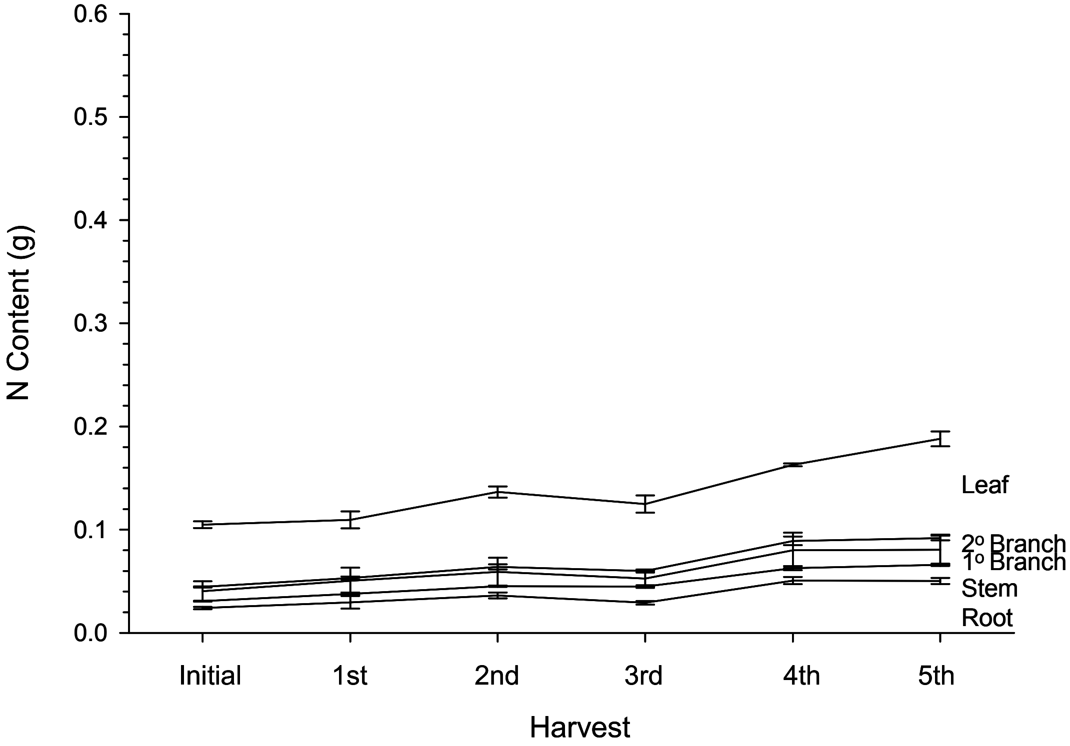


Figure C6-34. Average nitrogen partitioning of azalea given 25 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

