ABSTRACT

Title of Document: MODELING NITROGEN, PHOSPHORUS AND WATER DYNAMICS IN GREENHOUSE AND NURSERY PRODUCTION SYSTEMS

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Nutrient and sediment runoff from the six states and Washington, DC that form the Chesapeake Bay watershed is a major cause of environmental degradation in the Bay and its tributaries. Agriculture contributes a substantial portion of these non-point source loads that reach the Bay from its tributaries. Research in this area has traditionally focused on agronomic farm contributions, with limited research on the nursery and greenhouse industry. This research presents the first known attempt to model operation-specific information, validated by published research data, where multiple variables are assessed simultaneously. This research provides growers and researchers with a tool to assess and understand the cultural and environmental impact of current practices, and predict the impact of improving those practices. Separate models were developed for

greenhouse, container-nursery and field-nursery operations, since specific production variables and management practices vary. Each model allows for simple entry of production input variables, which interface with the Stella™ modeling layer. Each model was first calibrated with one published research study, and subsequently validated with another peer-reviewed study, with multiple independent runs for each model. Validation results for all three models showed consistent agreement between model outputs and published results, increasing confidence that models accurately process all input data. Validated models were then used to run a number of what-if scenarios, based upon a database of production practices that was gathered from 48 nursery and greenhouse operations in Maryland. This database provided a detailed analysis of current practices in Maryland, and adds significantly to our understanding of various operational practices in these horticultural industries. Results of the what-if scenarios highlighted model sensitivities and provided answers to hypotheses developed from the analysis of the management database. Some model functions, such as denitrification, would greatly benefit from additional research and further model modification. Models were designed to be easily adapted to local conditions for use throughout the U.S. and potentially other parts of the world.

MODELING NITROGEN, PHOSPHORUS AND WATER DYNAMICS IN GREENHOUSE AND NURSERY PRODUCTION SYSTEMS

By

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Dedication

There were many people that were instrumental in helping me complete my dissertation work. First of all, I would like to thank my wife, Shannon. Without you this work would not have been possible. You are an amazing wife and loving mother, both of which you do to the upmost of your abilities. Thank you for your patience, guidance, wisdom and encouragement during this long road. There is no one else I would rather be with on this journey of life. Samuel, my son, I love you more than you could ever know. I wanted to let you know that you probably made this project take longer than it did, but I would not have it any other way.

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Most importantly, I want to dedicate this work to my Lord and Savior Jesus Christ, who brings meaning and importance to everything that I do.

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A. Chesapeake Bay Restoration Efforts

At 64,000 square miles and 11,600 miles of tidal shoreline, the Chesapeake Bay is the largest estuary in North America, and the third largest estuary in the world (Chesapeake Bay Foundation 2009). The bay and its tributaries support a large variety of fish, birds, and plants, and act as a water filter for thousands of acres of watershed. The Chesapeake Bay is fed by more than 100,000 streams, creeks and rivers including 150 major rivers, with the Susquehanna, Potomac, Rappahannock, York and James rivers providing almost 90% of the fresh water to the Bay (Chesapeake Bay Program 2008). In addition to the large number of plant and animal species, the watershed also supports a large human population residing in several large urban centers, as well as many suburban and rural areas. There are currently about 17 million people living in the watershed with about 10 million living at or near the shores of the Bay (Chesapeake Bay Foundation 2009).

Along with a large population increase, development in the watershed has also increased dramatically in the recent past. From 1600-1949, 1.7 million acres of the watershed were developed, compared to 2.7 million acres that were developed from 1950-1980 (Chesapeake Bay Foundation 2009). Two of the top threats to bay health are nitrogen (N) and phosphorous (P) runoff from agriculture, sewage treatment plants, residential/commercial runoff, and air pollution (Chesapeake Bay Foundation 2009). The size of the watershed, and the fact that it includes parts of 6 states and the District of

Columbia makes cleanup efforts that much more difficult to coordinate with local, state, and federal governments.

For approximately 30 years, Bay restoration has been handled at the state level, with arguably little progress being made over that time. Starting in 2011, Chesapeake Bay and its tributaries will be subject to EPA mandated total maximum daily load (TMDL) limits for N, P, and sediment, based on section 303 (d) of the Clean Water Act (Sincock 2010). The Bay TMDL actually consists of 92 individual TMDLs for different watershed segments, which set pollution limits to reach state standards for dissolved oxygen, water clarity and chlorophyll-a (Sincock 2010). Table 1.1 gives the 2009 loading rates and proposed annual TMDL N, P, and sediment loading limits for all 59 watershed basins located in Maryland. Numbers are given in 1000s of pounds for each column. The complete list of loading rates for all Chesapeake Bay watersheds is provided in Appendix A (Table A 1.1).

The major focus of the Bay TMDL limits are to reduce nitrogen (N), phosphorus (P) and sediment runoff into the bay, which will then allow other recovery efforts, such as submerged aquatic vegetation, fish and shellfish restoration, to improve. Nitrogen and P are major nutrient inputs often associated with agriculture, wastewater treatment, and other anthropogenic sources, and can cause many water quality problems when they are found above ‘natural’ levels in water bodies, such as algal blooms and decreased dissolved oxygen levels. Increased sediment loads can cover aquatic vegetation, clams, and oysters, and alter water body dynamics by changing their shape and volume. Initial attempts on reducing N and P inputs focused on regulating point sources such as wastewater treatment plants and factories through system upgrades and a permitting

Table 1.1. Target and actual 2009 loading rates for N, P and sediment for Chesapeake Bay from Maryland watersheds. Modified from (U.S. Environmental Protection Agency 2010).

CB 303(d) Segment	**TMDL** 1000 lb N/ yr	**2009 Load** 1000 lb N/ yr	**TMDL** 1000 lb P/ yr	**2009 Load** 1000 lb P/ yr	**TMDL** 1000 lb sediment /yr	**2009 Load** 1000 lb sediment/ yr
Anacostia River, DC	46.1	54.3	6.80	10.77	0.890	1.616
Anacostia River, MD	421.8	500.3	40.70	61.55	70.171	111.376
Back River	1757.8	2257.5	92.27	75.58	16.386	9.428
Big Annemessex River	144.6	154.3	8.36	8.30	0.801	0.522
Bohemia River	135.1	180.1	15.17	20.17	3.251	3.759
Bush River	870.7	1000.5	37.87	63.79	24.088	35.409
C&D Canal, DE	0.1	0.2	0.01	0.04	0.004	0.005
C&D Canal, MD	48.6	59.2	5.45	6.49	1.083	1.259
Eastern Bay	906.8	1124.8	69.94	71.88	10.443	11.317
Elk River	361.6	467.8	26.28	30.12	8.736	9.989
Fishing Bay	732.6	874.0	73.24	78.24	4.679	5.114
Gunpowder River	1142.0	1289.9	30.51	58.61	33.801	57.277
Honga River	144.2	164.3	4.53	6.60	0.544	0.647
Little Choptank River	281.7	336.1	21.53	22.98	3.212	3.490
Lower Central Chesapeake Bay, MD	1141.7	1264.9	12.01	28.78	3.882	5.354
Lower Chester River	690.1	865.0	52.24	52.24	12.918	14.317
Lower Choptank River	543.1	656.1	37.56	40.92	4.966	5.816
Lower Nanticoke River	182.1	198.3	10.34	11.17	0.785	0.829
Lower Patuxent River	650.2	789.4	39.86	63.80	6.989	12.133
Lower Pocomoke River, MD	215.9	227.2	11.30	11.17	1.194	1.611
Lower Potomac River, MD	1125.5	1357.6	111.65	125.59	60.801	72.285
Magothy River	235.8	288.1	6.06	20.78	1.397	2.109
Manokin River	341.2	342.7	30.20	25.73	1.551	1.494
Mattawoman Creek	171.3	205.6	15.74	20.64	5.972	6.869
Middle Central Chesapeake Bay	1545	1716.6	20.08	35.62	1.786	2.035
Middle Chester River	591.5	839.0	63.18	67.79	9.687	10.775
Middle Choptank River	586.7	711.2	66.28	63.66	4.588	4.510
Middle Nanticoke River	677.2	839.3	79.38	84.22	7.622	8.164
Middle Patuxent River	315.2	388.1	18.04	31.32	5.909	10.781
Middle Pocomoke River, MD	110.4	117.5	8.52	8.18	0.686	0.714

Middle Pocomoke River, VA	62.7	69.3	8.14	7.73	0.691	0.978
Middle Potomac River, MD Mainstem	48.7	54.2	4.21	4.41	1.650	1.926
Middle Potomac River, MD Nangemoy Creek	136.9	151.5	10.08	11.39	2.306	2.653
Middle Potomac River, MD Port Tobacco River	128.0	143.0	9.39	9.96	3.035	3.514
Middle River	105.5	183.6	3.20	11.82	0.728	1.577
Mouth of Choptank River	478.0	521.8	40.50	41.66	3.956	3.790
Northeast River	220.7	251.4	12.41	13.21	14.587	16.453
Northern Chesapeake Bay	1481.4	1918.7	69.90	82.18	70.138	80.793
Patapsco River	4502.2	7821.1	210.30	397.28	79.455	113.382
Piscataway Creek	519.4	469.2	31.92	25.39	7.609	6.183
Rhode River	54.7	68.8	2.84	4.35	0.500	0.740
Sassafras River	269.8	394.5	32.89	36.92	8.628	9.990
Severn River	482.0	518.3	23.67	50.59	3.809	3.724
South River	225.2	261.6	9.54	19.71	1.931	3.030
Tangier Sound, MD	712.3	782.4	7.50	8.28	0.016	0.020
Upper Central Chesapeake Bay	745.5	771	16.69	23.94	3.637	5.412
Upper Chesapeake Bay	722.8	867.6	29.64	34.74	3.055	2.647
Upper Chester River	421.6	571.9	51.81	52.06	12.327	13.398
Upper Choptank River	1101.7	1473.7	134.42	147.15	19.338	20.301
Upper Nanticoke, DE	23.5	25.8	3.03	2.90	0.124	0.128
Upper Nanticoke, MD	52.7	67.7	6.69	7.01	0.513	0.557
Upper Patuxent River	1769.6	1766.9	127.07	150.61	59.403	67.342
Upper Pocomoke River	798.6	896.7	95.89	95.39	11.643	11.713
Upper Potomac River, DC	2209.9	2337.5	105.01	46.39	32.320	25.206
Upper Potomac River, MD	10944.7	13298.2	568.75	696.31	497.574	544.927
West River	54.4	60.7	2.56	4.23	0.518	1.001
Western Branch Patuxent River	214.6	236.8	19.89	25.99	16.939	23.234
Wicomico River	648.1	910.0	61.98	85.49	6.483	7.184
Maryland Total	**45251.8**	**56163.8**	**2715.02**	**3303.82**	**1171.735**	**1382.807**

process (Chesapeake Bay Foundation 2009). The majority of N and P reaching surface waters is from non-point sources, such as manure or other fertilizers, and urban/suburban wastewater treatment plants (Chesapeake Bay Program 2008). About 25 percent of the watershed is used for agriculture, totaling 8.5 million acres, and is the largest intensively managed land use in the Bay (Environmental Protection Agency 2009). There has been minimal research that has focused on defining N, P, and sediment contributions from the commercial nursery and greenhouse industry, and on quantifying the impact of this industry on local watersheds and the Chesapeake Bay.

B. The Nursery and Greenhouse Industry in Context

Maryland has about 1,246,000 acres of harvested farmland with about 93,000 of those acres irrigated (U. S. Dept. Ag. 2009). At approximately 20,000 acres, the nursery and greenhouse industry in Maryland represents a substantial portion of irrigated agricultural land (U. S. Dept. Ag. 2009). Gross receipts in the wholesale nursery and greenhouse industry were $422 million in 2007, representing a substantial part of the agricultural economy in the state (Dawson et al. 2009). Although the nursery and greenhouse industry makes up a relatively small amount of farmland, many operations are intensively managed, especially greenhouse and container operations. This leads to the *potential* for high levels of nutrient and sediment runoff *if* proper nutrient application and abatement practices are not followed.

Since almost all of the fertilizer used in these industries is water soluble, irrigation water management has a significant impact on nutrient management and the potential for leaching and loss to surface waters. There were two main purposes for this research project. The first was to develop a database of current nutrient and irrigation management practices for Maryland based on interviews from 48 field, container, and greenhouse operations. This provided a better understanding of current irrigation and nutrient application rates and timings, as well as general management practices in the state. Secondly, this project developed production-specific models that can serve as tools to both researchers and growers to better understand the interaction of management, fertilizer, and irrigation practices on plant growth, resource efficiency, and nutrient runoff. These management tools incorporate current management practices, and can quickly identify areas of increased efficiency at the management unit level.

Nursery and greenhouse production can range from extensive, field-production operations with low N and P inputs to highly intensive container-nursery and greenhouse operations, which have the *potential* to contribute large quantities of N and P to the surrounding environment, if appropriate management and water-control structures are not in place. As a result of the Maryland Water Quality Improvement Act of 1998, passed by the Maryland State Legislature, and under the regulations administered by the Maryland Department of Agriculture (MDA), almost every commercial greenhouse and nursery operation in the state is required to develop and implement a N and P-based nutrient management plan (Lea-Cox et al. 2001a). Due to the complex nature of these operations and the large number of ornamental species that are typically grown by any one operation, the nutrient management process is based on a risk-assessment strategy, not on a crop removal basis as is done for agronomic crops (Lea-Cox and Ross 2001). Since irrigation water applications are a dominant factor in nutrient application and runoff for these operations, the nutrient management process also incorporates irrigation and surface water runoff risk assessment components. This process ultimately assesses the potential for N and P runoff from individual operations based on the operations' specific practices, and provides guidance for the development and implementation of additional best management practices, if necessary (Lea-Cox et al. 2001a). It is important for the person that is developing the plan to do so in association with the producer, to ensure that the plan is properly understood and implemented so that it has the maximum effectiveness.

Since the first plans were written, it has been determined that many nursery operations in Maryland are in fact low-risk, based on their current set of nutrient application and management practices (Lea-Cox et al. 2006). Therefore, it is assumed that they pose a minimal environmental threat to surface waters of the state and the Chesapeake Bay, although this has not been proven. However, there were a number of operations that were initially classified as either medium or high risk, that were then required to assess their production methods and possibly implement better practices, to reduce water and nutrient runoff from their operations. A variety of best management practices are available to reduce nutrient and water runoff, such as reducing nutrient application rates, changing fertilizer type and/or method of application, changing irrigation type and/or frequency, capturing and recycling surface water runoff, and establishing riparian buffers or sediment ponds. There is currently no means available of evaluating the impact of implementing different management practices at a scale or level of complexity that would help growers and researchers assess the risk and benefit of any best management practice using single or multivariate analysis.

This research therefore was focused on developing a robust set of models for water and nutrient use in greenhouse, container, and field nursery production systems. These models were developed to help both researchers and growers in this industry identify ways to reduce nutrient and irrigation water inputs, without negatively impacting plant growth and production schedules, and to help assess those practices which pose the highest risk to water and nutrient runoff from those operations. These models were validated with the current best research-based information. In addition, a database of specific grower practices was developed and used to provide information for running a number of what-if scenarios, to illustrate the outcomes of those practices.

C. A Brief History of the Nursery and Greenhouse Industry

During the past 25 years, there has been a shift in how ornamental plants are produced in the United States. Before the energy crisis of the early 1970s, the production of ornamental plants was largely focused on maximizing plant growth rate using extensive (in ground) systems, given that the cost of most inputs was relatively low. Containerized production signaled a shift in the efficiency of ornamental production both in nursery and greenhouse environments, primarily driven by the increasing cost of resources. This trend has continued until today, with over 50% of plants now being grown in containers (U. S. Department of Agriculture 2007). In this way, the increased cost of production has been counter-balanced by increased productivity per unit area. This shift to containerization has resulted in much greater numbers of plants being grown per unit area (plant density), since they can be shifted from close-packed spacing to more open spacing when light interception limits growth (plant canopies interact). High-density production has therefore become the dominant method of growing most types of plants in both greenhouse and container-nursery operations. There has also been a cross-over shift within traditional field production to pot-in-pot operations, where large plants are grown in 27 to 175 L (7 - 45 gallon) containers. In the greenhouse industry, net profit is generally driven by turnover (profit per unit area) whereas in recent years the greatest net profits in the nursery industry have been realized by larger-sized plant material, together with sales of new (and unusual) plant introductions.

i. Economic Impact and Trends

The nursery and greenhouse industry ranks 6th in U. S. market value of agricultural products sold, and is in the top five market values of agricultural products sold for 34 states (U. S. Department of Agriculture 2009). Sales revenues have steadily increased at an average of 2.4% per year from $10.7 billion in 1987 to 14.7 billion in 2004, expanding even during recessionary periods (Hall et al. 2006). Nationally, the cost of production in the container and greenhouse industry has increased faster than the cost per unit of plant being sold in recent years (Jerardo 2006). This increase in cost is due to several factors, primarily the increased cost of labor. Increases in productivity may have been gained by more automation (with high initial costs) and/or by reducing the number of person-hours in the operation (Hodges et al. 1997; Hodges et al. 1998; Hall et al. 2006; Hodges and Haydu 2006). The net effect of these issues has forced many smaller and even medium size operations to reduce costs and/or produce more plants per unit time to maintain profits, or close due to competitive pressures in local areas (Hall et al. 2006). Consequently, many growers are very focused on increasing system production efficiency to significantly reduce expensive inputs, including fertilizer, growth regulators, labor and irrigation costs, without compromising plant growth or health.

ii. Operation Management

Together with shifts in the ornamental market and more intensive production practices over the past 30 or so years, there has been a growing recognition that intensive plant production operations are having a significant impact on the local environment. Starting in the early 1980s, a number of nursery researchers recognized that many best management practices could be implemented that would improve resource use efficiency, increase productivity and reduce the overall environmental impacts of those practices (Wright and Niemiera 1987; Yeager et al. 1997; Fain et al. 2000; Bilderback 2001; Yeager et al. 2007). This culminated in the development of the first set of Best Management Practice (BMP) guidelines for the nursery industry (Yeager et al. 1997), which was significantly reviewed and updated by Yeager et al. (2007). Water and nutrient management are inextricably linked in the production of plants in containers, since soilless substrates such as peat, pine bark and a large variety of organic and inorganic amendments are used. Readers are also referred to the latest editions of comprehensive textbooks on growing media (Handreck and Black 2002), soilless culture (Raviv and Lieth 2008) and greenhouse management textbooks by Hanan (1998) and

Nelson (2008). In addition, an expanded version of much of the information presented in this Chapter is available (Majsztrik et al. 2011).

iii. Specific Industry Issues

Water issues, specifically involving irrigation scheduling, surface and groundwater water supply and runoff water quality, including nutrient, herbicide, pesticide and pathogen-related issues are topics of major concern even in areas where rainfall is relatively abundant. Drought, salinity, urban competition for surface and groundwater reserves and increasing legislation at federal, state and county levels are all increasing the need for ornamental crop producers to manage water resources more effectively (Fernandez et al. 2009). Legislation regarding water use and/or water quality has been implemented in California, Delaware, Florida, Maryland, Michigan, North Carolina, Oregon and Texas (Fernandez et al. 2009). Optimizing the management of water and nutrients offers unique challenges and opportunities for nursery and greenhouse operations across the United States and in many other parts of the world.

With limited root volumes in containers, one or more daily irrigations – and often times daily or weekly fertilizations using soluble fertilizers, or seasonal applications of slow-release fertilizers (SRFs) – are required to optimize plant growth (Lea-Cox et al. 2001a). Irrigation of ornamental crops in containers therefore tends to be excessive, and water and nutrient use is known to be inefficient (Bauerle et al. 2002; Bilderback 2002; Ristvey et al. 2004; Ross and Lea-Cox 2004). Over half of the irrigation water used by intensive container nurseries is applied by overhead sprinkler systems (Beeson et al.

2004). Commercial nurseries commonly apply high irrigation rates of 25 mm·day^{-1} that can produce leaching fractions (volume leached as a percentage of volume applied to the container surface area) as high as 110%. This can generate from 18,000 to 90,000 L (5,000-25,000 gallons) of runoff per hectare per day (Huett 1997). It is known that improving irrigation efficiency can directly improve nutrient efficiency because the volume of water leaving production beds is reduced (Ristvey 2004) and therefore, the carrier for nitrogen (N) and phosphorus (P) leaching and transport is reduced (Bilderback 2002; Ristvey 2004; Ristvey et al. 2004; Bilderback and Lea-Cox 2005; Ristvey et al. 2007).

In 1994, Niemiera wrote a prescient chapter that provided an integrated view of water, nutrient and substrate management, with a focus on increasing resource efficiency and maximizing growth and productivity. Niemiera (1994) linked irrigation management with leaching fractions and nutrient leaching and gave specific recommendations for monitoring production areas, and reducing the environmental impact of current management practices.

Nursery and greenhouse operations can employ any number and combination of best management practices (BMPs) to increase the efficiency of water and nutrient management at their operation (Yeager et al. 2007). Best management practices can be defined as schedules of activities, prohibitions, maintenance procedures and structural or other management practices found to be the most effective and practical to prevent or reduce the discharge of pollutants (Yeager et al. 2007). The goal of a BMP is to decrease the environmental impact of plant production, while hopefully increasing the operations economic efficiency. There are usually several BMPs that can be used to achieve the same purpose, with the grower typically deciding which is best based on their particular situation and needs (Lea-Cox et al. 2001a). The problem is that published BMP recommendations are necessarily general, and are designed to give common-sense guidelines for nurseries to improve irrigation and nutrient management rather than provide information on specific practices. More specific BMPs reflect current scientific knowledge and, if used in combination, have been shown to demonstrably reduce the impact of excessive water and nutrient applications to nursery and greenhouse operations, e.g. cyclic irrigation (Beeson and Haydu 1995; Tyler et al. 1996a; Tyler et al. 1996b), calcined clay amendments (Owen 2006; Owen et al. 2008) and recycling and remediation of containment water (Taylor et al. 2005; Vymazal 2007; White 2007). For a more extensive list of irrigation best management practices, see Environmental Protection Agency (1993); Waskom (1994); Fain et al. (1999); Fain et al. (2000) and Mostaghimi et al. (2001).

In 2001, Lea-Cox, Ross and Teffeau developed the first comprehensive water and nutrient management planning process for nursery and greenhouse systems in the U.S. This process was developed in response to the Maryland Water Quality Improvement Act of 1998; a set of regulations that were intended to reduce non-point nutrient loading from agricultural operations into the Chesapeake Bay. Until that time, it was not clear how nursery and greenhouse growers could actually account for the primary nutrients (N, P, K) that were applied to the large number (typically >250 species) of plants that were grown by individual operations at any one time. To date, approximately 350 nutrient management plans have been written by nursery and greenhouse operations in Maryland,

and many operations have now implemented the site-specific best management practices that resulted from that planning process (Lea-Cox and Ross 2007).

D. Soilless Substrates

When containers were first used to grow ornamental plants, many growers quickly found that the use of native soils in containers led to the development of a “perched” water table at the base of the container, primarily because of the small particle size of most soils impedes water drainage from the container. Poor drainage led to aeration and disease issues in container production, which spurred the development of the John Innes Composts, the University of California (UC) mixes and the Cornell peat-lite mixes for container culture from the 1950s to 1970s (Hanan 1998). The development of these and many other soilless substrates has led to the majority of plants being grown in containers, ranging from small volume (< 4L) greenhouse containers to mid-size (4-28 L) containers for perennial production, to large (28-175 L) containers for large shrub and tree production. Soilless substrates are commonly selected for their low weight, relative low cost and favorable chemical and physical characteristics (Wright and Niemiera 1987; Raviv and Lieth 2008).

i. Key Physical and Chemical Properties

Since there is no ideal substrate with universal availability, substrate mixtures are often a compromise to achieve optimal growth for a relatively broad range of species, at reduced cost. Physical properties, such as bulk density, air-filled porosity, water holding capacity, particle size, cation and anion exchange capacities, pH, wettability after drying and longevity are important considerations when choosing a substrate (Raviv and Lieth 2008). The particle size fraction and component ratios of the substrate largely determine the physical (Argo 1998b) and chemical (Argo 1998a) properties of the substrate. However, container shape and geometry do play an important interactive role in the retention of water and nutrients in the root zone (Argo 1998b). The porous nature of soilless substrate often results in high potential for leaching of water and nutrients if irrigation scheduling and management are not given proper attention. Efficient fertilization and irrigation practices are therefore predicated by knowledge of substrate physical properties and container capacity.

Soilless substrates generally have a much higher percent of organic material, with higher air-filled porosity, but lower anion and cation exchange capacities in comparison to most native soils (Bilderback et al. 2007). It is this lower anion and cation exchange capacity that causes N, P and other nutrients to leach easily from soilless media. The addition of clay, humus, peat, composted pine bark, composted sawdust or vermiculite as a substrate amendment can greatly increase the cation exchange capacity, which decreases the leaching of cations such as H^{+}, Al^{3+} , Ca^{2+} , Mg^{2+}, K^{+}, NH_4^{+} and Na^{+} (Handreck and Black 2002). Typical amendments to increase anion exchange capacity are calcined clays, attapulgite and shale, which can bind negative ions such as PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^{2-}$, SO_4^{2-} and NO_3^{-} but in general, most soilless substrates have a low anion exchange capacity (Handreck and Black 2002). Calcined clay is a heat expanded clay that is resistant to chemical and physical degradation, has non-capillary pore spaces, and a high cation exchange capacity (Ingram et al. 2003). Although calcined clay is more expensive than other amendments it has the potential to reduce nutrient runoff of both N and P in container operations (White et al. 2006). For example, Owen et al. (2007) found that pine bark: sand substrate amended with calcined clay decreased N and P leaching by 39% and 34% respectively, and reduced water use by 15% compared with controls grown without calcined clay.

ii. Sustainable Supply and Amendments

There is an exhaustive literature on soilless substrates for use in the nursery and greenhouse industry (Raviv and Lieth 2008). The most recent research can be found in the Proceedings of the International Symposium of Growing Media (Carlile and Coules 2009). Locally available and sustainable substrates and amendments are playing an increasingly important role in what growers choose for soilless substrates, as the cost of basic materials and transport increases. Apart from cost, the major concerns for many growers is the continuity of supply, the uniformity and longevity of the substrate in the container and any added costs associated with a change in practice that is required to grow quality plant material. As current soilless substrates and amendments become scarcer or more expensive to ship, growers will likely look to alternative, locally available substrates and amendments to maintain profitability.

E. Nutrients

i. Historical Context

The advent of the Haber-Bosch process in the early 20th century allowed for the abundant production of fertilizers, which along with advances in crop breeding and new pesticides fueled the agricultural ("green") revolution starting in the mid 1940s. During the subsequent 60 plus years, fertilizers have been used extensively to maintain or increase plant production at increasing levels of intensity, as land values increase and economic returns for agricultural products have declined in real terms. Nitrogen fixed by humans is now thought to exceed the amount of N produced by all natural terrestrial N fixation combined (Zapata 2008). Worldwide, fertilizer use has been increasing at a rate of 5% a year since the 1940s, with agriculture using an estimated 86% of the total N used by humans (Jordan and Weller 1996). With increased fertilizer use, eutrophication and aquatic degradation has been seen over several decades from application of N and P fertilizers, wastewater treatment outflows and other anthropogenic sources, which has lead to the degradation of a number of watersheds in the U.S., including the Chesapeake Bay (Cerco and Noel 2004; Fisher et al. 2006; Howarth and Marino 2006) and the Gulf of Mexico (Mitsch et al. 2001; Livingston 2007). Optimizing the application and conservation of water and nutrients, to minimize N and P runoff from production systems should be a high priority in nursery and greenhouse systems.

ii. Nutrient Uptake Efficiency

Nutrient use efficiency is based on: (1) plant uptake efficiency, (2) metabolic assimilation into roots and shoots, and (3) utilization (or remobilization) efficiency (Baligar et al. 2001). Nutrient use efficiency is one way to gauge the impact that different fertilization techniques have on plant growth. Since (2) and (3) are largely due to plant genotype, nutrient uptake efficiency is the only variable that we have much control over, with fertilizer application rate or timing. There have been a number of studies that have showed that plants have a higher nutrient uptake efficiency at lower levels of nutrient application and nutrient uptake efficiency decreases significantly with increasing rates of nutrient addition (Cabrera et al. 1995; Kent and Reed 1996; Lea-Cox and Syvertsen 1996; Ku and Hershey 1997a; Cabrera 2003; Ristvey et al. 2007). For example, Cabrera (2003) found that for *Lagerstroemia* × ‘Tonto’ and *Ilex opaca* ‘Hedgeholly” nitrogen uptake efficiency was maximal at 30 mg $N \cdot L^{-1}$ at 49.6% and 48.0% respectively, and lowest at 300 mg $N \cdot L^{-1}$ at 7.9% and 6.5% respectively. Ristvey (2004) found that weekly uptake efficiency of N in *Rhododendron* ‘Karen’ azalea under different N and P rates in the greenhouse over 12 weeks was highest at 25 mg N per plant per week, while P uptake efficiency was highest at 5 mg P per plant per week (Table 1-2). These rates are much lower than those recommended for azalea, indicating that nutrient application can be significantly reduced, without impacting plant growth.

As previously noted, P application and use efficiency is of particular concern. There is widespread belief in the ornamental industry that P fertilization stimulates root growth over shoot growth. In a review of root: shoot ratios in trees, Harris (1992) cited seven examples of books or manuals on plant care that either stated or implied that increasing P rates promoted root growth and increasing N fertilization promotes shoot growth. The belief that P fertilization preferentially stimulates root growth over shoot growth persists in the industry, since fertilizers with low N:P ratios are still used extensively (Williams and Nelson 1996; Hansen and Lynch 1998). However, there are few definitive data in the literature to support this contention. 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. Since consumers focus on the top part of the plant, growers in the nursery and greenhouse industry tend to focus on maximizing shoot growth. In the nursery industry, this leads to the need to remove top growth or apply growth regulators to produce acceptable plants, which can be expensive. If growers were better able to adjust fertilizer rates to control growth, they could save both on labor costs and improving resource efficiency, by not having to prune the nutrients stored primarily in leaves (shoot growth). Ristvey (2004) showed that for azalea, root : shoot ratios were significantly higher at lower nutrient rates, which lessens the stress on the roots to supply adequate water and nutrients because of reduced shoot volume (Table 1.2). Cabrera (2003) also showed higher root : shoot ratios at lower nutrient rates for Ilex and Lagerstroemia.

Lower root: shoot ratios are also likely to result in higher survival rates after final planting. Baligar et al. (2001) stated that estimates of overall P uptake efficiency in agricultural systems are less than 10%, based on actual plant need. Presently, P fertilization in many nursery and greenhouse operations is likely in excess of plant requirements, resulting in low uptake efficiencies and increasing the potential for P runoff. Table 1-2 shows that P uptake efficiency for *Rhododendron* L. 'Karen' azalea was optimized at 5 mg P per plant per week, much lower than the rate applied by most nursery and greenhouse operations. Tyler et al. (1996a) recovered 50 to 80% of applied P in the leachate, substrate and plant, and found P uptake efficiencies to be between 17 and 25% in a field study examining leaching fractions and slow-release fertilizers (also called controlled release fertilizers) rates on growth in containerized cotoneaster plants. Please note that the term slow-release fertilizer (SRF) will be used throughout this dissertation, since the term "controlled release" is a misnomer for this type of fertilizer. The release patterns of these fertilizers are dependent on temperature, with higher release rates at higher temperatures. 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 (Lynch et al. 1991; Broch et al. 1998; Hansen and Lynch 1998) . However, there have been few integrated studies of P fertilization in container-nursery production systems.

Other studies in the literature illustrate the dynamics of nutrient uptake, which can help hone fertilization strategies. Studying 'Royalty' roses, Cabrera et al. (1995) found that total annual N uptake was 16.8 g per plant, with N uptake rate changing up to five-fold during a cycle of flower growth peaking at maximum flower shoot elongation, and lowest at maximum vegetative shoot elongation. Nutrient cycles have also been noted in other woody ornamentals including *Ilex crenata* and *Euonymus japonica,* where nutrient uptake is highest after a flush of foliage (Cabrera et al. 1995). There is evidence that suggests that this cyclical uptake is due to root growth and soil exploration, which then allows for shoot growth (Bilderback et al. 1999; Rose 1999). Rose (1999) reported that

Table 1.2. Nitrogen and Phosphorus uptake efficiency for azalea *Rhododendron* var. 'Karen' during a 12-week experimental period. Plants were deficit irrigated twice a week, then leached the day before treatments were applied at 250 ml per container. Plant nutrient uptake (N and P) is the accumulation of nutrient from initial to final harvest. Nitrogen and P uptake efficiency is the percentage of applied nutrient that was taken up after 11 applications. Standard errors are in parenthesis (n=5). Lower case letters indicate significant differences (LSD at P=0.05) between treatments. (Modified from Ristvey, 2004)

Treatment (mg N and P · week^{-1})	Plant N Uptake (mg)	N Leachate (mg)	N Uptake Efficiency (%)	Plant P Uptake (mg)	P Leachate (mg)	P Uptake Efficiency (%)	Root: Shoot Ratio
N250 : P25	324.9 (±34.1)	117.1 (±16.5) b	14.4	31.5 (±6.8)	8.3 (±1.3) b	14.0	0.25
N250 : P5	276.3 (±19.6)	152.3 (±17.6) a	12.3	21.8 (±0.9)	2.4 (±0.2) c	48.5	0.28
N250 : P0	313.4 (±37.6)	147.6 (±7.9) a	13.9	12.4 (±3.6)	2.0 (±0.8) c	-	0.28
N100 : P25	251.3 (±60.8)	35.6 (±7.5) c	27.9	33.7 (±9.1)	13.8 (±4.5) a	15.0	0.34
N100 : P5	222.2 (±22.1)	44.2 (±2.3) c	24.7	22.1 (±2.3)	2.7 (±0.9) c	49.2	0.34
N100 : P0	242.2 (±44.4)	41.9 (±8.8) c	26.9	17.6 (±2.3)	1.5 (±0.5) c	-	0.33
N25 : P25	84.0 (±13.3)	5.3 (±0.8) d	37.3	24.3 (±3.5)	16.3 ±1.3) a	10.8	0.53
N25 : P5	82.8 (±20.2)	3.6 (±0.8) d	36.8	18.0 (±5.1)	5.1 (±1.4) b c	40.1	0.64
N25 : P0	73.9 (±12.7)	3.8 (±0.4) d	13.0	13.0 (±4.2)	2.5(±0.9) c	-	0.51

for the fruit trees and container grown ornamentals studied, nutrient uptake and biomass accumulation are linked, so the highest nutrient concentrations are needed during times of active growth, e.g. late spring and late summer, with minimal growth during budbreak, leaf abscission and the hottest times of the year.

Based on the above information, it appears that most current fertilizer practices in containerized production are not timed to match plant nutrient uptake requirements. Plants that are fertigated are often supplied with a constant rate of nutrient applied at regular intervals, which is rarely changed during the production cycle. Encapsulated (SRF) fertilizers often have high initial nutrient release rates from broken prills or initial incorporation in the substrate, which are then dependent on temperature and water availability for release patterns. Slow-release fertilizers often release maximally during hot weather, which is the time when the growth rate, and nutrient uptake of plants are limited by those same high temperatures. Typical fertilization recommendations vary greatly between 48 - 287 kg or more per ha per year (40-250 lb $acre^{-1}$ $year^{-1}$), which are based on research from the 1950s to 1970s, when maximum growth response was the primary production goal (Rose 1999). It is clear from this and other research that nutrient recommendations should be based on a species' requirement, growth rate, time of year and the type of fertilizer used, rather than generic recommendations.

iii. Denitrification

Denitrification is the process by which bacteria in the soil break down nitrogen oxides (NO_3^- and NO_2^-) in the soil or substrate (as an electron acceptor), into N_2O or N_2. Although denitrification has been studied in detail in agronomic settings with soils, there appears to be minimal research on this subject in the ornamental literature, or its impact on container-production practices. It is important to understand the consequences of denitrification, and the role that it plays in nitrogen uptake efficiency. There are several conditions which are required for denitrification to occur regardless of whether it occurs in soils or soilless substrates. In order for denitrification to occur, there needs to be a carbon source (electron donor), a nitrogen source (electron acceptor), anoxic or low oxygen conditions (<0.2 mg/L), moderate temperatures and microbe availability. Under high oxygen conditions, bacteria preferentially use oxygen as an electron acceptor to produce energy. Under anoxic conditions, facultative anaerobic bacteria use nitrate, instead of oxygen (which has a higher energy yield), for electron transfer, which produces N_2O or N_2, and energy for the bacteria (Agner 2003).

Terrestrial soils are reported to contribute 22% of the total global loss of N through denitrification, with freshwater systems contributing an additional 20% (Seitzinger et al. 2006). Although denitrification is beneficial when excess nutrients are removed from water and soils from anthropogenic over-application, denitrification within the root zone can decrease the available N supply for plants, requiring additional N applications. Understanding the conditions in which denitrification occurs is a first step to reducing N loss. Ristvey (2004) concluded that N loss could be exacerbated by current container-nursery production practices, with high volume and frequency (often daily) irrigation applications. When nutrient budgets are reported in the literature, there is often a moderate to high percent of N that cannot be accounted for in the total budget, even with ^{15}N studies (Lea-Cox et al. 2001b). This N loss is typically attributed to denitrification. Cabrera (2003) reported 23% - 41% of the N could not be accounted for with N concentrations from 15 - 300 $mg \cdot L^{-1}$, regardless of concentration for *Ilex opaca* 'Hedgeholly' and *Lagerstroemia* × 'Tonto' in a 9 month container study. Nieder et al. (1989) reviewed a number of *in situ* denitrification experiments in field soils and found a range of 5 kg per ha to 60 kg per ha N losses using ^{15}N labeled compounds, and N loss rates of 0.7 to 233 kg per ha using the acetylene inhibition method over a variety of soil conditions. In a greenhouse study, Agner (2003) found that denitrification rates for *Pelargonium zonale* and *Euphorbia pulcherrima* were increased up to 36 hr after flood irrigation at a maximum rate of ~30 $\mu g \cdot pot^{-1} \cdot hr^{-1}$ in a peat substrate, with denitrification continuing until air volume reached ~30%, using acetylene inhibition. It was also reported that 8 week old *Pelargonium zonale* plants had higher denitrification rates compared with 4 week old plants, presumably because of higher carbon exudates from a larger root system (Agner 2003).

Since carbon (C) is the initial electron donor, it is essential for denitrification. Prade (1988) found that roots of wheat (*Triticum vulgare* 'Kolibri') significantly increased denitrification rates in containers with roots vs. containers without roots at air filled porosities below 10%. It is thought that root turnover, and root exudates have the potential to supply the soluble C necessary for denitrification in soils, with organic substrates also supplying C in soilless substrates. Since the nitrate (NO_3^-) or nitrite (NO_2^-) forms of N can be used for denitrification, any N that is supplied to the plant has the potential to be used for denitrification (Daum and Schenk 1996). Ammonium (NH_4^+) ions can also be broken down into NO_2^- and used in the denitrification process (Groffman et al. 2006). The higher the rate of N applied, the higher the potential for denitrification in the substrate. Low oxygen conditions are typically brought about by two different mechanisms in soilless substrates, high water filled porosity, and root respiration decreasing oxygen levels. Over application of irrigation water can quickly bring about anoxic conditions in containerized plants, especially in smaller containers, which have a larger proportion of the volume subject to a perched water table. Water can provide suitable conditions for microbial growth, restrict O_2 supply to microsites, release available C and N through drying and wetting cycles and provide a diffusion medium for substrates and products (Aulakh et al. 1992). Although soilless substrates tend to have a high air-filled porosity, applying too much or too frequent irrigation may increase the rate of denitrification. Aulakh (1992) reports that denitrification is negligible below 60% of water holding capacity, at least for mineral soils.

From this information, denitrification could reasonably be presumed to be a major loss mechanism for N from containerized production systems, and yet there is very little information on denitrification in the ornamental literature. This should be addressed, given the magnitude of potential N loss from production systems. Denitrification inhibitors, which can be mixed with fertilizers or potting media are a relatively low cost way of reducing denitrification rates; however, they have been shown to have limited ability to control denitrification in soilless substrates (Goh and Haynes 1977). It is likely that the highest reductions in denitrification rates will be seen with a combination of denitrification inhibitors, moderate rates of slow-release fertilizers and better irrigation practices.

iv. Water and Nutrients

There is a direct connection between the movement of water and nutrients at the micro-scale in the root zone and at the macro-scale in container-production operations. Our common goal is to increase the efficiency of water and nutrient applications to reduce the potential for nutrient leaching and runoff with surface water movement, and therefore to avoid expensive containment and remediation measures. Water is the main transport mechanism of nutrients into the plant, but also to the surrounding environment (Ross et al. 2002). Nutrients that are not taken up by the plant, adsorbed by the substrate, or utilized by microorganisms have the potential to leach into ground water, and/or runoff. The interaction of enhanced nutrient levels can be directly associated with algal blooms of surface water, eutrophication and other environmental problems. Excessive surface water erosion is also able to transport nutrients that are soil-bound (i.e. phosphorus) in sediments, when proper safeguards (e.g. buffer strips and sediment ponds) are not used. The primary goal of irrigation water applications in greenhouse and container operations is to apply the precise amount of water that meets the immediate water requirement of the plant without significant leaching, thereby maintaining available nutrients in the root zone and maximizing the time for uptake. This is much easier to control in greenhouse operations, which are not influenced by rainfall, compared to container and field nursery operations, which receive rainfall (uncontrolled leaching events) for at least part of the year.

F. Water

i. Global Issues

Over the past 50 years, the demand for fresh water in many states has been increasing (Hutson et al. 2004), while the quality of both surface and ground water has been decreasing due to pollution from both point and nonpoint sources (Secchi et al. 2007). Nitrogen, P and other organic pollutants such as pesticides and herbicides are being found at increasing concentrations in ground water under agricultural and other areas (Guimerà 1998). Recent studies have also found that N (Mahvi et al. 2005) and P (McCobb et al. 2003; Fuchs et al. 2009) that have been bound by soils are now entering streams and estuaries. Even though steps are being taken to reduce nutrient and sediment input into surface waters, those effects may be reduced by this additional N and P that continues to move through the soil environment to surface waters (Fisher et al. 2006). Now and into the future, regulators and scientists face the difficult task of determining what proportion of bio-available nutrients in a particular watershed are from recent applications, as opposed to historical applications of nutrients and other pollutants.

As the demand for water and the cost of purification increase, the cost of freshwater resources will increase, and the availability will likely decrease to individual operations. Population growth in the 20th century has increased by a factor of three while water withdrawals have increased by a factor of seven during the same time period, with little hope of these rates slowing in the near future (Agarwal et al. 2000). This is compounded by a migration of the world's population to cities and areas close to shorelines, where fresh water withdrawals may be complicated by salt-water intrusion.

These factors will make water conservation an important issue not only for the nursery and greenhouse industry, but for many aspects of human life in the near future.

ii. Water Rights

In the eastern states, water compacts began in the mid 20th century, mainly between states. These agreements were designed for agencies to consult and share information, but these agencies typically had little or no authority to make significant changes in water allocations (Dellapenna 2007). Conflicts have arisen over fresh water resources that form boundaries between states in the U. S. (Poff et al. 2003). Water conflicts in the U. S. have been occurring for the past 80 or more years, and are likely to increase as water becomes more limiting to growth and development (Cox 2007; Davis 2007; Dellapenna 2007; Phelps 2007). Currently, the majority of conflicts involving water have dealt with surface waters. It is likely that as surface waters become more taxed, conflicts will arise over transboundary aquifers, which currently are relatively free of conflict (Dellapenna 2007). This is especially true in "fossil" aquifers, such as the Ogallala aquifer which underlies parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming, which is not renewable in the near future, due to poor recharge (Torell et al. 1990; Draper 2007).

Most field (in soil) producers of ornamental trees and shrubs use irrigation water at some point during production, since growth rates will likely be reduced by water stress at some point during long production cycles (Fernandez et al. 2009). Many field producers use low-volume (drip) irrigation, and many also use this system to deliver soluble fertilizers during the growing season. While supplemental irrigation is at times advantageous in field production, it is essential for the container-production of ornamental plants. Container substrates need to be well drained primarily for disease prevention, but the container volume limits the amount of water that can be stored. This dichotomy results in frequent applications of irrigation water, with large volumes typically being used on a daily basis. In a recent survey, over 75% of nursery crops in 17 states were grown in containers and use irrigation (U. S. Department of Agriculture 2009). In Florida, container nurseries annually apply 140 to 300 cm (55-120 inches) of irrigation per year, in addition to the 100 to 150 cm (40-60 inches) of average annual rainfall (Fernandez et al. 2009). Container nurseries in Alabama were estimated to have used 37 to 49 billion L (10-13 billion gallons) of water in 1985 (Fare et al. 1992) and container nursery production in Alabama has almost tripled since 1987 (U. S. Department of Agriculture 1994; U. S. Department of Agriculture 2004).

Opinions from twelve scientists, growers and nursery organization leaders were summarized by Beeson et al. (2004) and highlight many of the water issues facing ornamental producers. Increased water demand, decreased availability and increased costs associated with water purification and delivery will force growers to limit water use, either by increasing their efficiency, or installing containment basins for recycling, especially in coastal and arid regions. Principle solutions suggested implementing effective management and BMP techniques such as microirrigation for larger containers (>28 L or 7 gallons), and recycling of irrigation water used for overhead irrigation (Beeson et al. 2004). Future areas of research such as outdoor sub-irrigation, plant-based sensor technology and container or production area modifications were discussed as possible solutions. However, the authors concluded that no one technology or management plan would provide all benefits, and site-specific decisions must be tailored to the individual operation and their needs.

iii. Water Quality

Humans have had major impacts on a variety of earth systems, and notably on fresh water supplies around the world. Eutrophication caused by nutrient pollution of rivers also has major impacts on estuaries and marine ecosystems, particularly in the Puget Sound, the Gulf of Mexico and the Mid-Atlantic states (Livingston 2007). In recent years, various environmental groups in the U.S. have been putting increasing pressure on the Environmental Protection Agency (EPA) to enforce largely ignored parts of the federal Clean Water Act of 1972, which would impose strict total maximum daily load (TMDL) limits for both point and non-point sources of pollution in all watersheds and bodies of water listed on the impaired waters list (Lea-Cox et al. 2002). The nursery and greenhouse industry faces additional difficulties compared to traditional agriculture, in that the nutrient requirement of many species being grown is not known, crop production times can vary from weeks to years, a variety of production systems exist which have differing impacts, and different nutrient and irrigation practices are used. Due to these variables, writing water and nutrient management plans requires a risk assessment approach, which has the advantage of allowing the grower to design and implement site-specific best management practices for the entire operation (Lea-Cox et al. 2001a).

Irrigation, in combination with high fertilizer and pesticide use, can lead to significant losses of agricultural chemicals in runoff water that transports agricultural chemicals to containment structures and/ or off-site into groundwater or surface water (Camper et al. 1994; Briggs et al. 1998; Briggs et al. 2002; Cabrera 2005). Irrigation water management is the key to nutrient management in ornamental crop production and reducing the impact of runoff water on local water resources (Tyler et al. 1996b; Lea-Cox et al. 2001a; Ullah and Zinati 2006). Increasing substrate anion and cation exchange capacity, for example through the use of aluminum or various clay amendments, can help to reduce leaching of nutrients from soilless substrates (Williams and Nelson 1996; Owen et al. 2008). However, the recycling of runoff water raises other management issues for growers, primarily in the form of disease pressure (Hong and Moorman 2005) and salinity management. Emerging constraints on water use and quality means that the ornamental industry needs to find ways to manage water without detracting from production schedules and crop health and quality.

The quality and quantity of water required by an operation is largely dependent on the irrigation system used. The smaller the emission orifice (typically with more precise water applications, e.g. drip), the higher the quality of that water must be in regards to particulate matter and water quality (e.g. pH, dissolved salts, alkalinity), to avoid problems. Higher volume overhead irrigation systems generally require less filtration compared to boom, micro-sprinkler or drip systems. Although the latter systems use smaller water volumes per plant compared to overhead, they may require additional filtration and better irrigation system design for precise water applications to individual plants. The reuse of water from an operation, either from rainfall or from recaptured surface water, is another important concern for water quality. This water may contain pesticides, herbicides, fertilizer, pathogens and particulate matter, which need to be treated and filtered before reapplication of this recaptured irrigation water.

iv. Irrigation Systems

The amount and quality of irrigation water that is applied varies greatly depending on plant needs, water source and system design. The irrigation system used by an operation will have a large impact on the amount of water used over a given time. The design of an irrigation system is largely governed by the size and type of plants grown, the size of the operation, water availability and cost. Overhead irrigation has the lowest cost to install and maintain, but also tends to have the lowest interception efficiency, requiring more water to irrigate the same number and size of plants compared to microirrigation or subirrigation. Besides a low initial cost, the other main benefit of overhead irrigation is the flexibility that this system allows. Plants of almost any size can be placed under overhead irrigation with few labor hours required to move and relocate emitters.

Increasing the efficiency of water application allows an operation to irrigate more plants, or irrigate the same number of plants with less, thereby conserving water. The design, implementation and maintenance of irrigation systems are critical factors for determining the overall efficiency of water applications. A variety of references are available for more information (Environmental Protection Agency 1993; Waskom 1994; Fain et al. 2000; Bilderback and Lorscheider 2007a; Bilderback and Lorscheider 2007b; Ross 2008b).

v. Increasing Water Application Efficiency

Irrigation is generally a small portion of the overall cost of producing a plant, which has the potential to lead to the over application of water out of concern for the plants experiencing drought or salinity stress. Over application of irrigation water can lead to nutrient leaching, surface water runoff, erosion and root diseases. Water conservation is typically only a concern for growers during drought, or when greater production acreages are planned if water availability is limited. Increasing irrigation efficiency can have a large impact on an operation by decreasing peak water demand, which can help conserve current and future water resources. In container production environments, irrigation scheduling and water management are critical factors in plant growth and salability.

Growers are usually constrained in the amount of water that is available for irrigation (Beeson et al. 2004; Mathers et al. 2005). Restrictions may be in the form of permitted withdrawals, well capacity, total production area or irrigation system design. Some of these constraints, such as system design can be changed, while others, (e.g. permitted daily volumes) are not under a grower's control. Unfortunately, we currently do not have very efficient methods to determine plant irrigation requirements for different species on a daily basis (Lea-Cox et al. 2009b). Most growers typically base irrigation decisions on substrate appearance, cumulative knowledge and experience which integrates recent weather and irrigation events and using subtle plant indicators (such as changes in leaf reflectivity), instead of quantifying water use data. These more subjective scheduling methods typically lead to over application of irrigation water, since the economic cost (risk) of reduced plant growth is much higher than the cost of water.