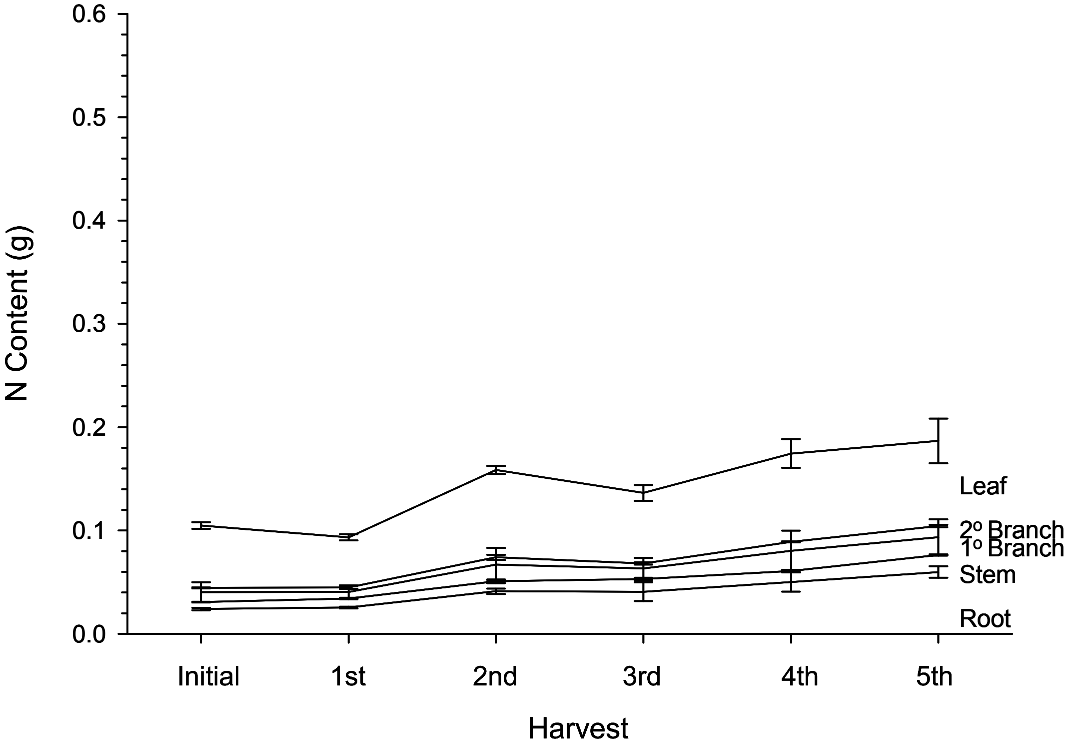


Figure C6-35. Average nitrogen partitioning of azalea given 25 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

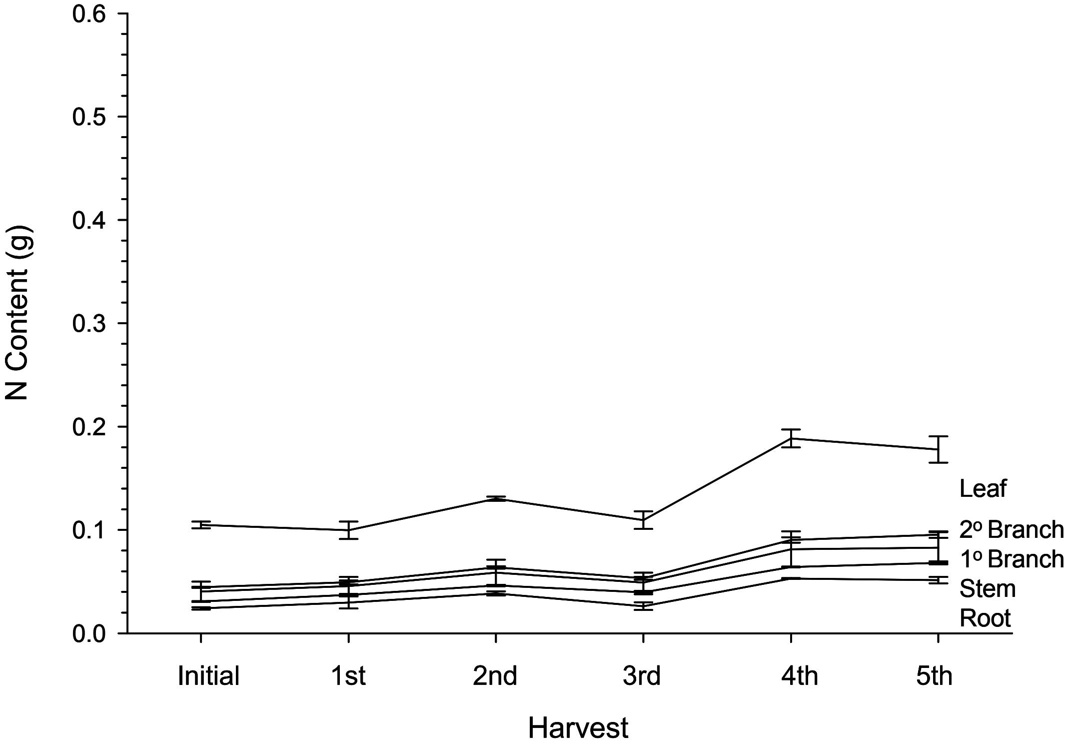


Figure C6-36. Average nitrogen partitioning of azalea given 25 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Harvests were two weeks apart. Error bars are based on n = 3.