Applying the correct volume of water at the correct time to maintain optimal growth rates is one of the most fundamental aspects of growing plants, but also one of the most difficult, since both plant water use and environmental conditions are constantly changing. Irrigation scheduling decisions are often based on intuition or an integration of tangible factors (pot weight, plant condition and size, time from prior irrigation and environmental conditions) rather than actual plant water use, which is difficult to determine quickly and accurately.

vi. Intercepting Runoff: Capture and Recycling

There are many ways to mitigate the effects of nutrients and sediment loading to surface water, but each method has a different cost, advantages and disadvantages associated with it. Unfortunately, there is limited information on the costs associated with implementing BMPs, and on the relationship between the cost and the benefit of those BMPs in terms of environmental and production benefits. Veith (2002) developed a program that begins to address this complicated task of balancing environmental benefits with cost of implementation, but more work is certainly needed in this area.

a. Open Systems

Capturing surface water runoff through the use of containment basin is an effective, yet expensive method for sediment and nutrient abatement, if land areas are available and groundwater tables are not too high. It has the advantage of collecting significant volumes of runoff water and nutrients can be returned to production areas for repeated use, especially where water supplies or rainfall are limited. Collection basins are ideally located at the lowest point in an operation to collect the maximum amount of irrigation and storm water runoff. Water is typically conveyed to ponds by lined or grassed drainage ditches or via underground pipes for maximum efficiency. Lined ditches and pipes will have faster flow rates compared to unlined ditches, so it is important that these structures have areas where suspended sediment can drop out of water, such as sediment ponds or rock structures (riprap) to slow water velocity before the water enters the containment basin.

The purpose of a sediment basin is to allow suspended sediment to settle out of the water column so the soil and any nutrients (particularly P) that it contains are retained before being discharged or recycled. Water from a containment basin can then be used to irrigate crops, or it may be discharged to surface waters after the suspended particles have settled. Containment basins are also valuable for nitrogen removal by aquatic plants and bacterial denitrification. Containment basins and sediment basins are becoming increasingly popular because of tighter water and nutrient management regulations, and the increased cost and decrease in availability of water.

The main issues with recycling runoff from production areas in an operation is the potential for recycling pesticides, herbicides and pathogens back into the operation (Hong and Moorman 2005). Typically, growers reduce pathogen loads by treating captured water using filtration, chlorination, or UV light. There has been some research to suggest that containment basin design and the placement of pump intake can reduce disease pressure (Hong and Moorman 2005; Ghimire et al. 2009; Kong et al. 2009). Hong and Moorman (2005) conclude that disease management is affected by the following factors:

quality of the water to be treated; quantity of water to be treated over a given time; allowable changes in water quality due to treatment; pathogen population reduction for crop protection; susceptibility of the crop to specific pathogens; cultural practices being used; economic resources together with level of experience and time required for control measure. Hong and Moorman (2005) report that there are a number of treatment methods available, but many have not been tested at the operation scale. Although additional research is needed in the area of pesticide and pathogen management, it is clear from many existing operations that recycling from catchment basins is an effective and efficient way to control nutrient and sediment runoff, and increase the resource use efficiency of an operation.

b. Vegetated Buffers

Vegetated buffer areas are probably the most cost-effective primary method for sediment and nutrient abatement in open production systems, both for field and container-nursery operations. Vegetated buffers can consist of various structures including grassed or vegetated ditches, swales and buffer strips. Various grass and/or tree species can be used to slow the velocity of surface water runoff from production areas to allow for sediment removal, infiltration of water, denitrification of N, plant nutrient uptake and the denaturing of herbicides and pesticides. A disadvantage is that unless they are used in association with containment ponds, there is no recovery of water and nutrients for re-use. Buffers do also require maintenance during the year such as occasional mowing and if necessary sediment removal to maintain sheet flow. Ideally, mowed vegetation would be removed, to remove stored N and P from the system. Although there are a variety of buffer widths recommended in the literature (Osborne and Kovacic 1993; Wenger 1999; Dosskey 2002; Todd 2002), a 15 m is width is often used for regulatory purposes. This width could be considered relatively arbitrary, since the efficacy of a vegetated buffer depends on many factors including volume (rate) of runoff handled per minute, the infiltration capacity of the soil, slope, the plant species used, the buffer condition and the amount of sediment/nutrients to be removed (Wenger 1999).

G. Research Significance

This research is important for two distinct reasons. First, this project provides an overall picture of the nursery and greenhouse industry in Maryland which currently does not exist. Currently, there is no aggregated information on the yearly N, P, and water application rates and timings from the nursery and greenhouse industry in Maryland to the Chesapeake Bay and its tributaries either in the Chesapeake Bay Model or available through any other sources. Although this database does not have application rates for all nursery and greenhouse operations in the state, it does provide detailed information about nutrient and irrigation management practices across the state on a management unit basis, which is much more refined than originally anticipated. With this information, the variability in irrigation and nutrient application practices at the management unit level can be determined. Since these data represent about 15% of the operations in the state, information gathered may be used to extrapolate N, P and water application rates to the state level. To my knowledge, a dataset with this level of detail, at the state level does not exist, and would be a major benefit to the industry. This will allow for the development of refined nutrient reduction strategies, and more targeted efforts (e.g. increased cost-share funding for implementing additional nutrient-reduction practices).

The second phase of this project developed separate models for greenhouse, nursery, and field operations that have the potential to help reduce N and P runoff from high-risk operations. These models are refined enough to identify variables that account for the highest reduction in N, P and water runoff, for the least cost of implementation. Each model includes environmental variables (e.g. monthly average max. and min. temperatures and rainfall) which by-and-large determine plant growth rates, and hence nutrient application rates and timing. These models were developed for use in Maryland, but can be easily adapted for use in operations throughout the United States, and other parts of the world since many of these operations have similar characteristics from an infrastructure and management perspective. Taken together, this project is expected to have a major impact on both the growers and researchers in the state by providing tools that will be useful for reducing nutrient and water inputs to surface waters, and how best to go about that reduction. The use of these models has the potential to help the state meet its TMDL guidelines, by reducing N, P, and sediment runoff from this segment of agriculture.

H. Conclusions

There have been a number of changes that have occurred in the production of container-grown ornamental crops during the past 30 years which have helped this industry grow and become more economically competitive. Water constraints due to growing demand, reduced supply and changing weather patterns now and in the future have the potential to further restrict irrigation use by the nursery and greenhouse industry. This provides a challenge to the industry to reduce water volumes using a variety of current management practices and new technologies. Concerns about nutrient runoff and infiltration should be met with additional research and better recommendations to reduce the potential for nutrient runoff from an operation. We need to develop a better understanding of plant nutrient requirements, better technology to assess root zone conditions and better fertilizers or practices that are able to match plant nutrient requirements during the growing season, to reduce nutrient runoff.

Increasing the anion exchange capacity by using a variety of soil amendments is important for N and P retention in soilless substrates. Additional research is needed to gain a better understanding of plant nutrient requirements for a variety of plant species to be used as models for nutrient application recommendations. New formulations of slow-release fertilizers are needed which match both the timing and amount of nutrient based on actual plant growth requirements instead of release rates being based on temperature. Liquid and solid fertilizer recommendations also need to be based not only on growth, but also on reducing the environmental impact of production. Better rates and timing of fertilizer applications have the potential to reduce leaching losses in both containers and field situations. Much more research is needed to thoroughly investigate denitrification in soilless substrates, as there is evidence that this is a substantial loss mechanism, both in field soils and in soilless substrates. It is important to both understand this loss mechanism, and determine ways to reduce its impact to increase N uptake efficiency. This is an area where significant gains in efficiency are possible, since both nutrient and irrigation reductions could decrease denitrification rates. We need to develop and implement irrigation scheduling based on actual plant water use, instead of the subjective methods that are typically used by most growers. Computer and sensor driven irrigation management and control technology represents a significant advancement over current irrigation technologies (Lea-Cox et al. 2009a,b). In order for growers to make informed decisions about changing practices, accurate information on the cost of BMP implementation, with the corresponding financial and/or environmental benefit would be beneficial. Local or regional BMP cost and benefit guides would enable growers to make informed decisions on how best to mitigate their impact on the environment.

Chapter 2: General Materials and Methods

A. Introduction

The Maryland Department of Agriculture (MDA) is responsible for ensuring that nursery and greenhouse operations are in compliance with current nutrient management laws. Any nursery or greenhouse operation that grosses more than $2,500 a year is required to file a nutrient management plan, unless no nutrients are applied at the operation, which is the case in some field operations (Maryland Department of Agriculture 2000). The MDA could not legally share nutrient management plan (NMP) information from the approximately 350 nursery and greenhouse operations that have filed management plans in the state, although they supported this project. Instead, growers were contacted directly, and asked to voluntarily participate in the project. In the long run, this was found to be more beneficial for a number of reasons, including building rapport with the growers, getting more detailed information, and making growers aware of how their data is being used and protected, which will be discussed in detail below.

B. Institutional Review Board (IRB) Procedure

The first procedural step was to gain approval for data collection from human subjects, in order to be in compliance with Federal policy, since this project would be dealing with personally identifiable information. It also provided additional reassurance for those operations choosing to participate, and included information on the procedures involved in this study, and their rights as volunteers. The appropriate documentation was filled out and submitted to the University of Maryland Institutional Review Board (IRB) (see Appendix B for IRB documentation). This project was considered exempt from full IRB review because it did not involve pregnant women, human fetuses, neonates, minors/children, prisoners, students, or individuals with mental or physical disabilities, and it fitted into exemption category 4, i.e.,

> "Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available *or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects*."

C. Database Development

The project database was developed to maintain the anonymity of the grower and specific operational practices, as noted above. Once IRB approval was attained, information packets were mailed out to 491 operations throughout the state of Maryland. Address information was gathered from three sources: the MDA Nutrient Management Office, MDA Plant Protection Office, and the Maryland Greenhouse Growers Association. This information was considered public record, and could be released by these agencies. The information from the three lists was combined, and any duplicate address/grower information was removed. Duplicate packets were sent to operations which had different addresses or contact information listed. It is believed that there were approximately 350 actively growing nursery and greenhouse operations in the state, so approximately 140 of the packets mailed out were potential duplicates. Since it was impossible to know which of the three sources of information was most accurate, it was decided to mail out information to all unique entries, out of concern for missing any operations.

Grower packets consisted of the following information (see Appendix B for the complete information mailed to growers). The first page accepted or declined participation in the study, and requested additional information for participating growers. If a grower volunteered to be included in the study, they were asked if they wanted the data accessed through the MDA database, via a site visit, or either means. Growers were asked to complete address and phone information to identify the operation, and update any out of date or incorrect information. If a grower was participating, they were asked read the consent form completely, date and initial page 1, and print and sign their name, and date page 2. This consent form was required by the IRB committee to inform participants about the benefits and drawbacks of the study, and to inform them of their rights as volunteers. In addition to the required consent form, a Memorandum of Understanding (MOU) was also included in each packet. The MOU is an additional binding agreement between the grower and the researchers at the University of Maryland, and was included as added assurance to participating growers regarding the use and protection of their operational information. Growers were asked to complete the first page of this form, and sign and print their name, and date page 2.

Approximately 30 information packets were returned undeliverable for various reasons. Any returned packets were followed up with a phone call (if number was available) and/or an internet search to determine if any information was incorrect or missing. If additional information was found, the packet was resent, and the additional information added to the final grower database that was compiled. If no new information was determined, the packet was determined to be undeliverable. Approximately 6 weeks after the grower packets were mailed out, a reminder postcard was mailed to any operation that had not responded to the original request (Appendix B). This reminder postcard included contact information for any questions or concerns the grower might have had. In all, 51 operations agreed to voluntarily participate in the study, a participation rate of 14.5% of the 350 estimated operations in Maryland. Table 2-1 gives a brief analysis of the number of operations by number of management units (MU), MU size, nutrient and water application rates. Three operations declined site visits for personal reasons, so 48 of the 51 operations that agreed to participate in the study were visited.

Table 2.1. Summary of values reported by growers based on site visits and interviews with 48 greenhouse, container, and field growers in Maryland. Some growers had more than one type of operation at the same site (i.e. greenhouse and container) so the number of operations visited for the three types of operations sums to more than 48 operations.

Variable	**Greenhouse Operation**	**Container Operation**	**Field Operation**
Number of operations visited	27	27	17
Number of management units reported	188	162	96
Average management unit size (acres)	0.45	1.1	11.1
Avg. N application rate in lb/ac/yr	177	771	60
Avg. P2O5 application rate in lb/ac/yr	109	348	18
Avg. K2O application rate in lb/ac/yr	175	496	22
Avg. water applied in gal/ac/application	13,500	38,700 (summer)	23,117

D. Data collection

By participating in this study, growers allowed us to access their nutrient management plans on file at the Maryland Department of Agriculture. The MDA has copies of the Nutrient Management Plans that were originally filed when the nutrient reporting laws went into effect, as well as any plan updates required by law. In addition, growers are required to submit an annual reporting form, which is filed by each grower on a yearly basis, indicating the amount of N, P_2O_5 and K_2O in pounds per acre per cycle applied to their various management units each year.

After coordinating with MDA, management plans and annual reporting forms were copied from MDA records, and MDA was given a copy of the signed release form for each operation for their records, which was then included in each operation's file. This allowed access to the nutrient management plans on file with MDA, as well as the yearly reporting forms. Per IRB requirements, all operational information was kept in a secured location, and any computer-based files that contained sensitive information were password protected, with access to identifiable information limited to the Principle Investigators.

Most of the operation information accessed through MDA records about individual operations was either incomplete, or outdated. Nutrient management plan (NMP) information had been collected by MDA mainly from 2000-2005, so by 2009 there was the potential for these plans to have outdated information due to change in practice, which would not necessarily have resulted in a new management plan. For example, this would be the case if the operation reduced the amount of applied nutrients, since they were still in compliance with regard to nutrient application rate per acre, but did not go through the steps of having their management plans updated. In addition, management plans did not contain information on irrigation type/frequency which is necessary for a complete understanding of nutrient and sediment runoff potential for the modeling portion of this project. It was determined that site visits were necessary to speak with growers directly about current irrigation and fertigation practices, and to collect information that was missing or deficient from their NMP. Forty-seven operations were visited between February and April of 2009 and one grower, who was not growing that year, was interviewed over the phone. Three growers who agreed to participate in the study declined to meet for a site visit for various reasons.

Five separate Microsoft Access databases were set up for data entry. One database was used to link the individual operations to their data via a random number assigned to each operation. A second general database contains information about the whole operation such as size, area under production and any N, P and K data for the whole operation (annual reporting form data). This database contains mainly information that was available in the MDA file about nutrient application rates for the whole operation. This database also has information on operational best management practices such as containment basins or vegetative buffer strips. The remaining three databases were set up for greenhouse, container, and field data at the management unit level. These specific databases have information about all management units identified by an operation code, such as size of the management units, container size, number of plants, plant type/species, production goal, frequency and type of fertilizer(s) applied, plant spacing, irrigation type and practices, substrate type and best management practices being used. An individual operation may have from one to ten or more management units, based on plant requirements and management decisions.

E. Rationale for modeling

There have been many research articles published about the nursery and greenhouse industry over the past 40 plus years. Each article typically focuses on only one or a few aspects of this industry, such as substrate properties, fertilizer use and/or uptake, irrigation application efficiency, etc. Growers and researchers know that there are many factors that can impact each variable in the nursery and greenhouse setting, some of which cannot be easily controlled (i.e. sunshine, rainfall, wind). In a research setting, as many factors as possible are controlled as part of the study to determine the significance of a set of variables, but it is economically impossible to measure all sources of variability within any reasonable time constraints. Modeling provides a much more time- and cost-effective approach to understanding the impact of changing different variables at the operational scale. In addition, models can be used as a learning tool for both growers and researchers, to help determine the most appropriate steps to take for future research or at their operation.

Models are often developed when large-scale or complicated experiments cannot be completed for a variety of reasons. Since models simplify systems that are often-times too complex to study directly, they are rarely completely accurate. If developed and validated using the best information available from controlled research studies, models allow us to ask and answer a variety of questions that would be difficult or impossible to answer using classical empirically derived experimentation. The main issue with modeling is validation, to ensure the model outputs approximate reality within the bounds of model parameters. The models presented here are the first known attempt to systematically incorporate published research for the nursery and greenhouse industry into a larger framework that can be used for modeling N, P and water runoff from greenhouse, nursery, and field operations.

F. General Model Development

The same basic procedures were used to develop the greenhouse, container, and field models. Each model was developed independently. The greenhouse model was developed first, since it was the least complex. The field model was developed second, and incorporated information and knowledge gained from greenhouse model development. Many of the factors included in the greenhouse model were included in the field model, along with additional factors such as rainfall, and soil information not found in the greenhouse model. The container model was developed last, since it combined aspects of both the greenhouse and field models.

Model development is based on various inputs including environmental data (e.g. monthly temperatures and rainfall), general cultural variables (e.g. plant density, management unit, fertilization rate and irrigation system), and land-use data (e.g. soil type, presence or absence of riparian buffers and containment structures). Since each type of operation (greenhouse, container, and field) uses resources in very different ways, each was modeled separately, to properly define the variables that are important for each operation. In each model, some variables are manually inputted by the user (i.e. number of plants, size of management unit, volume and frequency of irrigation, N and P rate (grams nutrient applied per plant) as inputs to the model, while other variables were defined based on available data and research (i.e. plant N and P uptake, evapotranspiration and denitrification rates). These variables are not designed to be controlled by a novice user, but advanced users are able to change rate constants such as evapotranspiration and denitrification rates, vegetative buffer removal efficiency, etc. through a web-based graphic user interface.

Each model was first conceptualized and discussed with faculty committee members and growers, to determine the most important factors for inclusion, as well as the general inputs and outputs of each model. Factors such as fertilizer rates and irrigation sources, typical management and mitigation practices, and substrate properties were discussed in regards to how they could be modeled by the Stella modeling program (isee systems Inc., Lebanon, NH; see below). As models were built, variables were defined using published research information, additional discussion with faculty advisors and information from grower visits.

Stella has three main "layers" that are used for model development and use. The interface layer (graphical user interface), is designed so that the end user can interface with the model, without being distracted by the intricacies of the model. The model developer places the relevant variables on the interface layer where the end user can interact with those variables, and see the results of those interactions. The modeling layer is where the actual model is built, and the interactions of the variables are defined. The modeling layer uses the building blocks discussed below to create the relationships that define how the model will run. The model also includes an equation layer, which automatically creates the equations (programming) behind the model, based on the relationships that are created with the building blocks. The equation layer contains every relationship that is built in the modeling layer.

Each model is constructed so that every variable in the model can be changed by the end user in the “model” layer, while the “interface” layer has the variables that most users will need to manipulate for the models to meet primary requirements. The interface layer was built so that general users will only have to change values that are specific to their operation, and can use default values for any variables they are unsure of; while more advanced users can change default values in the interface and model layers. Another benefit of the Stella modeling program is that all graphs on the interface layer can be easily returned to their default values by clicking on the “U” or undo button found on each graph. This should make users more comfortable changing values, since they know that the default values can be easily restored.

Stella has four main building blocks that can be used to construct models. The first building block is the stock, and is represented as a rectangle in the “model” layer. There are four types of stocks, Standard, Conveyor, Queue and Oven, with each having a slightly different ways that they process inflows and outflows. The purpose of a stock is to collect inputs and feed outputs and can be thought of like a holding tank. In the model, these are used mainly to represent the plant container or root volume (in the case of the field model). Stocks hold N, P and water until they are removed by various processes such as plant uptake, or loss through denitrification, leaching and runoff to containment basins, buffer strips, surface waters, etc. All models use the standard stock, which simply hold materials until they are removed. The container and field models also use the conveyor stock, which is used to move materials through the stock at a defined pace (like a conveyor belt). In the models, the conveyor stock is used to represent N and P movement through the soil profile.

The second building block is flow. Flows are used to fill and drain stocks, and can be set to flow in one direction, or in both directions. For this project, all models have unidirectional flows. The third building block is the converter. Converters perform a variety of functions in the software. They can be used to hold values for constants, define external inputs to the model, calculate algebraic relationships, and serve as repositories for graphical functions (www.iseesystems.com 2008). In general, converters are used to convert inputs into outputs in the model. The fourth building block is called the connector. Connectors are used to connect model elements, and define the relationships between elements. There are two types of connectors, action connectors and information connectors. Action connectors are signified by a solid directed wire, while information connectors are dashed. Action connectors are the only connectors used in the models.

Each model is built around three key components, nitrogen, phosphorus, and water. Each of these three components is necessary for plant growth, but in excess they can lead to nutrient leaching and sediment runoff from an operation. Nitrogen and phosphorus inputs in the model come from applied fertilizer, in its various forms (SRF, solid, or soluble). Water is included by the various types of irrigation systems present at different operations (overhead, drip, etc.), as well as rainfall in open container and field operations. Users input the application rate of the sprinkler/ emitter (gpm or gph) and the number of sprinklers/ emitters in the management unit, which are fixed values for the model run, along with irrigation frequency and duration information, which can be varied week by week. This will be discussed further in individual model chapters. In nursery and greenhouse operations, the concern is not only the rate of nutrient and water applications, but also in what happens to nutrients and water once they leave the plant container or root zone. Any N, P or sediment runoff leaving the growing area is conveyed by water from either irrigation or rainfall. The runoff can either be captured by the operation for reuse or appropriate removal, or can be further conveyed to surface and ground water and potentially cause pollution problems. Nitrogen and phosphorus can be conveyed to surface or groundwater, or can be captured and treated or reused at the operation. Sediment runoff (erosion) can be captured by various on-site practices such as sediment basins, or vegetative buffer strips. Ideally, nutrient and water application would closely match plant requirements, with appropriate management practices in place to treat occasional nutritional or irrigation over-application.

The main drivers of each model are plant N and P uptake, evapotranspiration, and natural microbial loss mechanisms such as denitrification and fixation. These variables actively function to remove N, P, and water at each step in the model. For example, if N is available in the substrate, the plant and microorganisms are both actively taking up available N, within the parameters of the model. The remaining variables such as container capacity and leaching are dependent on container size and substrate type, while leaching is dependent on N container capacity, nutrient uptake, microorganismal uptake, and evapotranspiration. For example, N is applied to the container or soil volume (root zone) through fertilization, which then accumulates in the stock (rooting volume), which is then removed either by plant growth, denitrification and/or leaching. If water applications or N in the container exceeds the water or nitrogen-holding capacity of the container, leaching occurs. This process will be discussed in more detail for each specific model (chapters 4, 5 and 6).

After all of the necessary inputs and model variables were accounted for, each model was calibrated and then validated, using peer-reviewed published data sets as model inputs. Some required input variables were not provided in the published research papers, such as the volume of irrigation water applied, the frequency of irrigation, or the N - P_2O_5 - K_2O ratio of fertilizer that was used. Some model inputs were not reported directly, but were based on published information in the data. For example, substrate N and P holding capacity were often not reported, but could be determined from the amount of N and P in the substrate at the end of the study (typically from the highest nutrient treatment). Assumptions were made based on the published materials and methods or standard practice for any inputs that were either not reported directly or could not be determined from the published article. All assumptions are noted for each model run. For all datasets, unreported information was not believed to be a substantial issue, since that factor was not under investigation, and was typically supplied in sufficient quantities for optimal growth. For example, precise irrigation scheduling/ applied volumes were often not reported, but plants were not grown under water limiting conditions, so assumptions had to be made about irrigation frequency and/or volume. In instances where assumptions were made, those variables could be adjusted if model validation did not function correctly, but this was rarely necessary (see individual model chapters for more information). Once model calibration was completed, assumed variables were not adjusted for the remaining runs of that dataset (validation).

During calibration, the model was run and the outputs from Stella were compared to the results reported in the published study. Any variables from the Stella output that did not match the published data sets were changed and the model was re-run. Due to the complexity of the models there were a number of possible reasons for error. For example, there could be a conversion error, an error in the equation, or a misunderstanding of how Stella was processing the equation. The cause of the error was determined and corrected, and the model was rerun. This process was repeated iteratively until the Stella outputs and published outputs were similar for all reported outputs. Once models were satisfactorily calibrated using a subset of variables from a published dataset, the remaining sets of variables were run, adjusting only the variables that the researchers changed in the original published study. For each run, the input variables were recorded in an excel spreadsheet, along with model outputs, and the results tabulated (see Chapters 4, 5, and 6).

For each model, an excel spreadsheet was set up to import and export data to/from Stella, as well as additional sheets for validation and "what-if" results. For each model, a "summary" sheet was created to summarize data outputs from Stella so all pertinent information is in one location and is easier to understand. Important factors such as N and P uptake and runoff, irrigation volume and runoff, and evapotranspiration are calculated automatically when the output data is copied from the output file, and pasted into the appropriate location in the summary file. The summary information was used to compare model outputs to published data sets, and provides an easy-to-read analysis of Stella outputs. In addition, a separate sheet in each spreadsheet was created for the inputs and outputs of each dataset that was run. If any of the model scenarios need to be recreated for future analysis, this can be accomplished using the inputs in each of the spreadsheets.

Once models were developed and validated, a variety of "what-if" scenarios were run to determine the sensitivity of each model to a number of variables, and determine the impact of a variety of standard practices on nutrient and sediment runoff, water leaching, and plant growth (see model chapters for individual what-if scenarios). Values from what-if scenarios were based on standard industry practice, the information gained from discussions with growers (primary concerns) and the hypotheses listed in Chapters 3-6.

G. Scope and Limitations

This project focused on nursery and greenhouse operations in Maryland. There are several primary reasons for limiting the scope of this project to Maryland. According to current regulations, the Maryland Department of Agriculture should have a nutrient management plan for each nursery and greenhouse operation in the state grossing $2,500 or more a year, along with records of yearly rates of N, P_2O_5 and K_2O applications starting in 2005. Using data from a single source decreases the complexity of the project, and ameliorates potential difficulties with using data from multiple sources (for example, regulatory agencies in other states). Also, the 51 operations in the state who generously agreed to share their information should have provided enough data to gain an understanding of the variability in irrigation and nutrient application rates and timings in Maryland, making the available data appropriate for answering the problems posed in this project.

The modeling portion of this project represents an initial attempt to provide a systematic understanding of nutrient and water dynamics in the nursery and greenhouse industry. One of the difficulties in developing and testing the models presented here is the lack of information available in the literature for some of the model variables. There are several different areas in this research project where reliable published information was not available at this time. In each case, assumptions or extrapolations had to be made from the published research for use in the models. For example in the area of nutrient uptake, there has been a lot of research in agricultural crops, but little research has been done on nutrient uptake in many ornamental species, especially woody perennials. For each of the models, assumptions were made for species and cultivars of plants that do not have specific research data available. There has also been limited research in the nursery and greenhouse industry on N loss due to denitrification, especially in soilless substrates. Areas of future research are discussed in each model section and in the final summary chapter. The goal of these models is to help the industry better understand nutrient and irrigation application and uptake in order to reduce N, P, and sediment runoff.

Chapter 3: Database Results and Discussion

A. Introduction

At approximately 20,000 acres, the nursery and greenhouse industry represents a significant portion of irrigated agricultural land in Maryland (U. S. Dept. Ag. 2009). Many operations are intensively managed, especially greenhouse and container operations. This leads to the *potential* for high levels of nutrient (greenhouse and container) and sediment (container and field) runoff *if* proper nutrient application and abatement practices are not followed. Since almost all of the fertilizer used in this industry is water soluble, irrigation water management has a significant effect on nutrient management and the potential for leaching and loss to surface waters.

Currently, there is no aggregated information on the yearly N and P application amounts from the nursery and greenhouse industry in Maryland to the Chesapeake Bay and its tributaries, either from the Chesapeake Bay Model or available through any other source. Although the database discussed below does not have application rates for all nursery and greenhouse operations in the state, it does provide detailed information about nutrient and irrigation management practices from diverse operations across the state on a management unit basis, which is much more detailed information than has ever been documented, until now. With these data, the variability in irrigation and nutrient application practices at the management unit level can be determined. Since these data represent about 15% of the operations in the state, information gathered could be used to extrapolate N and P application rates to the state level. This should be of major benefit to the industry, since these data will be useful to understand current practices in the nursery and greenhouse industry, for the development of better management (nutrient reduction) strategies, and for more targeted efforts (e.g. increased cost-share funding) to aid in implementing these practices.

B. Grower Database Development

i. Mailing procedure

Procedures for operation mailing, site visits, and database inputs were briefly discussed in Chapter 2, but will be expounded on here. The Maryland Department of Agriculture (MDA) is responsible for ensuring that nursery and greenhouse operations are in compliance with current nutrient management laws, and collect and store Nutrient Management Plan (NMP) and annual reporting form information. Any nursery or greenhouse operation that grosses more than $2,500 a year is required to file a nutrient management plan, unless no nutrients are applied to the operation (Maryland Department of Agriculture 2000). After repeated discussions with MDA, it was decided that releasing NMP information would potentially be a breach of privacy laws, and they could not share this grower information with us. Since MDA could not legally share NMP information, we decided to directly approach growers, and ask for voluntary participation in the project. This was found to be beneficial for a number of reasons, including building rapport with the growers, getting more detailed information, and making growers aware of how their data was going to be used and protected.

The first step in this process was to gain approval for data collection from human subjects through the University of Maryland Institutional Review Board (IRB), to be in compliance with University of Maryland and Federal policy (see Appendix B for IRB documentation). This project was considered exempt from full IRB review, and was granted expedited review status, as discussed in Chapter 2. Once IRB approval was gained, information packets were mailed out to 491 operations in the state. Address information was gathered from three sources: the MDA Nutrient Management Office, MDA Plant Protection Office, and the Maryland Greenhouse Growers Association. This information was considered public record, and could be released by these agencies. The information from these three lists was combined, and any duplicate address/grower information was removed. There were a number of operations that had different addresses or contact information listed, so a separate information packet was sent to each address/person to be certain all operations were included. The USDA specialty crops census (2010) published data which reported 368 actively growing nursery and greenhouse operations in Maryland in 2007, with Table 3.1 providing a summary list of the number of operations growing plants at different levels of total annual sales in dollars. From this information, it is assumed that about 120 packets out of the almost 500 mailed were most likely duplicates.

Table 3.1. Number of operations reported with ranges of total annual sales (in $) from nursery and greenhouse operations in Maryland. Data modified from (U. S. Department of Agriculture 2010).

Total Annual Sales ($)	**Number of Operations**
0 to 99,999	188
100,000 to 249,999	67
250,000 to 499,999	44
500,000 to 999,999	29
1,000,000 to 2,499,999	25
2,500,000 +	15
Total	**368**

Grower packets consisted of the following information (see Appendix B for the complete grower packet). The first page accepted or declined participation in the study, and asked for general operation information. If a grower volunteered to be included in the study, they were asked how they wanted their data accessed; either through access to MDA documentation, via a site visit, or if they had no preference. Growers were asked to complete address and phone information to identify the operation, and update any out-of-date or incorrect information. Participating growers were asked to read and complete the consent form required by the IRB committee to inform participants about the benefits and drawbacks of the study, and to inform them of their rights as volunteers. In addition to the required consent form, the grower was asked to complete and sign a Memorandum of Understanding (MOU). The MOU was included as added assurance to participating growers regarding the use and protection of their operational information.

Any returned packages were followed up with a phone call (if a number was available) and/or an internet search to determine if any information was incorrect or missing. If additional information was found, the packet was re-sent, and the additional information added to the final grower database that was compiled. If no new information was determined, the packet was determined to be undeliverable. Approximately 6 weeks after the grower packets were mailed out, a reminder postcard was mailed to any operation that had not responded to the original request (Appendix B). This reminder postcard also included contact information for any questions or concerns the grower had.

ii. Data collection

By participating in this study, growers allowed access to their nutrient management plans on file at the Maryland Department of Agriculture, which included their original management plan, any updates required by law, and annual reporting forms filed yearly indicating pounds of nitrogen (N), phosphorus (P), and potassium (K) applied per year for the operation. Management plans and annual reporting forms were copied from MDA records, and MDA was given a copy of the signed release form for each operation, for their records. As per IRB requirements, all operation information was kept in a secured location, and any computer-based files that contain sensitive information wee password protected, with access to identifiable information limited to the Principle Investigators.

iii. Site visits

It was determined that most nutrient management plans did not contain enough detailed information to be useful to this study. It was then decided that site visits would be necessary to conduct grower interviews, so that more detailed information could be collected about the operations than was available in the management plans on file with MDA. Growers were contacted and site visits were set up for all but three participating operations. Site visits were conducted from February through April 2009. During each interview, an interview form was completed that looked at operation wide and individual management unit practices (see Appendix B for grower interview form). The grower interview form guided much of the discussion that took place during the interview, and allowed for a thorough understanding of grower practices, with regard to operation and management decisions for irrigation and fertilization. In addition, any questions regarding information in the nutrient management plan were discussed with the grower. In general, growers were very willing to discuss their operation and its management, and were open and receptive to questions during the interviews. Interviews typically lasted 2-3 hours depending on the size and complexity of an operation. Before or after a grower interview, the operation was viewed either on foot or by vehicle, typically with the grower present. Each grower was asked if pictures of the operation could be taken, which was typically allowed. Pictures of different parts of the operation, including different management units, best management practices, and irrigation and fertilization practices were taken. After each site visit, a synopsis of each visit was prepared that included a summary of operational practices along with information about individual management units. This information is more organized than the grower interview form, since interviews did not always proceed in the same order as they were on the form.

After the operation summary was completed, data was entered into a Microsoft Access file. Five Microsoft Access databases were set up for data entry. One database contains each operation's name, along with its assigned random number which is used to link the individual operations to their data. This file contains the information that needs to be protected as per the IRB agreement. All other databases contain only the operation specific random number that identifies each operation, but cannot be linked back to the actual operation without the database key.

There is a general database which has information about the whole operation such as size, area under production, and any N, P and K data for the whole operation (annual reporting form data). This database contains mainly information that was available in the NMP and annual reporting forms regarding nutrient application rates for the whole operation. This database also has information on operational best management practices such as containment basins or vegetative buffer strips. The remaining three databases were set up for greenhouse, container, and field data at the management unit level. These databases have information about all management units identified by the growers, such as size of the management units, container size, number of plants, plant type/species, production goal, frequency and type of fertilizer(s) applied, plant spacing, irrigation type and practices, substrate type and best management practices being used. An individual operation may contain any number of management units for each operation type, based on plant requirements and management decisions made in the operation.

C. Database Hypotheses

Based on the information provided in Chapter 1, there are a large number of variables that can affect the efficiency of plant production in the nursery and greenhouse industry, both now and in the future. In chapters 3 through 6, I have developed a series of narratives around a number of important hypotheses that were generated in discussion with my advisory committee and growers. These hypotheses were tested by running the specific models developed and validated by this research (Chapters 4, 5, and 6), and with data collected and assembled into a database from 48 individual operations, on a management unit basis (this Chapter). As such, the database portion of this project provides a snapshot of 2009 practices in the nursery and greenhouse industry in Maryland. The modeling portion of this project allows for the testing of how 2009 practices impact a number of important cultural and environmental variables such as plant growth, denitrification, N and P uptake, water use, nutrient runoff and sediment loading. The models, of course, allow for the testing of many additional research questions, and can help answer questions about how changing different practices impact plant growth and nutrient runoff and capture at an operation beyond the scenarios outlined in this dissertation.

From previous work writing nutrient management plans (Lea-Cox, Ristvey and Ross, *pers. comm.*), there is anecdotal evidence that a variety of N, P_2O_5, and K_2O application rates are used to grow similar species of plants under similar conditions (e.g. container size, irrigation type, fertilizer type). If a variety of application rates are used at different operations, with similar results (e.g. same production time) nutrient reduction toward the lower end of the rate range should be possible. This knowledge could lead to reduced nutrient leaching from these operations.

Hypothesis #1: Based on the ranges of N, P, and K application rates collected during site visits, a "best management practice" range can be determined for

particular species or types of plants based on current grower practices. Reducing nutrient application rates would reduce nutrient runoff, which would decrease cost, and result in less ground water and surface water pollution.

Greenhouse and container operations are more intensively managed systems in regard to fertilizer and irrigation inputs, while field operations tend to apply lower rates of nutrients and irrigation.

Hypothesis #2: Greenhouse operations will apply the highest rates of fertilizer on a per acre per year basis, followed closely by container operations, especially at close plant spacings, while field operations will have the lowest application rates, with a lower potential for nutrient loss.

Hypothesis #3: With regard to irrigation water applications, container-nursery management units (MU's) using overhead irrigation will use the most water on a per acre basis, followed closely by greenhouse MU's, with field MU's having the lowest rate of water application, since they often utilize drip irrigation and irrigate less frequently.

There is often a misunderstanding in the nursery and greenhouse industry that over-application of N and P above a sufficient level can preferentially promote root, shoot, or increase flowering and fruit growth (Harris 1992; Williams and Nelson 1996; Hansen and Lynch 1998; Majsztrik et al. 2011). This leads to the application of "standard" fertilizer formulations such as 20-20-20 or Osmocote Pro 16-11-10 slow release fertilizers which have super-optimal ratios of P_2O_5. The ratio of N: P_2O_5: K_2O is important for optimal plant growth, since these nutrients are taken up and used by plants in the greatest amounts during growth. Based on tissue analysis from a variety of ornamental plant species, Sammons (2008) suggests a N: P_2O_5: K_2O ratio of 4-1-3 (which will be referred to as the "recommended" or "ideal" ratio throughout this paper) should meet the growth needs of most plants grown in the nursery and greenhouse industry, assuming the fertilizer is applied at a sufficient rate. Using the 20-20-20 and 16-11-10 example above, the 4-1-3 ratio would correspond to 20-5-15 and 16-4-12 respectively, based on the N rate. Applying fertilizer at a rate different from the 4-1-3 ratio could result in nutrient runoff of one or more nutrients which are applied in excess of plant requirements. Excess application can also lead to increased electrical conductivity levels in the root zone, leading to salt stress, and possible growth problems in the plant.

Hypothesis #4: Based on grower visits, more than 50% of management units surveyed in greenhouse and field operations are applying fertilizers with at least one nutrient that is in excess of the 4-1-3 ratio, while less than 50% of the operations using slow-release fertilizers (SRF) are applying fertilizer with at least one nutrient in excess of the recommended ratio of 4-1-3.

D. Database Results

Nutrient management plan (NMP) information had been collected by MDA mainly from 2000-2005. There was a potential for outdated information due to changes in practice which were not reflected in a new management plan. For example, this would be the case if the operation reduced the amount of nutrients they applied. The operation would still be in compliance with regard to nutrient application rate per acre, but did not go through the steps of having their management plans updated, since this represented a decrease in nutrient application rate. In addition, management plans did not contain information on irrigation type/frequency which were necessary for a complete understanding of nutrient and sediment runoff for the modeling portion of this project. It was found that a large portion of the operation information accessed through MDA records about individual operations was either incomplete or outdated, especially when compared to the amount of detailed information gathered from site visits.

Of the 491 grower packets that were mailed out (to approximately 368 operations in the state), a total of 82 responses were received, which is a 22% response rate. Eleven operations indicated that they were no longer growing plants, because they had either closed down or the person who was running the operation was deceased, with some operations closing as far back as 2004. Twenty operations mailed back responses declining participation in the project. Fifty-one operations agreed to participate in the project, which allowed access to nutrient management plans available through MDA. Three operations that agreed to participate in the study declined to participate in the site visit part of the project due to personal reasons. For 47 of the 48 operations, on-site interviews were conducted at the operation. One operation that was not currently growing was interviewed over the phone, at the grower's request.

During site visits, some growers did not have specific details about some aspects of their operations, such as management unit size, irrigation frequency, gallons per minute or gallons per hour per emitter, but could give estimates or general ranges for the management units. Therefore the numbers given in the database may be slightly different than actual practice, but should be fairly accurate. Seasonal and yearly variations in temperature, rainfall, relative humidity, amount of sunlight, and other factors, impact decisions that growers make on a daily basis. The numbers provided by the growers and presented below represent typical practices and should not be considered absolute. One of the difficulties associated with interviews is the accuracy of the information that is given, as opposed to more accurate methods of data collection that could have been used for this project. For example, data collecting devices could have been used, or growers could have recorded actual practices throughout the year for each management unit. Although other methods might have yielded better quality data, it would have been too expensive or labor intensive to gather this information simultaneously from the 48 operations. Grower interviews were believed to provide accurate information, in a cost and time sensitive manner, which was sufficient for the scope and intent of this project, and for use in the models that were developed.

A variety of operations were visited, representing everything from small backyard operations employing only one person to large operations growing on hundreds of acres and employing dozens of people. By the end of the interviews, a large majority of growers understood the importance of this research, even though some were initially reluctant to meet. A number of growers were interested in the model development and were interested in using the completed models at their operation.

i. Greenhouse

a. Results

The term "management unit" will be used throughout the remainder of this paper. As a definition, a management unit is a group of plants that are managed similarly at an operation, mainly in terms of container size and water and nutrient application rates and timings. Management units may or may not be located at the same location in an operation or be grown at the same time in the year. The management unit therefore represents the smallest division of an operation that is managed in the same way.

Of the 51 operations included in this database, 27 operations had a greenhouse component, with 188 management units present in these 27 operations. A total of 64 acres of actual greenhouse production area is represented by the management units reported in this study (excluding walkways, head-houses, buildings etc., including multiple uses of the same physical space). All three operations that were not site visited had a greenhouse component present, representing 19 management units. These were excluded from the database for subsequent analysis included below, since minimal information was available from MDA records. A total of 169 greenhouse management units are included below.

Containers ranged in size from 105 cell plug trays to 11 liters (3 gal) containers. A variety of plants were grown at these operations including a number of different annuals, geraniums, mums, poinsettias, herbaceous perennials, rooted cuttings, woody perennials, and pansies. Abridged spreadsheets for greenhouse, container, and field information are provided in Appendix C listing a number of important values reported by growers for all management units. Table 3.2 lists a number of important variables based on grower interview information. There is a large amount of variability in the number of plants per management unit, management unit size, and plants per hectare in the data collected listed in Table 3.2. For example the number of plants ranged from almost 12,000 to over 430 million plants per hectare (ha). This coincides with the container size numbers listed above ranging from 105 cell plug trays to 11 L (3 gal) containers. The N, P_2O_5 and K_2O application rates listed in Table 3.2 in kilograms per hectare per year are also worth mentioning. The minimum value of 0 is from propagation cuttings that did not receive nutrients during that stage of production. The highest values for N and K_2O were used in poinsettia production, while the highest P_2O_5 value is from aquatic operation which also had high N and K_2O values.

Table 3.2. Summary values based on site visits to 27 greenhouse operations in Maryland representing 169 managing units (MU's).

	Number of plants in MU	**Plants/ hectare**	**Kg N/ ha/yr**	**Kg P_2O_5/ ha/yr**	**Kg K_2O /ha/yr**
Minimum value	40	11,960	0	0	0
Lower quartile	3,411	107,499	59	20	60
Middle quartile	13,100	239,205	107	37	105
Average	134,920	3,900,392	253	155	254
Upper quartile	60,225	858,149	240	171	244
Maximum value	5,580,000	432,433,715	2,958	3,405	2,958

Many of the annuals grown in greenhouses had a typical production time of 4 to 12 weeks with larger plants such as mums, perennials, and poinsettias typically growing for 3 to 6 months (see Appendix C Table C 3.1for a list of production times for all MU's surveyed). Most of the plants grown in greenhouse operations are spaced container-to-container for most if not all of the time they are grown in the greenhouse, which allows growers to maximize production area. Hanging baskets and plants placed on drip irrigation are typically placed at final spacing after they are initially transplanted to minimize the labor involved in spacing plants.

Table 3.3 lists the N- P_2O_5- K_2O ratios reported by greenhouse operations that were interviewed, along with the number of management units reported to be using each fertilizer ratio. The most common fertilizer rate used was 20-10-20, which was reported in 40 of the management units, followed by 17-5-17 which was reported in 38 management units, and 20-20-20 and 20-7-20 reported in 12 management units each. A variety of other N-P-K ratios were reported for one to 11 MU's, in Table 3.3. If more than one fertilizer ratio was used for the same MU over the course of growing period, each ratio is listed separately.

Table 3.4 provides the different types of fertilizer reported for the management units in this study. A large majority of the greenhouse operations applied soluble fertilizer, with 146 out of 180 (81.1%) of the management units using soluble only, with one MU using soluble and slow release fertilizer. The term slow release is preferred over the term controlled release, since these fertilizers do not have a controlled release pattern, so the term slow release is more appropriate. Only 26 management units were reported to use SRF fertilizer, which was mainly applied to propagation material, some larger containers and hanging baskets. Two management units reported using aquatic fertilizer

Table 3.3. $N-P_2O_5-K_2O$ ratios reported by 27 greenhouse operations for 169 management units in the state of Maryland during site visits conducted February to April 2009. If a management unit had more than one ratio of fertilizer applied over the growing period, each fertilizer ratio is listed separately.

Number of Management Units using ratio	$N-P_2O_5-K_2O$ ratio of fertilizer
40	20-10-20
38	17-5-17
12	20-20-20
12	20-7-20
11	20-5-20
10	17-5-24
8	13-13-13
8	22-0-22
7	15-5-15
6	14-14-14
4	19-6-12
4	21-5-9
3	15-0-15
3	15-3-18
2	10-14-8
2	17-6-12
2	18-6-8
2	20-6-21
1	3-1-1
1	15-2-20
1	17-7-12
1	18-5-11
1	19-5-9
1	20-15-21

Table 3.4. Type of fertilizer applied and number of management units reporting each type of fertilizer for 27 greenhouse operations in Maryland, representing 180 management units.

Type of fertilizer	**Number of Management Units applying**
Aquatic	2
None	6
SRF	26
Soluble	146

(for growing aquatic plants), while six MU's reported no nutrient application, mainly for seedlings or rooted cuttings at early stages of production.

The amount of irrigation water applied to a given area is important since water is the transport mechanism for both nutrients and sediment at an operation. It is important to understand that water is the transportation mechanism both into the plant, but also into the surrounding environment. Over-application or misapplication of water can lead to nutrient and sediment runoff from an operation into the surrounding environment. Efficient water application is vital to reducing nutrient loss from the container and soils. In order to get an understanding of how much water is applied during a typical irrigation, information gathered from site interviews was used to gain a better understanding of irrigation practices. For the numbers listed in Table 3.5, any operation where the grower was not sure of the rate of emitter application, or time irrigation was applied was excluded from this analysis (23 MU's were excluded). For the remaining operations, irrigation volume was determined for a typical irrigation event. If the grower gave a range of time that irrigation was applied, the upper range was used, to represent the maximum water application per irrigation event. Table 3.5 shows the results of this analysis. On average, 65,193 Liters of water were applied per hectare (6,970 gallons/acre), with lower and upper quartiles of 40,820 L/ha and 86,555 L/ha respectively for a typical irrigation event.

Table 3.5. Amount of water applied per irrigation event, based on information from 27 greenhouse operations that were site visited in Maryland, representing 146 management units.

	Liters/hectare	**Gal/acre**
Minimum	5,282	565
Lower quartile	40,820	4,364
Middle quartile	89,497	9,568
Average	65,193	6,970
Upper quartile	86,555	9,253
Maximum	407,458	43,560

With regards to substrate, most operations grew in a peat-based soilless substrate, with 150 out of 170 management units (88%) reported peat as the highest percentage by volume, with only 20 MU's (12%) reporting bark or bark fines as the highest percentage by volume (data not shown). Peat has a number of properties such as its water holding capacity and air-filled porosity which make it beneficial for use in greenhouse instead of pine bark, especially in smaller containers where those two factors are very important for irrigation and disease management. In small containers (< 4L) water holding capacity is an important factor since there is a smaller amount of total available water compared to larger containers, with peat substrates allowing for more water storage per volume compared to pine bark substrates, which are typically used in larger containers (>4L).

Table 3.6 gives nutrient application ranges for 16 different plant type and container size combinations (see Appendix C; Table C 3.2 for standard U.S. values). Plants were sorted by management unit, and then by container size within the management unit. For each plant type and container size, the rate of N, P_2O_5 and K_2O per hectare per year are given for the average, minimum, lower quartile, middle quartile, upper quartile and maximum values.

Table 3.6. Variability in application rates of N, P_2O_5, and K_2O organized by plant type and container size for 27 greenhouse operations in Maryland based on data collected from site visits.