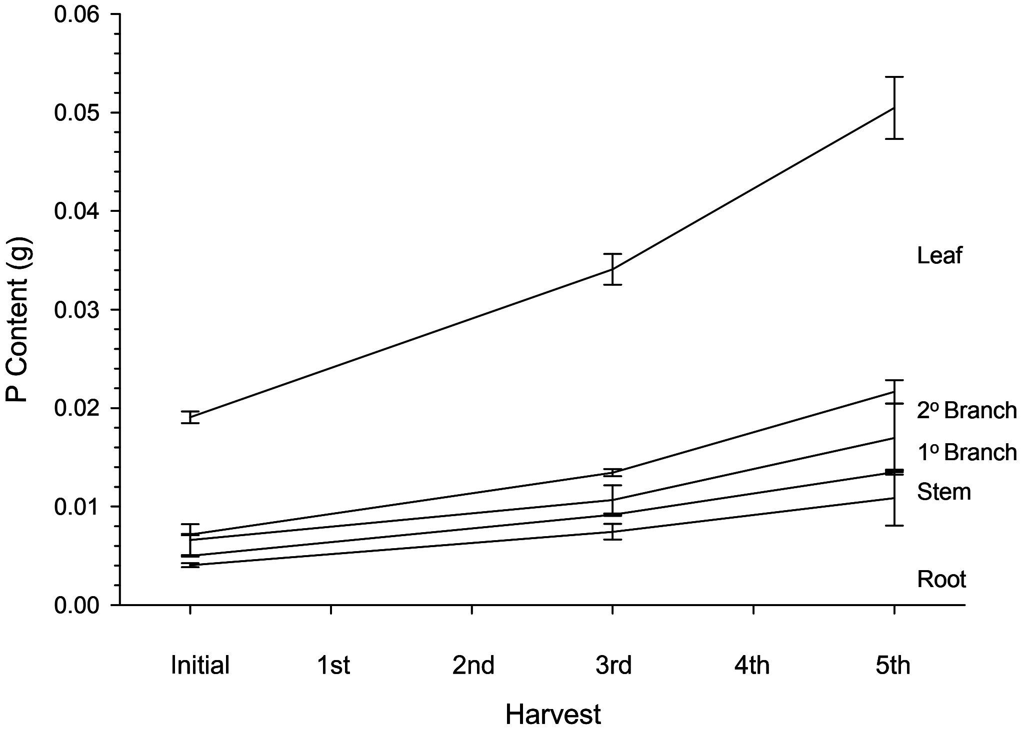


Figure C6-37. Average phosphorus partitioning of azalea given 250 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