Plant type and container size	Number of MU's represented		Kg N/ ha/yr	Kg P_2O_5/ ha/yr	Kg K_2O /ha/yr
Annuals 10-11 cm	13	Minimum	30	11	30
		Lower quartile	57	18	57
		Middle quartile	112	37	112
		Average	165	68	159
		Upper quartile	173	73	176
		Maximum	766	225	766
Annuals 13-15 cm	10	Minimum	30	10	30
		Lower quartile	40	13	43
		Middle quartile	73	22	73
		Average	107	65	108
		Upper quartile	166	64	174
		Maximum	265	265	265
Annuals 20-30 cm	9	Minimum	50	13	50
		Lower quartile	87	22	87
		Middle quartile	88	26	88
		Average	154	111	155
		Upper quartile	88	26	88
		Maximum	454	454	454
Annuals flats (i.e. 606, 1204 etc.)	15	Minimum	24	17	24
		Lower quartile	59	18	59
		Middle quartile	74	38	74
		Average	162	95	169
		Upper quartile	176	79	162
		Maximum	512	430	647
Geraniums 10-30 cm	6	Minimum	59	17	59
		Lower quartile	155	61	158
		Middle quartile	392	185	403
		Average	436	200	448
		Upper quartile	517	241	526
		Maximum	1,140	531	1,179

25 cm Hanging baskets	13	Minimum	36	20	36
		Lower quartile	90	36	105
		Middle quartile	206	129	194
		Average	389	160	371
		Upper quartile	579	258	579
		Maximum	1,082	440	979
30-36 cm Hanging baskets	6	Minimum	29	11	29
		Lower quartile	29	11	29
		Middle quartile	29	11	29
		Average	73	68	73
		Upper quartile	54	16	54
		Maximum	259	347	259
Herbaceous Perennials flats - 7.5 L	7	Minimum	104	21	125
		Lower quartile	121	44	132
		Middle quartile	220	164	220
		Average	282	225	288
		Upper quartile	334	281	334
		Maximum	739	739	739
Mums 8-20 cm	6	Minimum	87	22	87
		Lower quartile	99	58	99
		Middle quartile	175	191	175
		Average	415	255	405
		Upper quartile	285	262	285
		Maximum	1,657	828	1,598
Mums 4-8 L	7	Minimum	64	22	64
		Lower quartile	135	202	135
		Middle quartile	188	349	188
		Average	290	365	290
		Upper quartile	484	535	484
		Maximum	540	711	540
Pansies flats 20 cm	4	Minimum	59	15	59
		Lower quartile	97	32	79
		Middle quartile	118	40	91
		Average	106	35	85
		Upper quartile	127	43	98
		Maximum	129	44	99

Perennials 1-8 L	6	Minimum	97	19	102
		Lower quartile	106	53	116
		Middle quartile	150	75	150
		Average	274	154	277
		Upper quartile	239	216	239
		Maximum	887	443	887
Poinsettias 8-18 cm	11	Minimum	87	22	87
		Lower quartile	121	39	125
		Middle quartile	191	196	241
		Average	618	243	634
		Upper quartile	674	288	674
		Maximum	2,958	870	2,958
Poinsettias 20-25 cm	12	Minimum	52	13	52
		Lower quartile	112	35	112
		Middle quartile	256	110	262
		Average	348	186	367
		Upper quartile	406	229	498
		Maximum	1,265	781	1,265
Propagation flats 20 cm	17	Minimum	0	0	0
		Lower quartile	62	26	49
		Middle quartile	146	52	103
		Average	145	53	106
		Upper quartile	225	71	142
		Maximum	312	155	310
Seedlings flats 15 cm	5	Minimum	0	0	0
		Lower quartile	27	8	38
		Middle quartile	29	9	41
		Average	104	31	117
		Upper quartile	44	12	61
		Maximum	420	126	443

In order to be included in Table 3.6, there had to be at least four management units for a particular type, with at least 2 different operations represented. The more management units that are included in a given range, the better the data would represent the true population.

b. Discussion

Since quartile distributions are used throughout this chapter, a brief explanation of quartiles and their statistical value is given. Quartiles are a descriptive statistic for understanding the distribution of data. A quartile breaks a data set into three equal parts, with the lower quartile being the median of the lowest 25% of the values, the middle quartile is the median value of the middle 50% of the values (26-75%), and the median of the highest 25% (76-100%) of the values is the upper quartile (Ott and Longnecker 2001). Quartiles were used as a descriptive statistic because they provide more information than minimum, maximum and average values. This is especially useful for the information provided here, since the minimum and maximum values may be outliers, giving a false understanding of typical practices. Quartile values provide a better picture of the range of practices involved at different operations, and complement the minimum, average and maximum values provided.

Table 3.2 provides an example of the benefit of using the descriptive statistics of quartiles when looking at data distributions. The average and maximum values are skewed by a few management units that have a large plant density (from flats containing 30-100 plants per flat), which makes the average larger than both the middle and the upper quartile. For example, the average number of plants per hectare is given as 789,315 and the maximum value as 2,605,754 compared to the upper quartile value of 327,713. In looking at the data, there are a number of management units that have a plant density of over 1 million plants per hectare, which is typical for starter seedlings and plants in small containers such as market packs (i.e. 606, 306). The middle quartile value of 258,387 is more representative of larger container sizes such as 1L containers, for closely spaced greenhouse production in saleable containers. For most other tables though, the average and middle quartile values are similar to each other, suggesting that the values represented are not skewed due to an outlier, or a small number of MU's that are much larger and smaller than typical values. It is interesting to note that the fertilizer averages are higher than the upper quartile values, but not more than double the values like is seen for plants per hectare. This suggests that the values for fertilizer rates are a lot less skewed than the values for plants per hectare.

Table 3.3 allows for the analysis of the research hypothesis #4 stated above for greenhouse operations, which predicts that a majority of greenhouse growers are applying fertilizer ratios different from the recommended 4-1-3 ratio. A number of different N - P_2O_5 – K_2O ratios can be seen in Table 3.3, with very few applying the recommended ratio of 4-1-3 (Sammons 2008), which would be 12-3-9, 16-4-12, or 20-5-15. The fertilizer rates that corresponded most closely to the ideal 4-1-3 ratio were 17-6-12, 17-7-12, 18-5-11, 19-6-12, and 21-5-9, which represented 12 of 180 (6.6%) of the rates applied in the management units surveyed. If the parameters were expanded to look at just the N - P_2O_5 ratio, since N and P are the nutrients of concern for the Chesapeake Bay, the following additional fertilizers would be included, 15-5-15, 17-5-17, 18-6-8, 19-5-9, 20-

5-20, 20-6-21, and 20-7-20. This represents 73 (40.6%) additional management units or 85 out of 180 (47.2%) total operations with the "ideal" ratio, at least for N - P_2O_5 only.

Greenhouse operations overwhelmingly applied soluble fertilizer to their crops, representing more than 80% of the MU's, as shown in Table 3.4. This is not surprising considering that most greenhouse operations had a soluble fertilizer injector attached to irrigation lines during site visits. Soluble fertilizer is a convenient way for growers to apply nutrients to a container, and with the typically high interception efficiencies (amount of water intercepted by the container surface divided by amount applied), it is also highly efficient. Therefore the biggest concern with soluble fertilizers is leaching due to over-application of water and/or fertilizer. Fertilizer leaching can be due to applying more water than a container can hold resulting in a high leaching fraction (amount of water that comes out of the bottom of the container as a percentage of water applied), which also brings any soluble fertilizer along with it. Also, if more fertilizer is added than a plant requires without water leaching out of the container, excess fertilizer builds up in the substrate. This leads to an increased salt content which can stress the plant and cause root death until water leaching is implemented, at which point the excess fertilizer is leached out of the container. The application rate of soluble fertilizer ranged from 100-380 mg/L (parts per million) for operations applying soluble fertilizer, with most growers fertigating continuously, and some growers fertigating once out of every two to four irrigations (data not shown). Slow-release fertilizers were also reported to be used in a number of management units. Growers typically used SRF in larger and longer-term containers such as hanging baskets, mums, and slower growing perennials.

In addition to the rate and frequency of fertilizer application, the N - P_2O_5 - K_2O ratio of the fertilizer is also an important factor. As mentioned above, the recommended ratio of fertilizer based on plant uptake rates is 4-1-3. Only a small portion (6.6%) of the operations surveyed were applying a fertilizer ratio approximating the ideal 4-1-3 ratio recommended by research, with a greater number (47.2%) applying the correct N-P_2O_5 ratios (Table 3.3). Based on this information, the hypothesis would be accepted that more than 50% of greenhouse growers are typically applying an incorrect N-$_2O_5$ - K_2O ratio at their operations. If only N-P_2O_5 ratios are considered, still less than half (47.2%) of the operations are applying the correct ratios. What this means for the industry and the individual grower is that even if they are applying the correct amount of one nutrient, there is the potential for leaching of either one or both of the other major nutrients. For example, if growers are applying the correct amount of N, but they are using a 20-20-20 fertilizer, they are over applying P and K by 400% and 133% respectively.

It is important to mention that greenhouse operations typically grow several crops on the same area during the year. Many of the crops grown had a 4-12 week growth cycle, so the same area could be used for a number of rotations throughout the year. The fertilizer numbers reported in Table 3.6 for greenhouse operations might be multiplied three or five times since the same growing area can be used for several turns, easily applying more than 1000 kg / ha per year. The rates of N, P_2O_5 and K_2O are relatively high, especially when compared to agronomic crops. Peterson and Varvel (1989) for example, found that a N rate of 180 kg / ha per year produced the highest grain yield in continuously-cultivated corn. This means that greenhouse growers could easily be applying more than 5 times the rate of N applied to corn on a per hectare per year basis, although in greenhouse production the container with any nutrient included is removed at the end of the cycle, while only the leached nutrients remains behind.

Hypothesis #1 above stated that it would be possible to create recommended rates, based on data collected from operations throughout the state. Based on the ranges of N, P and K application rates collected during site visits, a "best management practice" rate can be determined for particular species based on current grower practices. Best management rates could be as low as minimum values, since these plants were grown in the same amount of time as plants fertilized at a higher rate. Since the rates listed in Table 3.6 are from the upper ranges of the numbers given by growers, it would be more likely that lower quartile or middle quartile rates could be applied, without negatively impacting plant growth. This would represent significant savings on fertilizer cost for an operation applying fertilizers at the upper part of the range. If the annuals grown in 13-15 cm containers are used as an example, the upper quartile rate is 166 kg N/ha/yr, 64 kg P_2O_5 /ha/yr and 174 kg K_2O /ha/yr compared to the lower quartile rate of 40 kg N/ha/yr, 13 kg P_2O_5 /ha/yr and 43 kg K_2O /ha/yr. This could yield significant savings on fertilizer cost for a greenhouse operation that decided to use these guidelines for reducing nutrient application. Further testing under production conditions would be recommended to determine if the application rate could be reduced even further, which would yield increased cost and environmental benefits.

ii. Container Operations

a. Results

Of the 48 operations that were visited for this research project, 27 of those operations had a container-production area, totaling 177 acres (not including roadways, buildings, vegetative buffers etc.). As with greenhouse operations, a variety of species grown, operation sizes, irrigation, nutrient, and runoff management practices were observed. A total of 155 management units were used for the analyses included below. Out of 155 management units, 125 (80.6%) were reported to use slow release fertilizer (SRF) as the only nutrient source. Six MU's reported using soluble fertilizer, three reported using a slow-release tablet that works differently from SRF, three used aquatic fertilizer for aquatic plants, and one used a foliar application of urea. The remaining 17 MU's either used a variety of different fertilizers, or were unsure of the nutrient content of their container operation (one grower received shipments of plants in from a corporate office, which already had an unknown SRF incorporated). Only five management units were reported to have two different fertilizer applications. Three MU's that received aquatic tablets were also reported to get a 30 day SRF, while two MU's received two different ratios of soluble fertilizer.

Table 3.7 gives the range of nutrient application rates for the 27 operations representing 155 MU's growing containerized plants in Maryland (Appendix C; Table C3.4 gives U.S. standard units). The minimum rate of 4 kg/ha (4 lb/acre) of N is for an operation that applies foliar nitrogen, and is the only MU represented that uses foliar application. The N : P_2O_5 : K_2O ratio reported in Table 3.7 much more closely matches the 4:1:3 ratio recommended by Sammons (2008). This can also be seen in the list of N - P_2O_5 - K_2O ratios reported in Table 3.8. Using the average values listed in Table 3.7, the ideal rate based on N would be 680-170-510 kg / ha / yr for N, P_2O_5, and K_2O respectively compared to the reported value of 680-295-417 kg / ha / yr for N, P_2O_5, and K_2O respectively.

Table 3.7. Application rates of N, P_2O_5 and K_2O based on information gathered from site visits to 27 container operations in Maryland representing 155 management units. Values in the same row are not necessarily from the same operation.

	Number of plants (MU)	**Plants/ ha**	**N kg/ha/yr**	**P_2O_5 kg/ha /yr**	**K_2O kg/ha/yr**
Minimum	20	1,236	4	0	0
Lower Quartile	1000	17,824	184	69	103
Middle Quartile	4,094	47,840	465	164	262
Average	23,984	351,374	680	295	417
Upper Quartile	18,900	178,905	855	377	547
Maximum	450,000	7,750,006	6036	6036	6036

Table 3.8 provides the N - P_2O_5 - K_2O ratios reported for the operations that were interviewed for this project, along with the frequency with which each fertilizer was applied. It can be seen that typical N - P_2O_5 - K_2O ratios are similar to the recommended 4-1-3 for a number

of fertilizers, with the most common deviation represented as a lower K_2O ratio. There were nine MU's applying 13-13-13, five applying 14-14-14, three applying 20-10-5 and 20-20-20, and one each of 4-6-4, 8-5-6, 10-10-10, and 36-0-0 as the main deviations from the 4-1-3 ratio recommended by Sammons (2008), representing 24 out of 152 or 15.8%

Table 3.8. Fertilizer ratios for the 27 container operations interviewed in Maryland with the corresponding number of management units reporting each fertilizer ratio.

Number of Management Units	Fertilizer ratio N-P_2O_5- K_2O
15	18-6-8
13	18-5-11
13	18-6-12
12	17-7-8
12	19-5-9
9	12-5-6
9	13-13-13
9	17-7-12
7	17-7-14
7	18-5-9
6	12-6-8
6	19-6-12
5	14-14-14
3	10-14-8
3	12-4-8
3	13-4-9
3	15-9-12
3	20-10-5
3	20-20-20
2	10-6-4
2	12-7-7
2	15-3-18
1	4-6-4
1	8-5-6
1	10-10-10
1	10-4-7
1	36-0-0

of the MU's. The remaining 128 MU's (84.2%) either have an acceptable N - P_2O_5 - K_2O ratio, or at least an acceptable N-P_2O_5, with the most frequent observations that the PP_2O_5 level is too high relative to N, and the K_2O level is too low, relative to N. A combined 64 (42.1%) MU's reported using either a 18-5-11, 18-6-12, 19-5-9, 17-7-12, 18-5-9, 19-6-12, 13-4-9, and 10-4-7, which are similar to the 4-1-3 ratio.

The amount of irrigation applied on a per hectare and per acre basis is reported in Table 3.9. Similar to the greenhouse irrigation rates, if a range of time was provided for irrigation, the longer irrigation timing was used, to represent the maximum amount of irrigation per application. Both spring and summer rates are reported to determine the difference in application rates during different growing seasons. Most growers typically irrigate about the same amount of time during spring and fall, so only spring and summer rates are included in Table 3.9 (data not shown).

Table 3.9. Summary spring and summer irrigation rates for container management units for 27 interviewed operations in Maryland, representing 155 management units. Numbers reported are for a single irrigation application.

	Spring		**Summer**	
	L/hectare	**Gal/acre**	**L/hectare**	**Gal/acre**
Minimum	7,335	784	7,335	784
Lower quartile	79,215	8,469	91,923	9,827
Middle quartile	132,921	14,210	228,652	24,444
Average	303,791	32,477	361,823	38,681
Upper quartile	325,615	34,810	356,149	38,075
Maximum	3,507,728	375,000	3,507,728	375,000

Spring and summer irrigation rates per application are relatively similar on a L/hectare basis. For example, the average rate applied was 303,791 L/hectare in the spring versus 361,823 L/hectare in the summer, or 84% of the summer rate. Similar trends can be seen in the lower and upper quartile, with spring rates being about 85% of summer rates. The middle quartile shows a 58.1% lower rate in the spring, compared to the summer, suggesting that growers at the extremes tend to vary their irrigation less than growers in the middle range.

Actual application rates were determined for eleven different plant type and container size combinations. Rates were determined in a similar manner to those described for the greenhouse data. Management units were sorted by plant type being grown, then by container size. Table 3.10 lists the plant type and container sizes that were included in the analysis, the number of management units that were used to derive the value (the more MU's the better the data would represent the true population), the statistical value that is represented and the kg per hectare of N, P, and K. Appendix C Table C3.5 provides standard U.S. container size and fertilizer rates in pounds per acre per year. There had to be at least four values, and two operations represented to be included in this analysis.

Table 3.10. Fertilizer rates reported by similar management units (MU's) based on information from 27 container operations in Maryland, representing 155 MU's. There had to be at least four values, and two operations represented to be included in this analysis.

Container size and plant type	MU's in value	Statistical value	Kg N/ ha/yr	Kg P_2O_5/ ha/yr	Kg K_2O/ ha/yr
Aquatic 4-27 L	8	Minimum	14	20	11
		Lower quartile	21	30	17
		Average	54	75	43
		Middle quartile	111	139	98
		Upper Quartile	145	188	124
		Maximum	352	416	321
Cuttings 98 cell flats to 8 L	9	Minimum	181	60	121
		Lower quartile	497	193	332
		Average	684	321	547
		Middle quartile	848	352	658
		Upper Quartile	947	410	780
		Maximum	2,176	896	1,792
Ericacious 4-19 L	4	Minimum	4	7	4
		Lower quartile	212	72	142
		Average	356	119	237
		Middle quartile	378	127	253
		Upper Quartile	522	174	348
		Maximum	798	266	532
Mums 4-8 L	14	Minimum	5	5	5
		Lower quartile	33	11	21
		Average	62	17	38
		Middle quartile	63	24	33
		Upper Quartile	92	34	48
		Maximum	122	50	57
Herbaceous perennials 50 cell flats to 19 L	22	Minimum	20	20	20
		Lower quartile	231	83	119
		Average	333	196	255
		Middle quartile	965	671	767
		Upper Quartile	1,108	438	695
		Maximum	6,036	6,036	6,036
Woody perennials 1-4 L	12	Minimum	47	9	54
		Lower quartile	219	94	130
		Average	577	160	280
		Middle quartile	683	302	407
		Upper Quartile	915	388	593
		Maximum	2,972	1,224	1,398

Woody perennials 8 L	22	Minimum	34	7	17
		Lower quartile	116	104	67
		Average	386	161	217
		Middle quartile	535	211	338
		Upper Quartile	709	273	382
		Maximum	1,812	604	1,208
Woody perennials 11 L	21	Minimum	22	6	11
		Lower quartile	220	95	146
		Average	667	185	340
		Middle quartile	680	251	402
		Upper Quartile	975	376	498
		Maximum	1,890	756	1,323
Woody perennials 19 L	12	Minimum	92	38	43
		Lower quartile	229	72	134
		Average	372	122	176
		Middle quartile	544	187	310
		Upper Quartile	756	252	389
		Maximum	1,753	673	1,346
Woody perennials 27 L	6	Minimum	92	38	44
		Lower quartile	193	63	112
		Average	422	135	234
		Middle quartile	462	146	248
		Upper Quartile	544	183	275
		Maximum	1,734	482	867
Woody perennials 38 L	6	Minimum	194	65	86
		Lower quartile	405	118	187
		Average	800	241	433
		Middle quartile	915	261	482
		Upper Quartile	930	258	568
		Maximum	2,448	680	1,224

b. Discussion

Unlike Table 3.2, the average rates for N, P, and K reported in Table 3.7 for container operations across all management units are in line with the quartiles that are reported. This suggests that the data are not skewed for the container operations like they were for greenhouse operations. The average rates reported in Table 3.7 of 680 kg/ha/yr N, 295 kg/ha/yr P_2O_5 and 417 kg/ha/yr K_2O are higher than the rates reported for greenhouse operations in Table 3.2, which were 253 kg/ha/yr N, 155 kg/ha/yr P_2O_5 and 254 kg/ha/yr K_2O. It is worth repeating that container nurseries typically do not have more than one rotation per year on the same area, while greenhouse operations may use the same space to grow three or more cycles of plants over the year. Greenhouses are also typically used year-round, which would increase nutrients applied per area, while container operations are usually covered for about 4 months out of the year in Maryland, at which time plants are dormant, and the only management is typically irrigation as needed inside overwintering houses. Based on this information, I would conclude that greenhouse operations apply higher rates of fertilizer on a per acre per year basis, when all of the MU's grown in the same area are accounted for. This would mean accepting hypothesis #2 which says that greenhouse operations will generally apply higher rates than container operations on a per acre per year basis. There are a number of factors that can influence this, and there are certainly some greenhouses that apply lower nutrient rates than some container operations. Both greenhouse and container operations have very high rates of fertilizer application compared to agronomic crops and field operations (which will be discussed below).

Table 3.7 shows the differences in the number of plants per hectare across the quartiles, similar to the range of values in Table 3.2. Container nursery operations reported anywhere from 1,236 to over 7.7 million plants per hectare, highlighting the impact that container spacing has on plant density. A potential problem with the greenhouse numbers is that if growers over- or under-estimated small growing areas that could lead to large differences in nutrient and water application rates when numbers were converted to a plants per acre basis.

Based on the information from Table 3.8, 84.2% of the MU's had an acceptable N - P_2O_5 - K_2O ratio, while 42.1% had an acceptable N - P_2O_5 - K_2O ratio approximating the 4-1-3 ratio recommended, compared to the greenhouse values, which were only 47.2%, and 6.6% respectively. This suggests that the ratios applied by container operations are more in line with plant uptake ratios, accepting hypothesis #4. Using a correct ratio of macronutrients will help reduce nutrient leaching and runoff, since nutrients are applied in similar ratios than they are used in the plant. These numbers do not take into account how much fertilizer is applied to each plant, only the ratio of N - P_2O_5 - K_2O in the fertilizer applied. Growers can still have nutrient runoff by over-applying the amount of fertilizer, even if the fertilizer ratio they are using is appropriate.

Greenhouse operations reported 24 different fertilizer ratios used compared to container operations, which reported 27 different ratios. In general, greenhouse operations were more likely to use different fertilizer ratios on different plants, or at different times of the year. This was often used to regulate substrate pH, or create a balanced fertilizer program for particular plants. In container operations, an operation typically applied one or a few different fertilizer N - P_2O_5 - K_2O rates, which were used on a wide variety of plant species, with different operations typically using different fertilizer blends (data not shown). In other words, SRF's tended to be operations specific, while greenhouse fertilizers tended to be more plant specific.

Container operations did tend to run irrigation systems longer in the summer compared to spring, but there was not generally a large difference between spring and summer rates per application seen in Table 3.9. The biggest difference can be seen in the rates for the middle quartile, which are almost doubled from spring to summer. This suggests that growers who irrigated with the middle rates tend to vary the length of their irrigation more during the year than growers at the high and low end. It makes sense that growers do not typically vary the amount of time a management unit is irrigated, since it is a function of container size, plant size and architecture, substrate and irrigation efficiency, which do not vary over the course of the growing season, except plant size. The major difference in irrigation application was not in amount of time the irrigation was run, but in the frequency of applications during a typical week. Spring and fall applications per week were typically less than summer applications, which were often 3-5 days per week, and 5-7 days per week respectively (data not shown). This should lead to more runoff in summer compared to spring and fall, since summer irrigation is applied more frequently, although evaporation rates are higher in the summer compared to spring and fall.

To put these numbers in perspective, numbers were converted to acre-inches of water per application. The spring lower quartile is 0.31 acre-inches per application (8469 gallons = 1132 ft^3/43560 ft^2/acre= .026 ft/acre x 12 inches/ft = 0.31 acre-inches), average is 1.2 acre-inches (4342 ft^3), and the upper quartile 1.3 acre-inches (4653 ft^3). This agrees with numbers from Warren and Bilderback (2004) who gave a range of 0.8 cm – 3.3 cm (0.3-1.3 acre-inches) as typical daily irrigation depth in container operations, based on a survey of growers in the Southeast United States. When this is compared with recommended rates for in-ground plant production, which is typically about 1 acre-inch per week, container operations can use more than 7 times the weekly rate of in-ground plants, especially in the summer. These larger, and more frequent irrigation applications per week would have an impact on nutrient and sediment runoff in container operations. This is especially true given the fact that SRF's release nutrients at a higher rate as temperature increases above the typical test rate of 21°C (70°F) (Cabrera 1997; Huett and Gogel 2000). Summer temperatures and more frequent irrigation scheduling would most likely lead to a greater potential for nutrient runoff during this time of year, compared to spring and fall, especially if fertilizers are applied at a rate above plant requirements.

Table 3.5 and Table 3.9 show the differences in irrigation amounts per application between greenhouse and container operations respectively. Greenhouse operations applied less than half as much irrigation on a per hectare basis compared to container operations across all quartiles for both spring and summer irrigation for container operations. Based on this information I would accept hypothesis #3, which says that container operations use more water per application per hectare compared to greenhouse operations. It is surprising that container operations use more than twice as much water per hectare, especially at tight spacings, which should have high interception efficiencies. This is perhaps due to the larger container sizes, which require more water to completely bring the container up to capacity. In addition, container operations most likely have lower interception efficiencies using overhead irrigation compared to the more precise irrigation used in greenhouse operations, even at close spacings. There are also environmental factors such as wind and higher evaporation rates outside, which may require longer irrigations times to sufficiently wet containers.

Table 3.10 provides nutrient application ranges for eleven different types of plants and container sizes. The rates reported for aquatic plants and mums are lower than the rates reported for all other plant types averaging 54 kg/ha/yr N, 75 kg/ha/yr P_2O_5, and 43 kg/ha/yr K_2O and 62 kg/ha/yr N, 17 kg/ha/yr P_2O_5, and 38 kg/ha/yr K_2O respectively. Ericaceous plants averaged 356 kg/ha/yr N, 119 kg/ha/yr P_2O_5 and 237 kg/ha/yr K_2O, which is a relatively low rate compared to the other rates reported for woody plants. This is reasonable since ericaceous plants are typically considered low nutrient using plants. Woody perennials did not seem to have a correlation between container size, and application rate. Average rates varied between 372- 800 kg/ha/yr N, 122-241 kg/ha/yr P_2O_5, and 176-433 kg/ha/yr K_2O for 1 L to 38 L woody perennials, which encompassed a variety of species grown. There does not appear to be a trend among woody plants, with average rates differing between container sizes. This suggests that the application rate of fertilizer per container is based on factors other than container size, such as grower preference, or rate suggestions from fertilizer companies. Most growers applied fertilizer based on container size and not on the species being grown (data not shown). The numbers above are not sorted by container spacing, which is an important factor to consider, but in general similar container sizes had similar spacings (data not shown). Based on the information in Table 3.10, it is possible for growers to reduce nutrient application rates for particular types of plants or container sizes, since a variety of rates are used for similar container sizes with similar results. Growers should be able to apply a recommended rate somewhere between the lower and middle quartiles and still achieve maximal plant growth while minimizing nutrient runoff during water leaching events. This would decrease nutrient application rates, and therefore nutrient runoff, particularly for operations applying upper quartile rates.

iii. Field data

a. Results

Field operations typically require less care and maintenance compared to containerized plants, since plants are better buffered from nutrient, water, and temperature extremes. The tradeoff is a longer growing period, compared to container plants. This trend was evident in the field operations that are presented below. A total of 17 field operations were visited in Maryland, with a reported 96 management units, covering approximately 1050 acres of growing area (not including roads, buildings etc.). A wide variety trees and shrubs were grown anywhere from 1-16 years until maturity, with a typical range of 4-8 years (see Appendix C Table C3.6 for additional information). All operations that were visited had vegetative buffers between rows, and were all grassed at the end of rows to minimize soil erosion loss, which is considered a best management practice. The average spacing in field operations was 1.7 m x 2.6 m (5.5' x 8.6'), and ranged from 0.9 m to 2.4 m (3ft – 8 ft) in row and 0.9 m to 3.4 m (3ft-11ft) between rows (excluding seedling beds).

For applying irrigation, three management units used traveling guns, five used overhead impact sprinklers, seven MU's were reported to not use any irrigation and one used a garden hose. The remaining 76 MU's use either drip or pressure compensating drip emitters. It is worth mentioning that one operation contributed 58 MU's and 441acres to the total, which represents 42% of the total area recorded. This operation reported similar management of each MU, except there were differences in plant spacing, and the amount of fertilizer applied per acre. Management units were not consolidated in the spreadsheets, like they were for many other operations. Some of the data below does report the 58 MU's as one or two MU's, which is noted in their respective sections.

Out of the management units that applied fertilizer, 70 out of 89 MU's (78.7%), used solid (dry chemical) fertilizer, with four of those operations additionally mixing in a biosolid (compost, manure, "green manure" etc.). Seven (7.9%) MU's applied soluble fertilizer through drip lines. Another seven used various forms of slow release (i.e. agritabs) that were added at the time of planting and were supposed to release nutrients over several growing seasons, with three of those operations also mixing in biosolid at the time of planting. Four MU's (4.5%) used biosolid only, and one (1.1%) MU reported applying foliar urea. Seven (7.9%) management units reported not apply any type of fertilizer.

Since a single operation applied 20-8-8, for the following analyses, it is going to be treated as a single MU. Using Table 3.11, only one fertilizer rate, 12-3-10, is similar to the 4-1-3 (N -P_2O_5 - K_2O) ratio recommended for plants, which was used in 2 MU's out of 28 (7.1%) (Sammons 2008). The following ratios were considered acceptable, using only the N:P_2O_5 ratio; 20-8-8, 16-8-8, 14-4-6, and 33-3-6. This resulted in an additional 5 MU's (17.9%) applying acceptable ratios of N-P_2O_5. From this information, less than 50% of the MU's surveyed for field operations apply fertilizers with at least one nutrient in excess of the 4-1-3 ratio, accepting hypothesis 4 for field operations.

Field operations typically reported applying irrigation 10 times a year or less (see Appendix C Table C3.6 for additional irrigation application information by MU). Most operations also reported only applying irrigation for the first few years while a plant is being established to promote maximum growth during this important time. Once plants are established, they were reportedly not irrigated, or irrigated only during prolonged droughts (data not shown). Table 3.12 gives irrigation volume, when field-grown plants were irrigated. The one operation which had 58 management units were consolidated into two management units, representing the two different in and between row spacings used at the operation, which impacted irrigation application rates.

Table 3.11. Fertilizer ratio of applied fertilizers for 17 field operations representing 28 management units, for operations site visited in Maryland. (Note: The 58 MU's that applied 20-8-8 are all part of the same operation, and were combined into 1 MU.)

N- P_2O_5- K_2O ratio	Number of MU's reporting fertilizer rate
20-0-0	4
8-0-0	3
10-10-10	3
15.5-0-0	3
4-6-4	2
10-20-10	2
12-3-10	2
16-8-8	2
5-3-3	1
5-10-5	1
14-4-6	1
25-15-15	1
20-8-8	1
33-3-6	1
36-0-0	1
None	7

Table 3.12. Irrigation volumes per application on a per area basis for 29 management units in Maryland, based on site visits to 17 field operations in the state.

	Liters/hectare	**Gallons/acre**
Minimum	5,612	600
Lower quartile	32,597	3,485
Average	105,174	11,244
Middle quartile	42,783	4,574
Upper quartile	128,349	13,721
Maximum	499,815	53,434

Information about N, PP_2O_5, and K_2O application rates are given in Table 3.13. One operation with a single MU growing zoysia grass was removed, since there were no other similar operations which to compare it. Three MU's growing seedlings were included in the initial analysis, but are not included in Table 3.13. Average application rates varied from 28 to 77 kg/ha/yr for N, 6 to 24 kg/ha/yr for P_2O_5, and 13 to 27 kg/ha/yr for K_2O. In order to be included in Table 3.13, there had to be at least four MU's, and two operations represented.

b. Discussion

Of the operations that applied fertilizer, there was no clear pattern of fertilizer ratio or rate used correlated to specific species or management practices (Appendix C Table C3.7 lists MU's with corresponding nutrient rates). It is important to keep in mind that native soils with clay and loam have a higher anion and cation exchange capacity, and are able to adsorb P and K ions better than soilless substrates. Since field growers are required by the Maryland Department of Agriculture to keep yearly soil samples to show they are not over-applying P to their soils, the different rates applied might be due to soil test results. This is unlikely considering only two growers specified that they applied a fertilizer with no or low P due to soil test results, both of which had high P values present in soil. Many of the operations applied higher ratios of N compared to P_2O_5 and K_2O, which is reasonable considering N leaches more easily through the soil profile compared to P and K ions. After talking with growers, anecdotally I would conclude that the main difference in fertilizer rate is due to grower preference for a particular fertilizer N - P_2O_5 - K_2O ratio and application rate, except in a few operations that are using specific soil test information to inform their nutrient management decisions.

The rates reported in Table 3.13 are relatively low when compared to the greenhouse and container rates given above, and rates reported for agronomic crops. Average rates across operations listed in Table 3.13 are 50 kg/ha or less except for one N rate reported at 77 kg/ha/yr. Even at the highest rates seen, 203 kg N/ha/yr, 305 kg P_2O_5/ha/yr, and 252 kg K_2O /ha/yr are consistent with the upper ranges applied to corn, although this rate would be considered excessive compared with the numbers reported here for the majority of species grown. Based on this information, a rate of 25-50 kg/ha /yr N, 6-15 kg/ha/yr P_2O_5, and 20- 40 kg/ha/yr K_2O is recommended for all in-ground woody plants, based on the information provided in Table 3.13. Given the low rates of N, P_2O_5 and K_2O applied, it is likely that most field operations are not a significant source of N and P runoff into the Chesapeake Bay. Also, nutrient and sediment runoff is also likely minimal due to good management practices that were reported above such as grass buffer strips between rows, and grass strips at the end of rows, which were seen at

Table 3.13. Fertilizer application rates reported by 17 growers during site visits, representing 92 management units.

Plant type	MU's represented		Kg N/ ha/yr	Kg P_2O_5/ ha/yr	Kg K_2O /ha/yr
Deciduous	6	Minimum	0	0	0
		lower quartile	20	0	0
		middle quartile	28	9	9
		Average	41	12	26
		upper quartile	34	21	21
		Maximum	137	30	114
Evergreen	13	Minimum	0	0	0
		lower quartile	0	0	0
		middle quartile	7	0	0
		average	28	6	13
		upper quartile	28	9	17
		maximum	160	34	106
Mixed	73	minimum	0	0	0
		lower quartile	38	9	9
		middle quartile	67	19	19
		average	77	24	27
		upper quartile	107	26	26
		maximum	203	305	252

all operations that were visited. The biggest concern in these types of operations is what happens when mature plants are removed, and new plants are established in a row. If rainfall occurs while rows are being prepared for a new planting, this could lead to a greater chance of sediment and nutrient loss, compared to after rows are established. If the 17 operations that were site visited are representative of the field operations in the state, it is likely that field operations are not a significant contributor to nutrient and sediment loading to the Chesapeake Bay.

Irrigation for field operations was markedly different from greenhouse and container operations. Containerized plants typically require irrigation a few times a week to daily during the active growing season, resulting in high volumes of irrigation. Field plants on the other hand are typically only irrigated when they are newly planted, in order to establish plants and promote rapid growth early, or under drought conditions for established plants. The average application rate of 42,783 L/hectare (11,244 gallons/acre) reported in Table 3.12 equals an application of 0.41 acre inches of water. Since most water is applied as drip, if we assume that only half of the area in a management unit is wet from the drip lines (since application is more precise than overhead), that is 0.82 acre inches of water to actual growing areas. Since most field growers do not apply irrigation more often than once a week, this average rate is close to the recommended rate of 1 acre-inch per week. Field operations likely do not apply excess amounts of irrigation, so any erosion loss of sediment and nutrients would be due to rainfall events, which as mentioned above would most likely be limited to the time when new rows are being established.

Chapter 4: Greenhouse Model

A. Introduction

Greenhouse operations allow for a higher level of management and control compared to container and field operations. Greenhouses are covered structures which exclude rainfall and wind, which allows for more precise irrigation and fertilization compared to container and field nursery operations. Greenhouses also have some ability to regulate temperature and relative humidity, which allows for better control of the growing environment compared to container and field operations. They provide growers with a number of advantages over container and field operations, but also a different set of challenges. In this chapter, I will discuss the process of developing the greenhouse model so that it matched, as closely as possible, the unique qualities of greenhouse operations. The different factors involved in modeling greenhouse operations will be discussed, and the results of running a variety of model scenarios are provided.

B. Materials and Methods - Model development

General model development was discussed in Chapter 2. Below, specific information regarding the development and validation of the greenhouse model will be discussed for several important processes in the model. All of the values in the model represent a single container in the management unit (except in specific cases where summary information is being provided), and any inputs such as irrigation that are applied uniformly to a management unit are calculated and applied on a per plant basis. The models differentiate between P_2O_5 that is applied in fertilizer, and P that is taken up by the plants, so these different forms of phosphorus will be clearly distinguished throughout this chapter, as well as in Chapters 5 and 6.

Each of the models described are intended to provide growers and researchers with an understanding of how specific water and nutrient management practices impact plant growth, nutrient uptake and water use, and how those practices impact resulting losses and inefficiencies. Models are not meant to specifically indicate when a crop should be irrigated, or how much water or fertilizer to apply in a certain situation, or on a daily basis. The greenhouse model was set to run on a weekly time-step, to reduce complexity, but provide quality information. This was done to simplify inputs, and should not have a significant impact on the overall predictive results, merely on precision. By varying inputs weekly, the number of inputs that needed to be changed for input graphs, such as days irrigated per week is reduced (Figure 4.1). The models are designed to use actual grower management practices, validated with the latest research, to provide information on how management decisions effect plant growth, irrigation and nutrient efficiency, and leaching loss.

i. Nitrogen

As previously noted in the review of the literature (Chapter 1), nutrients move with irrigation water and in many greenhouse operations nutrients are often delivered to a plant as soluble fertilizer delivered through the irrigation system, via fertigation. Fertigation is an efficient way of providing nutrients to growing plants, but when water and nutrients are applied in excess it can also easily lead to nutrient runoff through water leaching. Figure 4.2 provides an image from the model layer of the various inputs and outputs that are used in the greenhouse model for nitrogen (N). The variables will be discussed roughly in order from left to right. Liters per hour per emitter (LPH per emitter) multiplied by the number of emitters in the management unit gives the liters per minute for the whole management unit. This is then multiplied by the minutes of irrigation applied per day (which may be varied during the growing period using the graph input device on the interface layer of the model (Figure 4.1)) to give the liters applied / management unit / day. This value is then divided by the number of plants in the management unit (MU) to give liters applied per plant per application, since the model runs on a per plant basis and not on a management unit basis. This factor takes into account different methods of irrigating, and different number of sprinklers/ emitters in a MU, so that irrigation on a per plant basis can be calculated. Liters applied is then multiplied by the N rate in mg/L (parts per million) to get milligrams of N applied. This N is then transferred into the container as many times as the plants are fertigated per week. This is accomplished with a “pulse” function, which adds the mg of N at equal intervals during the week, depending on fertigation frequency. If plants are fertigated every day, then the pulse happens daily, whereas if they are fertigated 3 times a week, it would happen perhaps Monday, Thursday, and Saturday. As the plants grow, the grower can change fertigation during the growing period on a weekly basis to match actual practice. Fertigation frequency is varied using the graph input on the interface layer to match actual practices, (see Figure 4.1 for an image of the interface layer listing all variables that can be controlled by the user). The interface layer includes three different types of input devices. Graphical input devices, allow the user to change values on a weekly basis, such as irrigation length, days irrigated/ fertigated per week, plant water and nutrient uptake, and temperature effect. A sliding bar is used for the percent of runoff recycled, and interception efficiencies, since these values remain constant during the run, and have a range between 0 and 1. The table inputs (Figure 4.1 right side) are values that remain constant during a run, and include general management unit (MU) information, and information for N, P and water inputs into the model.

Interception efficiency allows us to divide overhead applied nutrients into the container or onto the ground. If interception efficiency is set to less than 100%, the amount of N that is applied overhead to the crop is split between the container and the ground by multiplying by interception efficiency or the reciprocal function (i.e. 1-interception efficiency), respectively. In Figure 4.2, both the unintercepted nitrogen (1-IE) and any N that is applied above the container holding capacity of the container (leached N) are transferred into the stock labeled “N mg leachate accumulation”, which represents the accumulated N that could runoff an operation. The user should be made aware that this stock is not exclusively leached N, but represents unintercepted N as well. The greenhouse model does not determine if this N goes into the ground, or is transported

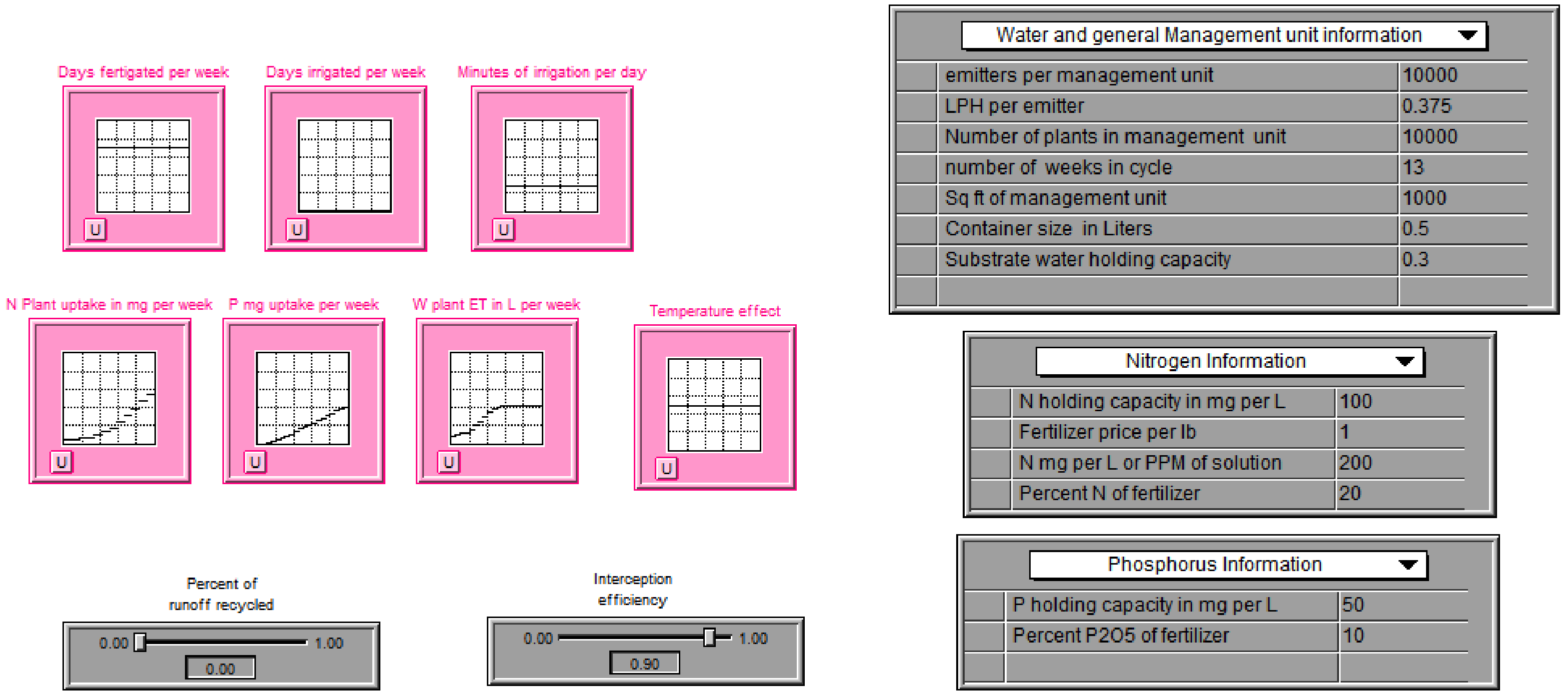

Figure 4.1. Interface layer graphic, which includes graphical inputs for values that change during a run (minutes of irrigation per day, days irrigated per week etc.) on the left (in pink), slider bars for adjusting runoff recycling (%) and interception efficiency on the bottom left, and inputs for general management, nitrogen, phosphorus, and water values that remain constant during a run on the right.

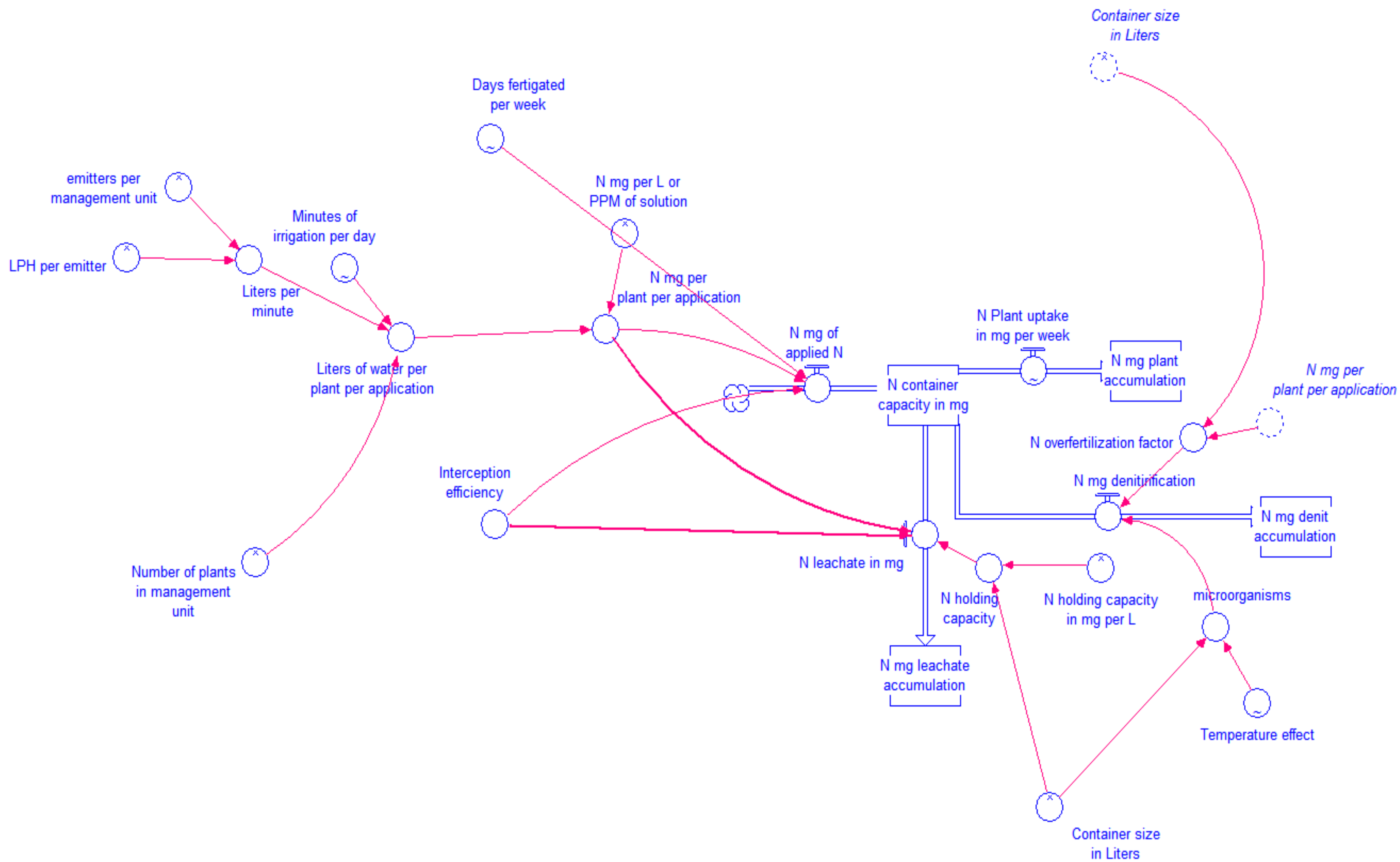

Figure 4.2. Model layer visualization of greenhouse model nitrogen inputs and outputs. Circles are converters, squares are stocks, arrows are connectors, and circles with bars on top (with arrows) are flows.

by surface water flow. At this point, the nitrogen that *is* intercepted is now transferred into the container (N container capacity in mg). If more N is applied than can be stored by the container (which is determined based on container size multiplied by substrate N holding capacity in mg/L, and is also dependent on how much N was in the container before N addition), it leaches out of the container. In an actual container, excess water over container capacity must be applied in order for N to leach.

Currently, the water, nitrogen and phosphorus subroutines are not linked nor do they interact in the model, so over-applying water does not lead to additional N leaching over container capacity N. The model leaches only the N that is applied above the containers N holding capacity, regardless of whether excess water is applied at that time. The model assumes that enough water is applied so this leaching occurs. This assumption is likely to be accurate, for all but the driest growers in the industry. A leaching fraction of 10-20% is considered a best management practice in low pressure/low volume systems (Bilderback and Lorscheider 2007a); however, lower leaching fractions are more efficient, as long as salt concentrations (EC) does not rise too high in the substrate. It is likely that most growers are leaching at least several times over the crop cycle, or at minimum monitoring electrical conductivity (EC) levels, and leaching when salt concentrations are too high. When leaching does occur, excess nutrients over container capacity, should be released from the container. Under most greenhouse conditions, this separation of N leaching and water leaching should not be a problem, but it is something that the user should be made aware.

Once nitrogen is in the container, it can be used by the plants for growth or by microorganisms for denitrification. Plant nitrogen uptake can be controlled by the user on the interface layer using the graphical input device for N uptake (Figure 4.1). This allows the user to adjust nitrogen uptake on a weekly basis. Since N uptake is one of the main drivers of the nitrogen portion in the model, it is important for this factor to be as accurate as possible in the model. There are a number of sources available for accurate N uptake information. The numbers available from Ku and Hershey (1997a, 1997b) should be valid for greenhouse-grown poinsettias (and potentially mums), while the values reported for azalea (Ristvey et al. 2007) should be similar for other ericaceous greenhouse plants as well. El-Jaoual and Cox (1998) report an N uptake rate of 1.1 g in New Guinea impatiens, and .5 g of N uptake for marigold over a 70 day period, with marigold uptake rate higher in the early part of the growing cycle, and impatiens uptake higher later in the cycle. The range between the marigold and impatiens numbers (0.5-1.1g) would likely be useful in a number of short production bedding plants such as pansies and geraniums. In addition, any research publishing dry weight for a species could also be used. Nitrogen typically makes up 2-3% of the dry weight of most plants, so this could be used as a guide for plants that have dry weights reported (Dole and Wilkins 1999). It is important for the N uptake to be distributed over the course of the run, with the grower using their knowledge of the plant as guidance. For example, plants grown from seeds are likely to have much lower uptakes at the beginning of the run while plants are getting established, with higher uptakes at the end, while plants started from plugs are likely to get established and continue growing much more quickly. For the model, actual plant uptake on a weekly basis was not available in any of the model runs. General growth trends were used to extrapolate weekly plant uptake based on the total N uptake reported, with model values similar to those reported (see results section below).

Plant uptake is typically a relatively small amount of overall N applied, and there is likely a range of N uptake values that could be used each week without reducing overall N uptake, as long as the total N uptake is correct. The model should allow for flexibility in N uptake, while still providing accurate results, since N stored in the substrate is available for future use.

It is important to understand that when weekly plant uptake of N, P, or water are inputted into the interface layer, that represents the maximum uptake level over that week. If the container has a shortage any time over that period, less nutrient or water will be taken up during the time of the shortage, and the program will not compensate for the lost amount of nutrient or water when it is in abundance, as a plant would in reality. Plants are able to adjust for periods of lower nutrient uptake by increased growth when nutrients are abundant, which is not currently replicated in the models. Fortunately, growers aim to apply sufficient (or excess) nutrients and water, so plants should not be in a deficit situation at any time during production, especially in greenhouse production, which is typically monitored very closely.

Denitrification is the last process that will be discussed with regards to N in the model. As discussed in Chapter 1, denitrification is a complex process and is impacted by many factors. This causes the rate of denitrification to change constantly, depending on ambient conditions in the container, specifically with regards to temperature and carbon availability. As discussed previously, there is a paucity of information regarding denitrification in the greenhouse environment. The numbers used in the model represent the best information that is currently available but this sub-process could be improved with more research.