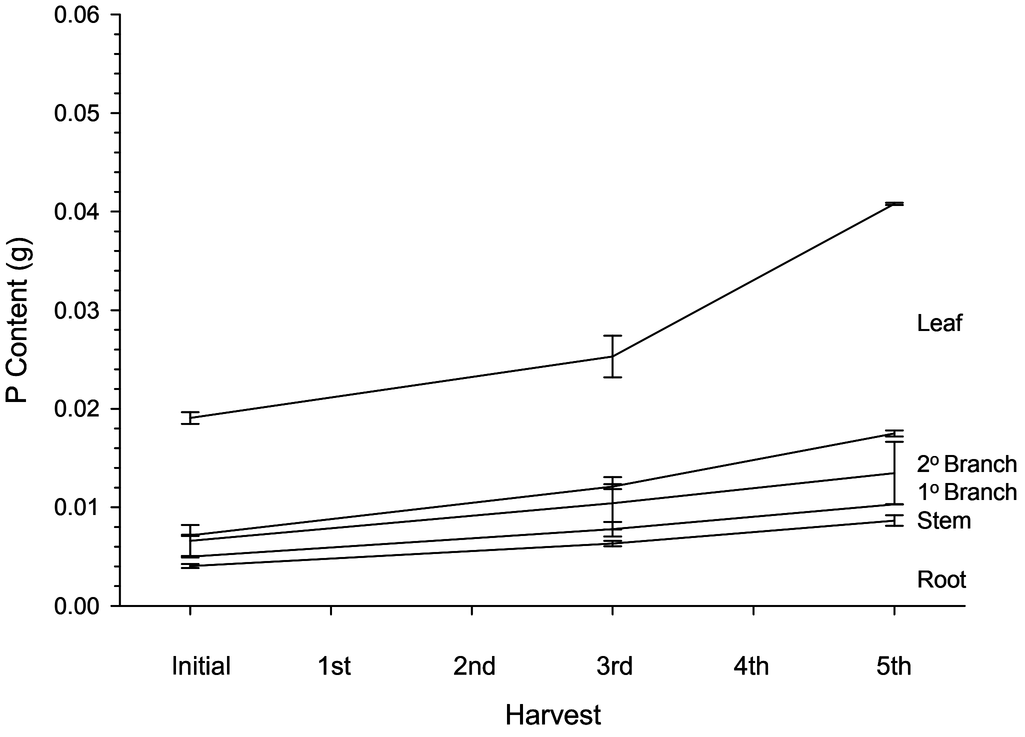


Figure C6-38. Average phosphorus partitioning of azalea given 250 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

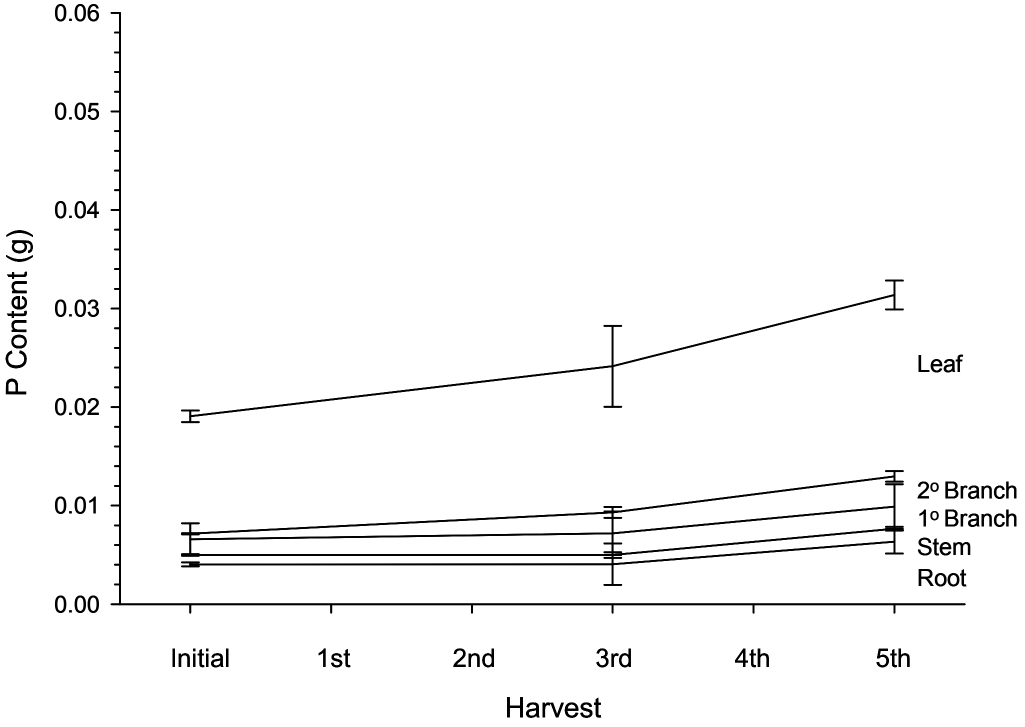


Figure C6-39. Average phosphorus partitioning of azalea given 250 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

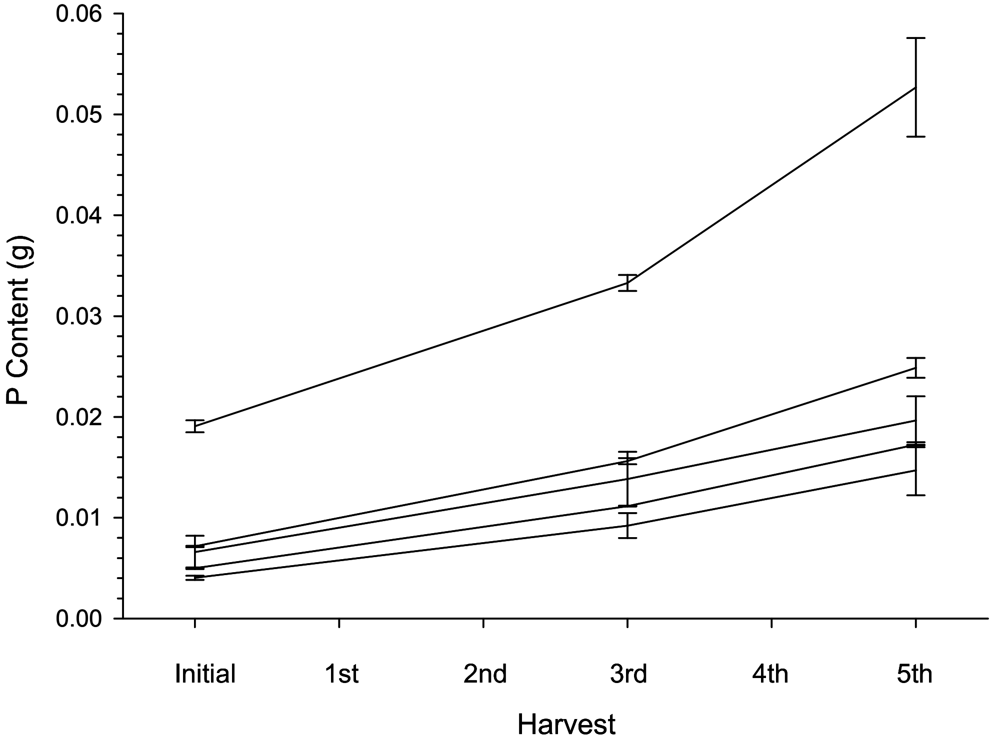


Figure C6-40. Average phosphorus partitioning of azalea given 100 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

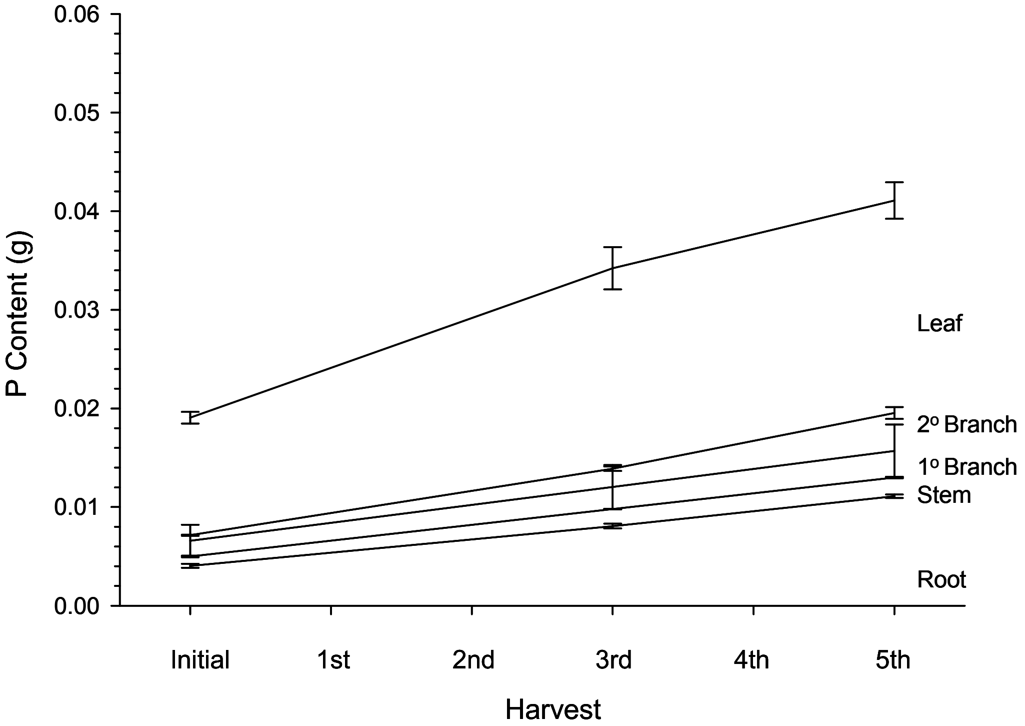


Figure C6-41. Average phosphorus partitioning of azalea given 100 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