Agner (2003) found a variety of denitrification rates in the same soilless substrate by varying plant age, nitrogen level, carbon content (by adding glucose), substrate compaction, and temperature. The model does take temperature into account, since it is known and controlled by the grower within limits, and the amount of N in the substrate, since it can be determined. A baseline rate of 20 µg/pot/hr for a 0.33 L (0.7 pint) container from Agner (2003) was used as the starting point for the model. It was assumed that denitrification was occurring 50% of the time in the substrate, or a total of 84 hours per week. If this is scaled up to a 1 L container that would be 20 µg/0.33 L/hr = 61 µg/L/hr x 84 hours of denitrification per week = 5.1 mg/ Liter/ week. This value of 5.1 mg/L/week was therefore used as the baseline for the model, when N is at 20% of container capacity or less. This factor is scaled up with container size, by multiplying 5.1 mg/L/week by container size in liters. When N is greater than 20% of container capacity the denitrification rate is increased to 25.5 mg/L/week, which is the highest rate reported by Agner (2003), multiplied by the ratio of N in the container / total N holding capacity (which represents the relative abundance of N). It should be noted that there have been a number of studies that have shown higher rates of denitrification at higher N concentrations (Firestone et al. 1979; Haider et al. 1987; Daum and Schenk 1996; Cabrera 2003), but we decided to be relatively conservative with this loss mechanism in the model, given the uncertainties.

There have also been a number of studies that show higher rates of denitrification at higher temperatures, with a Q_{10} ranging from 1.6 to 2.4 for temperatures ranging from 10 – 60 °C (Dawson and Murphy 1972; Stanford et al. 1975; Nommik and Larsson 1989). The Q_{10} value is the difference in rate constants for a 10 °C temperature difference. A Q_{10} of 2 means that for every 10 °C change in temperature, the rate increases or decreases by a factor of 2, so in the baseline above, a temperature of 31 °C would yield a rate of 10.2 mg/L/week instead of 5.1 mg/L/week. A Q_{10} of 2 was used in the model with a baseline of 21 °C (70 °F). Together, N availability and temperature values closely matched published results (see below) although additional testing would be beneficial to further refine denitrification values.

ii. Phosphorus

Phosphorus (P) was the other major nutrient modeled, due to its importance not only in the plant, but also its impact on the aquatic environment when it enters surface waters. In the greenhouse model, P enters the container in the same way as was described for N, i.e. through irrigation, although it is recognized that some operations may pre-incorporate P in the substrate (Figure 4.3). It is important to note that the models differentiate between P_2O_5 from fertilizer and actual P uptake by plants (i.e. what is reported when plants are analyzed). In order to account for this difference, P_2O_5 is used as an input from fertilizer, and is converted by the model to P. Conversion occurs when the P is added to the container or is leached, by multiplying the P_2O_5 amount applied by 0.4324 to convert P_2O_5 to P. All values after this conversion represent P not P_2O_5. Excess P that is applied over the holding capacity of the container, which is determined by multiplying container size in liters by P holding capacity in mg/L, is leached out of the container.

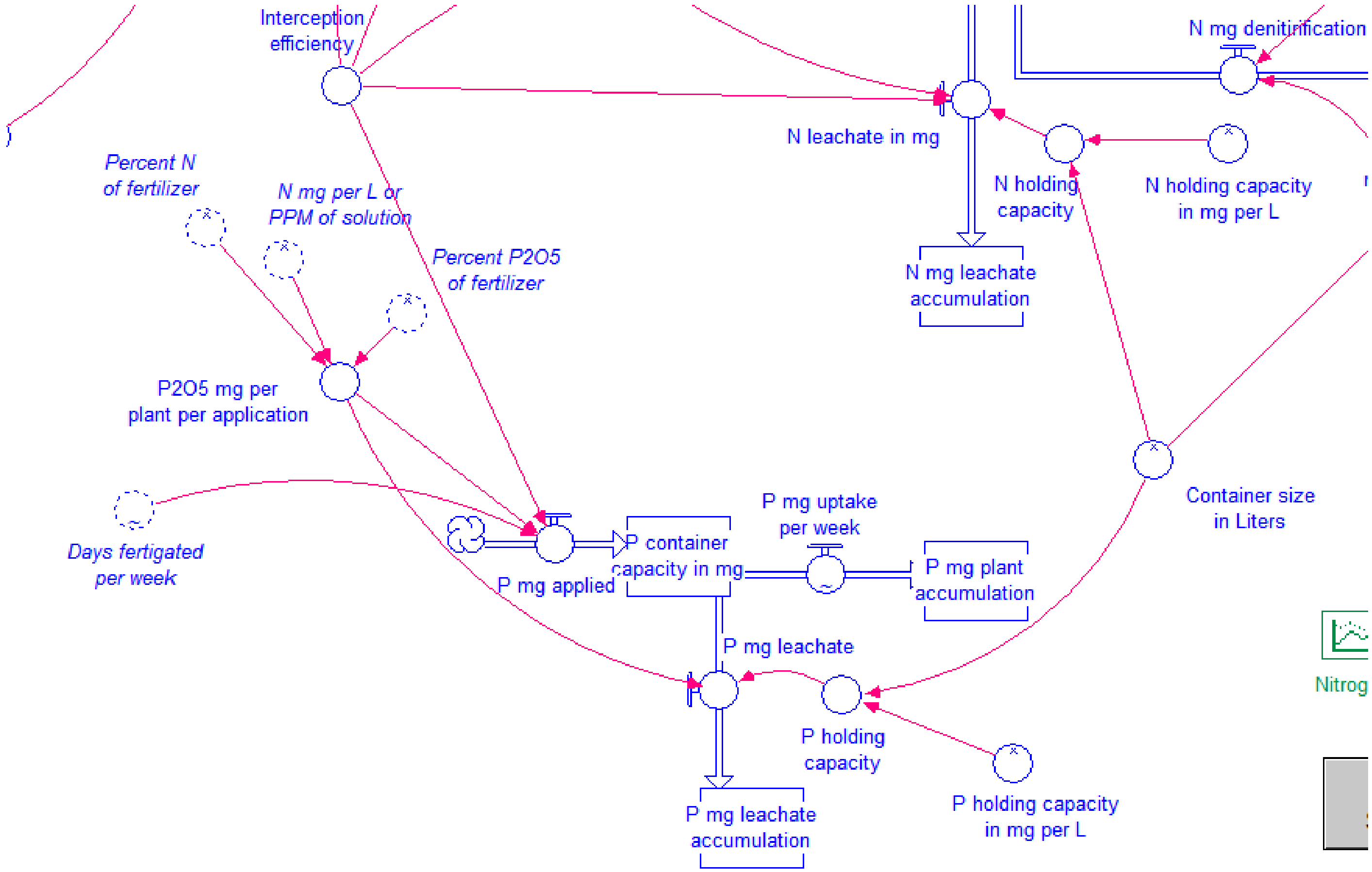

Figure 4.3. Model layer visualization of greenhouse model phosphorus inputs and outputs. Circles are converters, squares are stocks, arrows are connectors, and circles with bars on top (with arrows) are flows.

P remains in the substrate until it is either leached, is used for microbial growth or is removed by plant growth. It is likely that some P is used for microbial growth, but there we found no values in the literature for how much microbial growth might deplete P stores; we assumed a relatively low value of 0.075 times the amount of P in the container over the course of the week was used (i.e. 7.5% of available P). This is a factor that should be updated in the model with better research. Soluble fertilize is typically added as mg per liter (parts per million, ppm) of N. By using mg/l of N and the N:P ratio from the bag of fertilizer, the mg/l of P can be determined using the formula mg/l N x percent P/ percent N.

iii. Water

Water inputs into the model are similar to N and P, since the irrigation system is used to transport nutrients into the container. This model uses liters of water per plant per application to determine the volume of water applied to the container. To determine irrigation frequency, both days irrigated per week and days fertigated per week are used to pulse irrigation into the container, similar to fertigation pulses used for N and P. The drawback of using separate pulses for irrigation and fertigation is that there is no way for the program to separate the pulses so that irrigation and fertigation should not happen on the same day. For example, if the grower both fertigates and irrigates 3 days a week (6 irrigation events) the program will add water and fertigation on the same 3 days. One of the inadequacies of the Stella model was that there was no way to only add one or the other on any given day, without severely compromising another area in the model. I had a discussion with Stella technical support about mitigating this problem, and they were unaware of a viable software solution at this time. The net effect is that any time plants are both irrigated and fertigated either an even or odd number of times during a given week, the program may add both volumes at the same time. This will lead to an artificially high level of leaching if the user is not aware of this limitation. Many of the growers interviewed fertigated continuously, so this should not be an issue in most greenhouse operations. If a grower fertigates intermittently, it would be important for them to adjust their irrigation or fertigation inputs to avoid having both even or both odd irrigation and fertigation scheduling in the same week (e.g. it should be 3 fertigations and 4 irrigations).

Interception efficiency (as defined in the models) impacts the amount of water delivered to the container and therefore impacts water leaching (which is the transport mechanism for nutrients), similar to that described for N and P. The total amount of water applied to the container area (the area allotted to each container consisting of both the surface area of the container and the portion of ground, or bed area, for each plant) is multiplied by IE. This determines how much of the water goes to the container. To determine the amount of water that is unintercepted (i.e. goes directly into the "Water leached L accumulation" stock) the amount of water that is applied to the total area for the container is multiplied by 1-IE (Figure 4.4). This stock contains both the water that leached out the bottom of the container, and the water that was unintercepted (never went

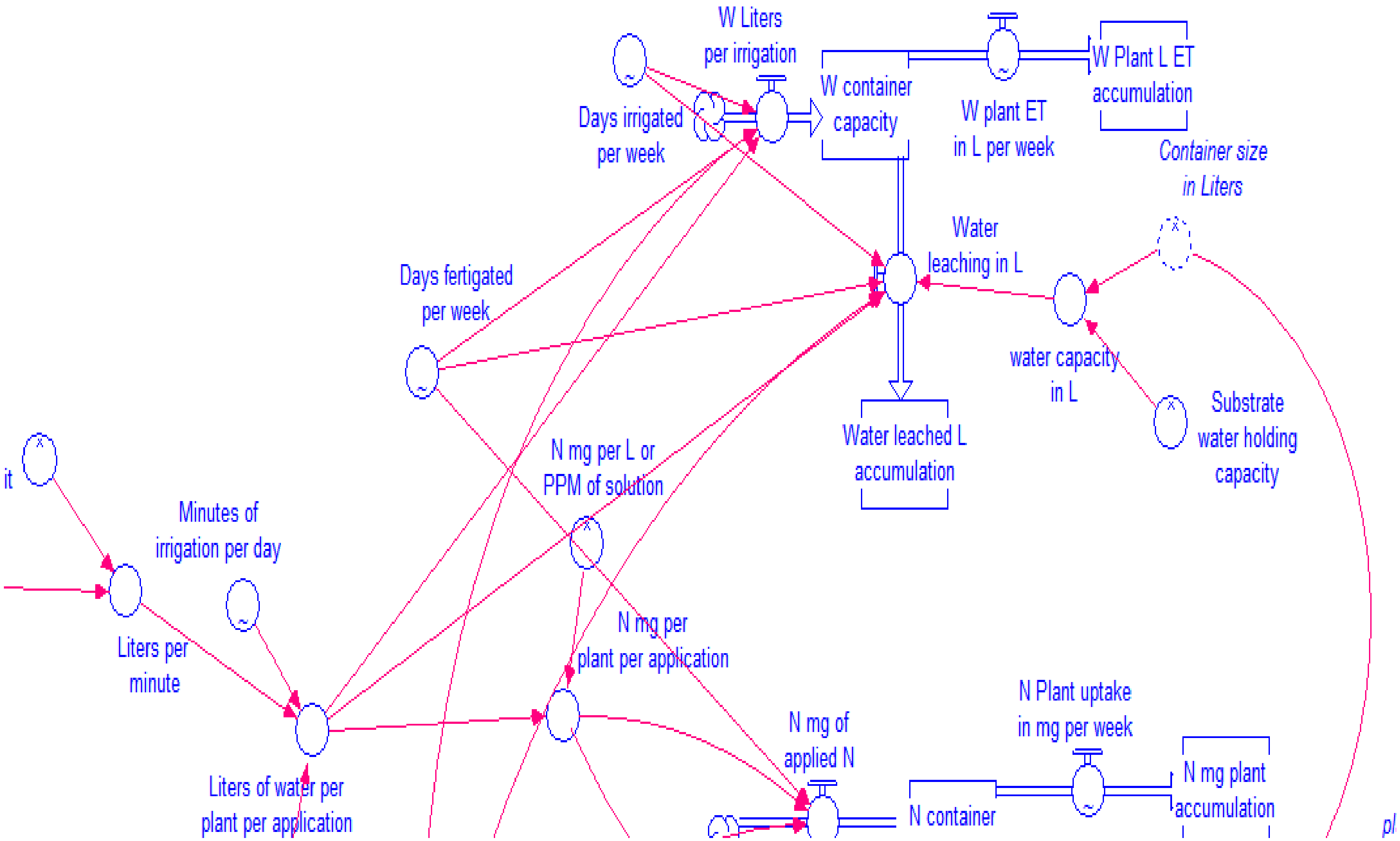

Figure 4.4. Model layer visualization of greenhouse model water inputs and outputs. Circles are converters, squares are stocks, arrows are connectors, and circles with bars on top (with arrows) are flows.

into the container). The total amount of water a container can hold is determined by container size, and the substrate water holding capacity in liters. Water that is applied above the holding capacity of the container is immediately transferred to leachate. Water in the container is removed by evapotranspiration. In a greenhouse environment, there is likely to be a small range of ET values compared to container and field operations, especially when plants are small. van Iersel (2010) showed that four bedding plants (*Impatiens* 'Accent Coral Star', *Dianthus* 'Chiba Strawberry', P*etunia* 'Dreams Burgundy' and *Ageratum* 'Blue Danube') grown at volumetric water contents from 0.10 to 0.45 m^3 x m^{-3} used similar amounts of water per day regardless of species, when water was supplied at optimal levels, which should be the case for greenhouse operations. Daily light integral was also found to have a significant impact on plant water use, but this factor was not included in the model due to the complexity involved in incorporating this variable into the model, since it is based on real-time information, which is not incorporated into these models. Future models may incorporate daily light integral, which would help models to be more predictive of when to irrigate plants.

iv. Additional calculations

Additional calculations, shown in Figure 4.5a and Figure 4.5b, were used in the greenhouse model to create summary calculations. The summary values for N and P application rates are given in pounds per acre. These units were used since these are the

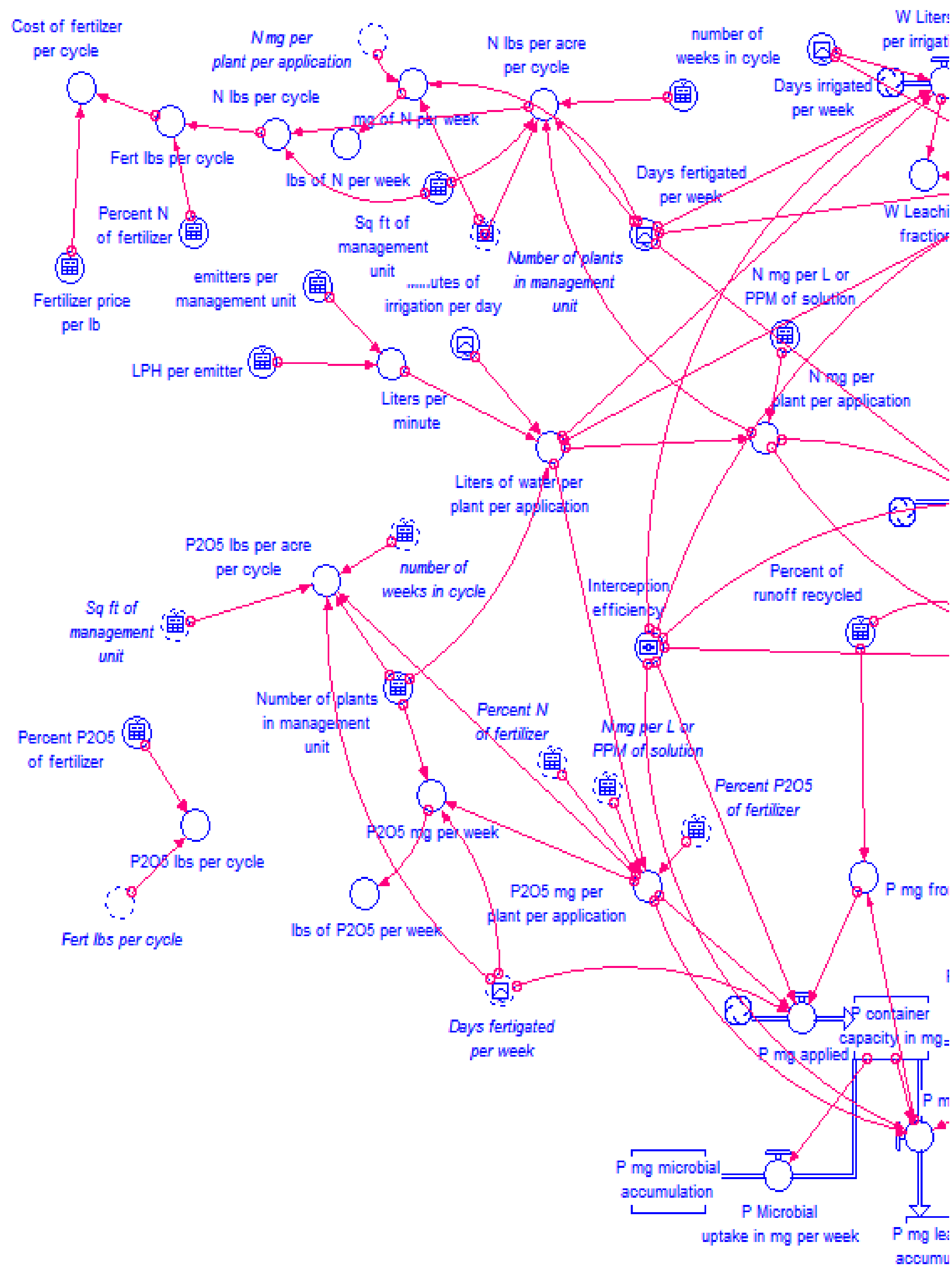

Figure 4.5a. Complete (with Figure 4.5b) greenhouse modeling layer, showing the interactions between variables. Circles are converters, squares are stocks, arrows are connectors, and circles with bars on top (with arrows) are flows.

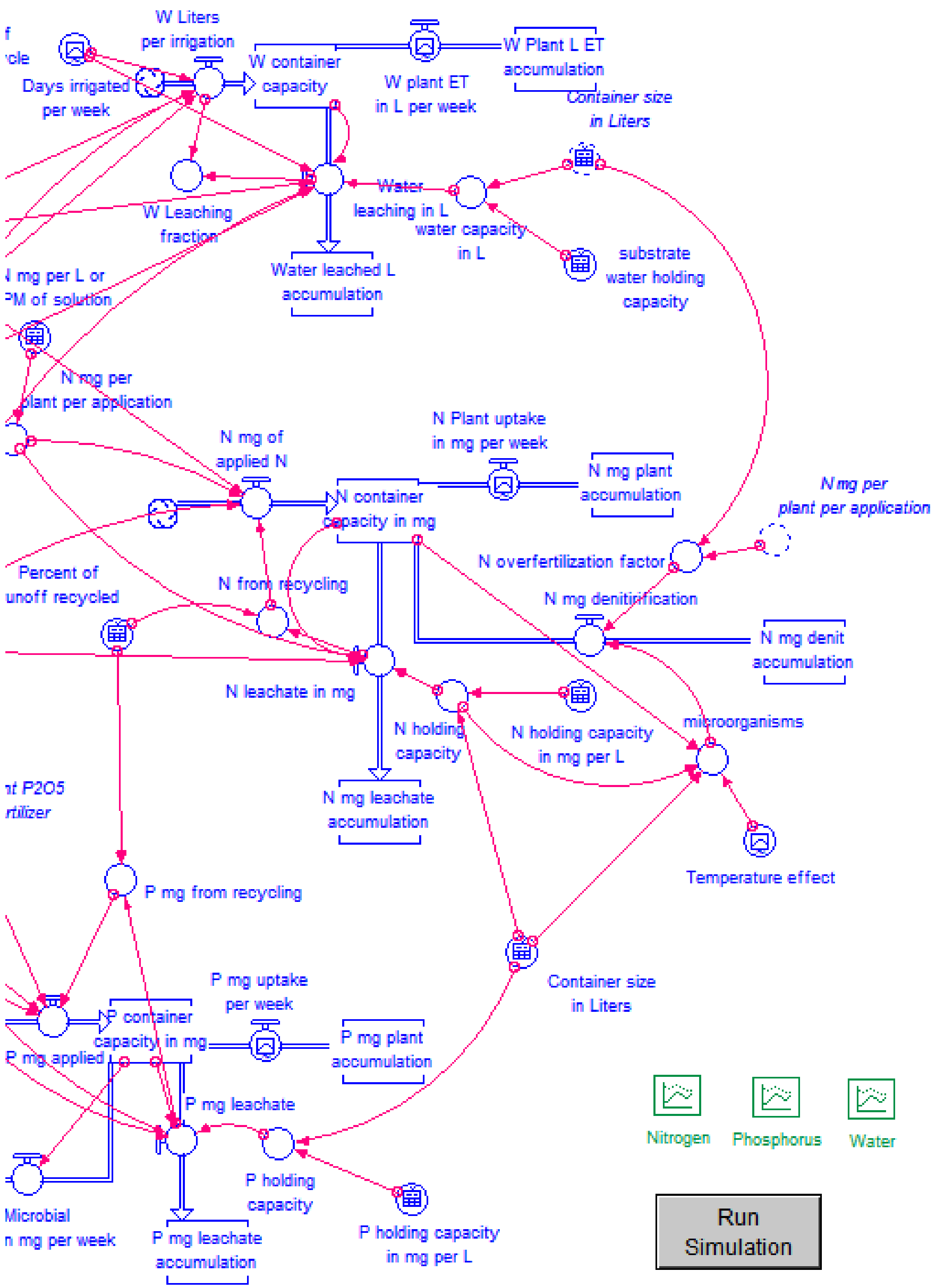

Figure 4.5b. Complete (with Figure 4.5a) greenhouse modeling layer, showing the interactions between variables. Circles are converters, squares are stocks, arrows are connectors, and circles with bars on top (with arrows) are flows.

units most growers in the United States are familiar with, and can understand compared to kg/hectare, which may be unfamiliar to them. The other model outputs are reported in metric units, since they are the units used in the model for all calculations. Any values that are input as standard units on the interface layer are converted in Stella to metric units. Pounds of N and P per acre per cycle give the grower an understanding of the impact of current fertilization practices, and how changing a practice impacts fertilizer application rate, in addition to nutrient runoff rate, which is reported with N values. The values for pounds per acre for N and P are not calculated directly, since they can change on a weekly basis in the operation, depending on fertigation length and frequency. In order to calculate this factor, the average N and P rate over the growing period is used, which takes the variation of application rates over the weeks into account. All of these values are summarized and calculated using an excel spreadsheet that will also be included with the model, along with instructions for their use. All Greenhouse model calculations can be found in Appendix D, and in the "equations" layer in the model.

C. Model Calibration

After the model was fully developed, with all necessary variables accounted for, the model was calibrated with research data from the literature. Input parameters for calibration were derived from Ku and Hersey (1997a; 1997b) (Table 4.1). These articles were part of the same research study, which applied two different rates of phosphorus, and three different leaching fractions to determine their impact on growth of Poinsettia

(*Euphorbia pulcherrima* Willd. ex Klotzsch 'V·14 Glory'). Since plants were irrigated by hand with a specific amount of water per plant in the original paper, one emitter was placed in each container. The rate in liters per hour per emitter was adjusted to give the leaching fraction volume in the time allocated, while keeping the length of irrigation in minutes the same for each run. The volume of irrigation water applied was not reported by the authors, so leaching fraction and ET were used to determine irrigation rates. Based on the spacing (38cm x 38 cm) reported in the original article, 640 plants were placed in an area of 1000 ft^2. The container size was 1.3 L and plants were grown for 13 weeks. The substrate N holding capacity was calculated from substrate analysis (Ku and Hershey 1997a) using the 60% NO_3 and 0.4 leaching fraction data (which should leach all non-substrate bound N), i.e., 297 mg/1.3 L = 230 mg/L. During calibration, it was determined that this 230 mg/L did not match the leaching and substrate N values reported by Ku and Hershey (1997a). The model run values were too low, so N storage in the 1.3L container was adjusted to 100 mg/L, which most closely matched the analytical values obtained by Ku and Hershey. This value was then used for all further runs for this dataset.

The volume of water applied at each irrigation event was not reported in the original article. Irrigation volume in the original paper was varied to achieve target leaching fractions of 0, 20% (0.2) or 40% (0.4). The total mass of N applied was provided in the original article, as was the irrigation rate for N (210 mg/L), and the number of irrigations (two per week for 13 weeks) (Ku and Hershey 1997a). From this information, I back-calculated that plants averaged 0.31 L per irrigation (i.e. 1700mg/210 mg/L = 8.1 L/26 irrigation events = 0.31 L per irrigation) for the zero LF experiments. Smaller plants

Table 4.1. Values for calibration run that were constant during model run based on information from Ku and Hersey (1997a; 1997b). Fertilizer price was from Maryland Plants and supplies online catalog (http://www.mdplantsandsupplies.com/ accessed 12/20/09) for 20-10-20 general purpose low phosphate at 22.88 for a 24 lb bag, and was used for comparison purposes only.