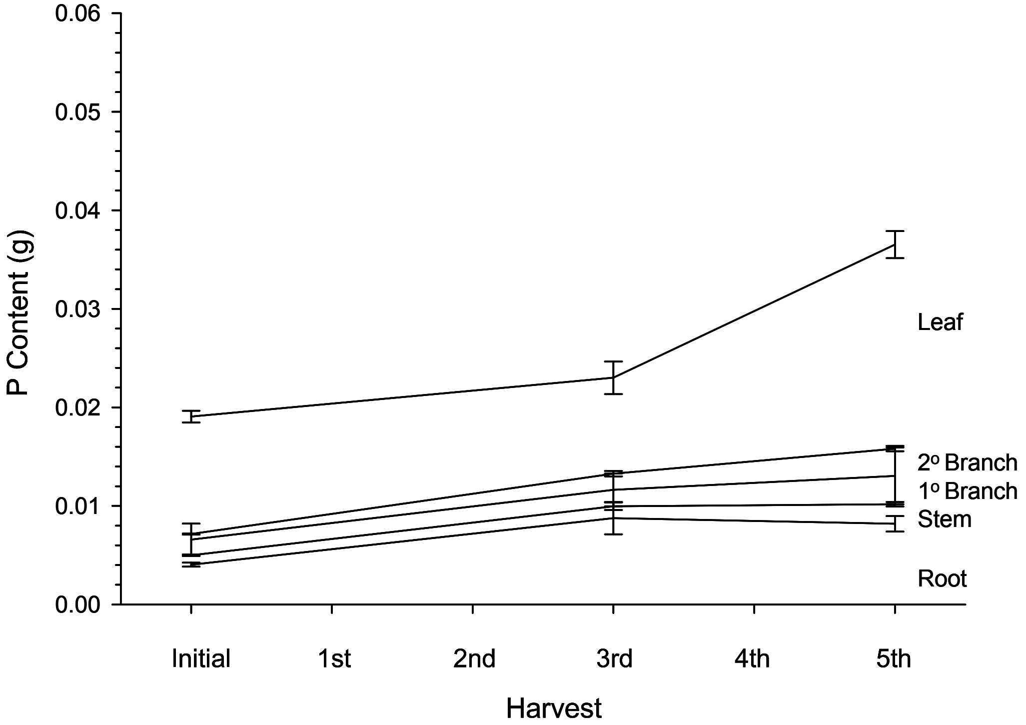


Figure C6-42. Average phosphorus partitioning of azalea given 100 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

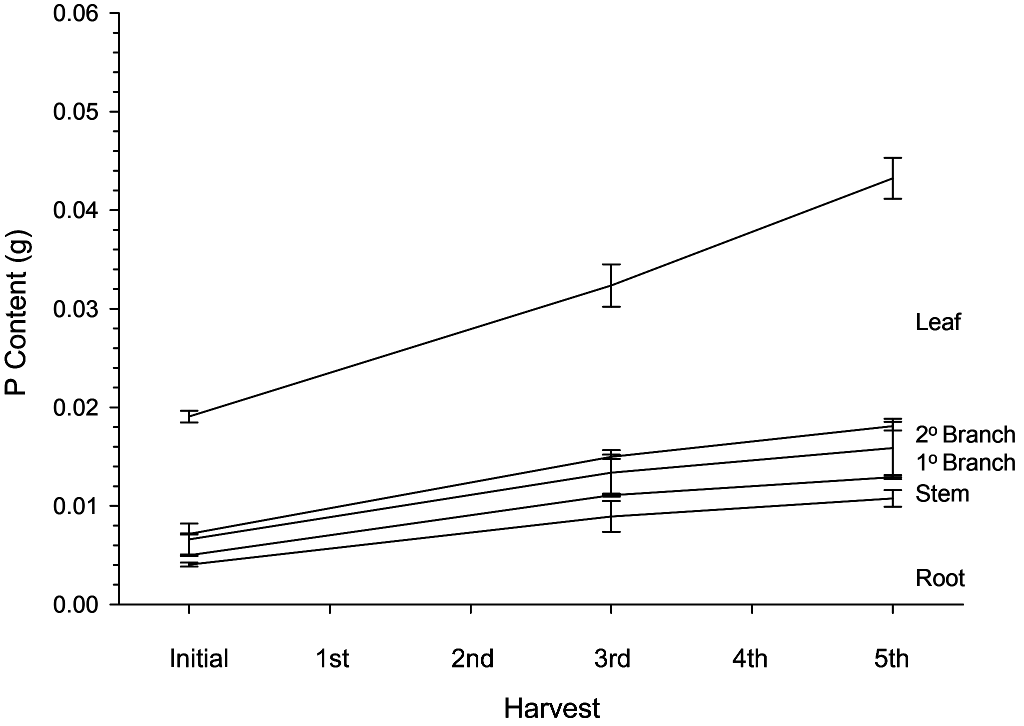


Figure C6-43. Average phosphorus partitioning of azalea given 25 mg N and 25 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

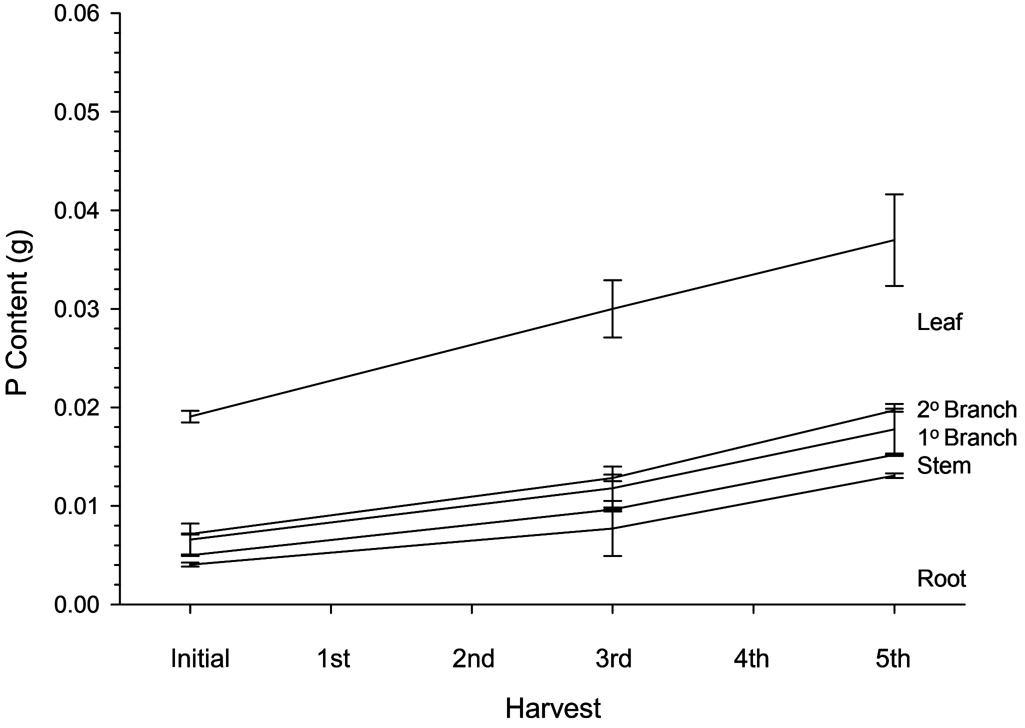


Figure C6-44. Average phosphorus partitioning of azalea given 25 mg N and 5 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

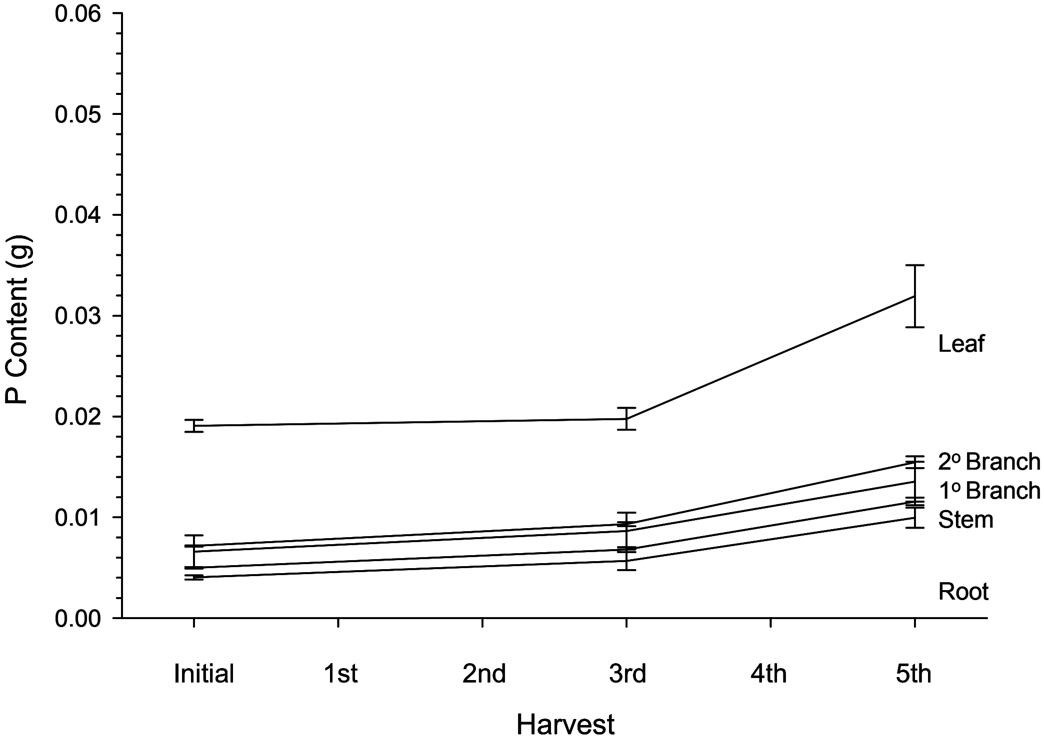


Figure C6-45. Average phosphorus partitioning of azalea given 25 mg N and 0 mg P per week over a period of 11 weeks in the second spring study. Tissue P analysis included initial, third and last harvests. Error bars are based on n = 3.

Glossary

Control Release Fertilizer – fertilizer that is encapsulated by polymers of different forms and thickness, released at a rate based on temperature and moisture, the higher the temperature, the greater the rate of release.

Cyclical irrigation – a form of scheduling water application, which entails the daily water allotment to be applied in a series of cycles comprising of both irrigation and rest periods. Smaller volumes applied more frequently have a tendency to increase the percentage of applied water held by the substrate (Tyler et al.,1996a; Fare et al.; 1996; Beeson 1995; Fare et al.,1994; Kerr 1985) and in turn, maintain adequate moisture levels in the substrate for plant use.

Interception Efficiency - the fraction of applied water and rain that is potentially available to the plant and canopy-captured water that may not enter the substrate but is not directed to the ground.

Fertigation – application of soluble nutrients through irrigation.

Orthophosphate - the salt of phosphoric acid. It is the form of phosphorus that is readily available for plant uptake.

Nutrient Uptake Efficiency – the fraction of nutrient applied that is taken up by the plant.

Nutrient Use Efficiency – (NUE) the efficiency at which plants take up, incorporate, and utilize nutrients. NUE is the amount of biomass produced per unit of nutrient. i.e. mole of carbon per mole of nutrient.

Time Domain Reflectometry – analysis of a conductor (wire, cable, or fiber optic) by sending a pulsed signal into the conductor, and then examining the reflection of that pulse. When used for determining water content in a substrate, it measures the apparent dielectric permittivity of the substrate to electromagnetic pulses. The dielectric constants for oven-dried soil, air and water are 1, -4, and 80 respectively.

Time Domain Reflectometry: Models and Manufacturers
1. Tektronix 1502 B or C models: Tektronix, Beaverton, OR
2. Campbell TDR100: Campbell Scientific, Inc., Logan, UT

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