Variable	
Emitters per MU	640
LPH per emitter	0.311
# of Plants in MU	640
# of weeks in cycle	13
Sq ft of MU	1000
Container size (L)	1.3
Substrate water capacity L/L	0.3
Runoff recycled(%)	0
N holding capacity (mg/ L)	100
Fertilizer price/ lb ($)	0.95
Fertilizer N (%)	20
N mg/ L or PPM of solution	210
P holding capacity (mg/ L)	50
Fertilizer P (%)	5
P mg/ L or PPM of solution	53

were assumed to require less irrigation than larger plants, so for the first four weeks of a run, half of the average amount (0.16 L) was applied per irrigation, for the middle five weeks the average amount (.31 L) was applied, and for the last four weeks .62 L was applied per irrigation.

The fertilizer ratio was determined based on the values reported in the papers. Nitrogen was reported as 210 mg/L, while P was reported at 7.8 or 23 mg/L for the low and high P values respectively. To calculate from P to P_2O_5, P values were multiplied by

2.31 to yield 18 mg/L and 53 mg/L respectively for the low and high P_2O_5 rates. Fertilizer price was based on catalog information from Maryland Plants and Supplies online catalog (http://www.mdplantsandsupplies.com; accessed 12/20/09) for 20-10-20 general purpose low phosphate at $22.88 for a 24 lb bag. This value was used for comparative purposes only, to determine the difference in cost of different application rates and timings between runs.

Table 4.2 provides the values for variables that changed on a weekly basis for model calibration. The leftmost column indicates week number in the simulation, and the remaining columns give N and P uptake, evapotranspiration (ET), temperature effect, and minutes of irrigation. N and P uptake were based on total shoot N uptake (Ku and Hershey 1997a) and P accumulation (Ku and Hershey 1997b). The values for N and P were multiplied by 1.25, to account for N and P that accumulated in the roots over the 13 week growing period, assuming a 3:1 shoot : root ratio, since root N was not included

Table 4.2. Values for calibration run that changed during model run based on information from Ku and Hersey (1997a; 1997b).

Week	N uptake (mg)	P uptake (mg)	Evapotrans-piration (L)	Temperature effect	Irrigation (min)
0	10	1.0	0.20	1.80	30
1	11	1.3	0.22	1.70	30
2	13	2.5	0.25	1.60	30
3	14	3.7	0.28	1.50	30
4	18	5.2	0.35	1.45	60
5	24	6.0	0.45	1.40	60
6	31	7.2	0.50	1.35	60
7	42	9.2	0.62	1.30	60
8	53	11.6	0.735	1.25	60
9	63	14.8	0.79	1.20	90
10	78	16.4	0.85	1.15	90
11	89	17.2	0.885	1.10	90
12	100	19.2	0.92	1.05	90

in the published results. The total N and P values were then distributed across the 13 weeks of the study, with lower values early in the run to indicate smaller root and shoot requirements, and increasing over time. Evapotranspiration was based on irrigation volume, since leaching fraction was controlled in the experiment. Calibration was accomplished using the zero LF treatment, so ET was approximated to match application amount, with ET increasing as the run progressed to simulate plant growth.

Temperature effect in the model has an impact on denitrification rate since, as discussed above, higher temperatures produce higher denitrification rates. Ku and Hershey (1997a) reported daytime greenhouse temperatures between 19 to 24 °C from mid September to mid December. Higher temperatures were assumed earlier in the study, and the numbers reported for temperature in Table 4.2 are based on Q10 information given above (from Agner, 2003), and decrease over time to simulate decreasing greenhouse temperatures over time.

D. Model Validation

i. Ku and Hershey (1997a; 1997b)

After calibration was completed for the 0 LF and 53 mg/L P_2O_5 run, the remaining data from Ku and Hershey was run through the model scenarios. Table 4.3 provides the inputs for the constants for the remainder of the data from Ku and Hershey. Graphical inputs (Table 4.2) were not changed for the remainder of the runs of this dataset. The N, P, and ET values in Table 4.2 represent plant water and N and P requirements under ‘adequate’ conditions to allow optimal plant growth. Although higher rates of N and P uptake are reported at higher LF, these most likely represent luxury consumption of nutrients above those required for maximum growth, since 0 LF plants were reported to grow just as well as 0.2 and 0.4 LF plants.

Irrigation volumes for 0.2 and 0.4 LF values were determined similarly to zero LF. It was reported that 2280 mg and 3270 mg N were applied to the 0.2 and 0.4 LF treatments, respectively. As previously discussed, by back-calculating from 210 mg/L N and a total of 26 fertigations, this equated to an average of 0.42 L, and 0.60 L of solution respectively for 0.2 LF and 0.4 LF treatments. Half of the volume was applied during the first four weeks, and double the volume was applied for the last four weeks of the 13-week cycle, with the middle five weeks receiving the average volume.

Table 4.3. Greenhouse validation inputs into Stella for constants, based on information from Ku and Hershey (1997b; 1997a). (Note: Information from calibration run (Table 4.1) is included in Table 4.3 to be comprehensive.)

Variable	0 LF	0.2 LF	0.4 LF	0 LF	0.2 LF	0.4 LF
	53 mg/L P_2O_5			18 mg/L P_2O_5		
Emitters per MU	640	640	640	640	640	640
LPH per emitter	0.31	0.42	0.6	0.31	0.42	0.6
# of Plants in MU	640	640	640	640	640	640
# of weeks in cycle	13	13	13	13	13	13
Sq ft of MU	1000	1000	1000	1000	1000	1000
Container size (L)	1.3	1.3	1.3	1.3	1.3	1.3
Substrate water capacity L/L	0.3	0.3	0.3	0.3	0.3	0.3
Runoff recycled(%)	0	0	0	0	0	0
N holding capacity (mg/ L)	100	100	100	100	100	100
Fertilizer price/ lb ($)	0.95	0.95	0.95	0.95	0.95	0.95
Fertilizer N (%)	20	20	20	20	20	20
N mg/ L or PPM of solution	210	210	210	210	210	210
P holding capacity (mg/ L)	50	50	50	50	50	50
Fertilizer P (%)	5	5	5	2	2	2
P mg/ L or PPM of solution	53	53	53	18	18	18

ii. Ristvey et al. (2007)

After running the remainder of the input data from Ku and Hershey, data from Ristvey (2004) was then run through the model for validation. The Ristvey (2004) data was used to further validate that the model is able to consistently match published outputs under different scenarios. The data from Ristvey (2004) was chosen since, like Ku and Hershey (1997a; 1997b), it was a rigorous study that reported much of the information necessary for validating model outputs, as well as providing quality information for model inputs. The study by Ristvey (2004), published by Ristvey et al.,(2007) investigated the effect of N and P fertilization rate on azalea nutrient partitioning and uptake efficiency, using 3 rates of N (250 mg/week, 100 mg/week and 25 mg/week) and P (25 mg/week, 5 mg/week and 0 mg/week). The information found in Ristvey et al. (2007) provided useful information for model validation, and was used for comparing model results to published results.

Table 4.4 reports constant values derived from data reported in the two papers (Ristvey 2004; Ristvey et al. 2007). Plants were spaced at 11 plants/ m^2 (1 plant/ ft^2), with a total growing area of 93 m^2 (1000 ft^2). Ristvey et al. (2007) reported deficit irrigation of azaleas once a week, a leaching irrigation (1 liter) 1 day before fertigation, and fertigation with 250 ml of fertilizer solution once a week, but actual volumes of deficit irrigation were not reported other than 250 ml of fertilizer solution.

Table 4.4. Constant values input into greenhouse model for nine separate runs, based on data from (Ristvey et al. 2007). mg/L N and P were adjusted to match published values, while all other values remained the same between runs (except fertilizer % N and % P, which were varied to match application rates).

Variable	**250 mg/ week N**			**100 mg/ week N**			**25 mg/ week N**		
Mg/week P	**25**	**5**	**0**	**25**	**5**	**0**	**25**	**5**	**0**
Emitters per MU	1000	1000	1000	1000	1000	1000	1000	1000	1000
LPH per emitter	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
# of Plants in MU	1000	1000	1000	1000	1000	1000	1000	1000	1000
# of weeks in cycle	10	10	10	10	10	10	10	10	10
Sq ft of MU	1000	1000	1000	1000	1000	1000	1000	1000	1000
Container size (L)	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Substrate water cap. L/L	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Runoff recycled(%)	0	0	0	0	0	0	0	0	0
N holding capacity (mg/ L)	93	93	93	93	93	93	93	93	93
Fertilizer price/ lb ($)	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Fertilizer N (%)	20	20	20	10	10	10	5	5	5
N mg/ L or PPM of solution	1000	1000	1000	400	400	400	100	100	100
P holding capacity (mg/ L)	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Fertilizer P (%)	5	2	0	5	2	0	5	2	0
P mg/ L (ppm) of solution	231.2	92.8	0	231.2	92.8	0	231.2	92.8	0

For each model run, both irrigation (twice per week) and fertigation (once a week) were applied at 250 ml/hr, with 30 minutes of irrigation for the first 3 weeks, 60 minutes the middle 4 weeks, and 90 minutes the last 3 weeks, over the 10 week run. Plants were grown in 7.6 L (2 gal) containers, and N and P holding capacity were set to 93 mg/L and 6.3 mg/L based on average substrate values for 250 mg/week N and 25 mg/week P. In order to achieve appropriate fertilization rates, without changing volume of irrigation applied, the rate of N and P in mg/L of solution were adjusted for the different values in each run.

Table 4.5 reports graphical input values used for all nine runs. The graphical input values (Table 4.5) remained the same for each of the nine runs, and represented the lowest reported values that produced maximum growth. Nitrogen and P uptake amounts were set to 278 and 27 mg respectively, based on the upper values reported in Ristvey et al. (2007). Plant N and P uptake per week were based on destructive harvests (Ristvey et al. 2007).

Table 4.5. Graphical values input into greenhouse model, based on data from Ristvey et al. (2007). The same values were used for each of the nine model runs.

Week	N uptake (mg)	P uptake (mg)	Evapotrans-piration (L)	Temperature effect	Irrigation (min)
0	10	1.0	0.20	1.02	30
1	11	1.3	0.22	1.10	30
2	13	1.5	0.25	1.12	30
3	14	1.9	0.28	1.24	60
4	18	2.3	0.35	1.44	60
5	24	2.7	0.45	1.56	60
6	31	3.2	0.50	1.68	60
7	42	3.7	0.62	1.78	90
8	53	4.3	0.74	1.84	90
9	63	4.9	0.79	1.88	90

Rates of evapotranspiration were not reported by the authors, so ET levels were approximated based on irrigation information provided (as previously described). Temperature values are based on reported greenhouse temperatures of 20 to 28 °C, which were assumed to increase over the course of the experiment from March to May. Graphical values were not changed so that plant response to maximum N and P uptake, under non-luxury consumption conditions were represented in Table 4.5. The impact of not changing the values in Table 4.5 will be discussed in the results and discussion section below.

E. Results and Discussion

i. Ku and Hershey (1997a; 1997b)

Table 4.6 provides summary results for the six runs for fertilizer information. The table provides information about the amount of fertilizer applied per cycle, and the N and P_2O_5 rates in pounds per acre per cycle. The rate of fertilizer applied almost doubles between the 0 and 0.4 leaching fractions (5.4 kg vs 10.5 kg respectively), which indicates the important role that leaching fraction has on fertilizer use in soluble fertilizer systems.

Table 4.6. Fertilizer applied per cycle, and N and P pounds per acre per cycle, based on input information from Ku and Hershey (1997a, 1997b). Results based on six different runs, with 3 different leaching factions (0, 0.2, 0.4) and two different rates of P_2O_5 (53 mg/L and 18 mg/L).

Leaching Fraction ; P_2O_5 rate (mg/L)	**Fertilizer applied/ cycle kg; (pounds)**	**N/ acre/ cycle kg; (pounds))**	**P_2O_5/ acre/ cycle (kg(pounds))**
0.0 : 53	5.4 (12.0)	117.0 (104.4)	29.5 (26.3)
0.2 : 53	7.4 (16.2)	157.9 (140.9)	39.9 (35.6)
0.4 : 53	10.5 (23.1)	225.6 (201.3)	56.9 (50.8)
0.0 : 18	5.4 (12.0)	117.0 (104.4)	10.0 (8.9)
0.2 : 18	7.4 (16.2)	157.9 (140.9)	13.6 (12.1)
0.4 : 18	10.5 (23.1)	225.6 (201.3)	19.4 (17.3)

Table 4.7 provides a comparison of model outputs to published results for Ku and Hershey (1997a) for Nitrogen. The rates of nitrogen applied are very close to the actual values reported in the paper for all leaching fractions and phosphorus rates. This is not unexpected since model inputs were designed to be similar to the inputs reported in the article.

It should be noted that neither Ku and Hershey (1997a, 1997b) nor Ristvey et al., (2007) measured denitrification rates, so the column labeled “denitrification” for both sets of reported data actually represents N that was not unaccounted for in the nutrient budgets of the respective papers. For the model runs, these numbers are calculated denitrification rates over the course of the model run, and the unaccounted for N was close to zero or actually zero for each model run (data not shown). The amount of denitrification from model outputs was higher and more variable than the N that was unaccounted for by Ku and Hershey (1997a). This is probably partially due to the lower N uptake rates in the model for 0.2, and 0.4 LF, which would cause a greater accumulation of N in the container, which would lead to higher denitrification rates by the model. It is also possible that the denitrification rates used in the model are

Table 4.7. Model outputs for Nitrogen compared to published results from Ku and Hershey (1997a), with published results shaded. Results based on six different runs, with three different leaching factions (LF) (0, 0.2, 0.4) and two different rates of P_2O_5 (53 mg/L and 18 mg/L). The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value. **Note:** Value reported for published data is N that is unaccounted for in the results, while model results report denitrification value.

LF and P_2O_5 rate (mg/L)	N per plant (mg)		Deviation	Unaccounted / Denitrified N (mg)		Deviation	N uptake (mg)		Deviation
0.0 : 53	1700	1698	0.00117	443.7	522	0.176	476	542	0.139
0.2 : 53	2280	2293	0.00570	303.2	601	0.982	521	542	0.0403
0.4 : 53	3270	3276	0.00184	366.2	693	0.892	646	542	0.161
0.0 : 18	1620	1698	0.0481	408.2	522	0.279	328	542	0.652
0.2 : 18	2250	2293	0.0191	355.5	601	0.691	385	542	0.408
0.4 : 18	3070	3276	0.0671	279.4	693	1.480	421	542	0.287
Avg. Deviation			**0.0238**			**0.750**			**0.281**

Table 4.7 (Continued)

LF and P_2O_5 rate (mg/L)	N leached (mg)		Deviation	Container N (mg)		Deviation
0.0 : 53	0	539	-	35.5	109	2.07
0.2 : 53	1010	1056	0.0455	31.0	107	2.45
0.4 : 53	1970	1949	0.0107	35.9	105	1.92
0.0 : 18	0	539	-	78.7	109	0.385
0.2 : 18	1080	1056	0.0222	76.8	107	0.393
0.4 : 18	2050	1949	0.0493	67.5	105	0.556
Avg. Deviation			**0.0319**			**1.30**

overestimating this value under these specific conditions. The denitrification rates used in the model are based on information from an acetylene inhibition study discussed in Chapter 2, and are most likely not valid under varying conditions which would be more accurately estimated by a rigorous denitrification model. Better greenhouse research is necessary to determine how denitrification rates vary with decreasing N rates, all other factors remaining constant. The unaccounted N loss rates (assumed by the authors to be due to denitrification) reported by Ristvey et al., (2007) are more closely aligned to reported values (see Table 4.11 below).

The columns labeled deviation represent the mathematical difference between published results and model outputs. The deviation value was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model output was to the published value. There are a few limitations to this value that are important to understand. The same value, (i.e. 20 mg) is going to produce a higher deviation when the published value is smaller (i.e. 1000 mg vs. 50 mg). Also, if the model reports a 0 value, the deviation is always going to be 1, while a published result of 0 will produce an invalid equation. The deviation value reported provides a general understanding of how similar the model results are to the published results. The closer the value is to 0, the more closely the model results match published results for that run. Statistics could not be run on the model outputs, since for each run n=1, so there are 0 degrees of freedom.

As mentioned previously, plant N uptake was not varied over the different model runs of these datasets. This was done partially to determine the model's sensitivity to N uptake under the conditions described in the article. In addition, the plant N uptake rate chosen represented the minimum rate for sufficient growth, while minimizing luxury consumption of N, as reported by the authors. This rate was chosen as the uptake rate that applied “just enough” N to meet maximum plant demand, without the plant accumulating N for a later time. Since plant N uptake is a driver of the model, changing the uptake would also impact the other variables reported in Table 4.7 (as well as Table 4.11 below). In this case, it was my intent to know how the other variables in the table responded to plant N uptake, without the impact of luxury N uptake by the plants. One of the benefits is that the model can be easily be re-run which includes luxury N consumption, and increased N uptake to more closely match reported results for each run.

Model values of N leached in Table 4.7 are similar to published results for both 0.2 and 0.4 LF for both the 53 mg/L and 18 mg/L rates (0.03 deviation), which indicates that the interactions between container storage, plant uptake and denitrification closely match those reported by Ku and Hershey. The rates for 0 LF are not similar, but this is because of a limitation in the model, since as discussed previously, the water and nutrient portions of the model are not linked. The nitrogen portion of the model will leach N, if more N is applied than the container is able to hold. The model assumes that there is water leaching out of the container to carry the N out. Under most growing conditions, there is always some fraction of water leached from the container, even if it occurs relatively infrequently. If a grower does not leach frequently, they would monitor their EC levels in their substrate using the Virginia Tech pour-thru method (Wright and Niemiera 1987), or some other means. If EC levels are too high, indicating that fertilizer salt levels are too high in the container, containers are typically leached with fresh water, and excess salts are flushed from the container. In a large majority of commercial operations, and in all of the greenhouse operations that were in this study, substrate leaching occurs on a regular basis (at least once per week). Thus, as long as leaching is occurring, the model assumption of leaching is being met.

Thus, in the specific case of the Ku and Hershey (1997a) 0 LF data, no leaching was allowed during the course of the 13-week experiment. According to the model, if the substrate was leached, approximately 540 mg of N would have come out in the leachate, but since the containers were deficit irrigated, no leaching occurred. The 539 mg of N leached reported in Table 4.7 represents the amount of nitrogen that was applied above the amount of N that the container was able to hold, the plant was able to take up, and microorganisms were able to denitrify between fertigation events. If water was applied to this container so that leaching occurred, the model predicts that 529 mg of N would come out in the leachate. This will be further discussed under the model validation results for Ristvey et al., (2007) (next section).

The value reported in Table 4.7 for the amount of N in the container is higher for the model runs compared to those reported by Ku and Hershey (1997a), especially for the higher P_2O_5 rate of 53 mg/L, with an average deviation of 1.2. It is important to understand that for both the model and the reported results, the amount of N in the container is a single data point collected at the end of the growing cycle, whereas all the other numbers in Table 4.7 are cumulative values. The amount of N (as well as P and water) in the container at the end of the run could be impacted by a number of values including when the last fertigation/irrigation occurred, the holding capacity of the container and plant uptake/ denitrification that occurred since the last fertigation.

Another limitation of the model, which is important to understand, is that if the amount of N, P or water is limiting to plant growth, this will be reflected in that particular nutrient or water values, but will not be reflected in the other values, which is not necessarily true, in reality. Nitrogen, phosphorus and water uptake occur independently of the others, which is a limitation of the current model. There is no practical way that Stella could link these three processes together so that by limiting one factor, the other two would be limited as well. If this could be accomplished with future iterations of the model, it would be beneficial, especially for researchers. For most growers and researchers, nutrients and water are added at adequate amounts to meet plant growth requirements, but this is an important factor for users of the model to be aware of.

Results for P comparison between model runs, and those reported by Ku and Hershey are reported in Table 4.8. The mg of P applied are similar between the reported values and the model runs, with the model values tending to be slightly higher than reported values with an average deviation is 0.13. The reason why the number are slightly higher in the model runs is because the total irrigation volumes assumed, based on the amount of N and P applied do not exactly match up. For the N numbers reported above, the average volume of irrigation applied was determined to be 0.31 L for the zero LF plants. Using the value of 174 mg applied for the 0 LF at 23 mg/l P (53 mg/L P_2O_5), that would equate to 174 mg/ 23 mg/L = 7.6 L/ 26 irrigations = 0.29 L/irrigation versus the 0.31 calculated for N above. For the low P value of 50.8 mg total applied P and 7.8 mg/L P, the value would be even lower at 0.25 L per irrigation. For model runs, the fertigation volumes (N irrigation volumes) were used, leading to higher application of P compared with those reported by Ku and Hershey. In addition to the P applied, the substrate was also reported to have 79 mg of P at the time of potting (Ku and Hershey 1997b). The model was started with 13 mg of P in the container, which was 20% of the container capacity for P, which was partially offset by the higher volumes of fertigation applied compared with the values that were calculated based on the published results. These differences may explain some of the slight inconsistencies between the model outputs and those reported by Ku and Hershey in Table 4.8.

The rate of plant uptake (maximum rate) was based on the reported plant uptake of the 0.2 LF and 53 mg/L rate, which was 116.2 mg (Table 4.8). All of the 53 mg/L runs returned the same uptake of 114.3 mg, which was close to the maximum uptake of 116.2 mg, indicating that during the course of the run, there was sufficient P present in the container to meet plant growth needs. The same was not true for the 18 mg/L rate. Although the plant uptake values were not changed, these runs returned values that were similar to the reported rates, indicating that the model accurately predicted P uptake under limiting conditions, which indicates decreased plant growth. The model plant uptake values for 0, 0.2 and 0.4 LF are very similar to the reported research results. P leaching rates were also similar between reported model runs and published results, with larger variation seen within the 0.2 LF and 53 mg/L run and the 0.4 LF and 18 mg/L results. These variations may be due to less overall P availability in the models, compared with the published results. The paper reported 66 mg of extra P was in the container at the beginning of the published run (79 mg vs. 13 mg), with the models still applying 25 mg or less P over the course of the run, even though models are applying higher rates of P per application due to higher volumes of irrigation than those reported. The leaching that occurred in Ku and Hershey may have happened in the beginning of the run, when the substrate was at or near holding capacity of P, which could explain why the model did not produce leaching at the lower rate of 18 mg/L. The higher amount of P in the initial substrate would also help explain the lower amount of P in the container in the model scenarios at the end of the runs.

Since bacteria require P for growth, the models also account for microbial accumulation of P. As mentioned above, no rates could be determined from the literature for microbial P use, so a relatively low value of 0.075 (7.5%) times container capacity was used (which factors in container size). Microbial accumulation was lower than reported values for unaccounted for P in Table 4.8, suggesting that the rates used in the model are at least not overestimating microbial accumulation.

As mentioned above, Ku and Hershey did not report the volume of water applied, leached or transpired over the course of the experiments. The values reported in Table 4.9 consist of information from model runs only, and could not be verified by information from Ku and Hershey. Evapotranspiration rates used for these data sets were based on information from total amount of irrigation applied as discussed in the materials and methods section. The 0 LF plants were irrigated to replace only the amount of water lost by evapotranspiration, so they give an accurate indication of the ET loss over the course of the experiment, although they do not give the amount of water provided with each fertigation. This information was used to approximate ET losses for the models. Table 4.9 shows that the evapotranspiration reported by the models were lower than the volume of water applied, leading to 1.6 L of water leached for the 0 leaching fraction runs. Leaching numbers could have been reduced by either increasing the substrate water

Table 4.8. Greenhouse model outputs for phosphorus compared to published results from Ku and Hershey (1997b), with published results shaded. Results based on six different runs, with three different leaching factions (LF) (0, 0.2, 0.4) and two different rates of P_2O_5 (53 mg/L and 18 mg/L). The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

LF : P_2O_5 rate (mg/L)	P applied (mg)		Deviation	Plant uptake (mg)		Deviation	P leached (mg)		Deviation
0 : 53	174	185	0.0632	98.2	114	0.1609	0	0	0
0.2 : 53	228	250	0.0965	116.2	114	0.0189	50.1	34	0.3214
0.4 : 53	360	357	0.0083	149.7	114	0.2385	132	135	0.0227
0 : 18	50.8	63	0.2402	67.8	63	0.0708	0	0	0
0.2 : 18	71.8	85	0.1838	79.4	81	0.0202	7.2	0	1.0
0.4 : 18	102	121	0.1863	100.5	109	0.0846	20.6	0	1.0
Avg. Deviation			**0.1297**			**0.0990**			**0.3907**

Table 4.8 (Continued)

LF : P_2O_5 rate (mg/L)	P in container (mg)		Deviation	Unaccounted / microbial P (mg)		Deviation
0 : 53	78.7	45	0.4282	76.1	29	0.6189
0.2 : 53	76.8	62	0.1927	63.9	43	0.3271
0.4 : 53	67.5	62	0.0815	89.8	49	0.4543
0 : 18	35.5	1	0.9718	26.5	2	0.9245
0.2 : 18	31	2	0.9355	33.2	4	0.8795
0.4 : 18	35.9	4	0.8886	24	10	0.5833
Avg. Deviation			**0.5830**			**0.6313**

holding capacity from 0.3 or increasing the ET rates slightly each week to decrease the water leached closer to 0. Changing these numbers would not have an impact on either N or P numbers, so it was decided to leave these values at their current level, especially since there were no values to compare them to in the published papers. Even though these values are slightly higher than they should be, they do show that increasing water application produces increased leaching, without increasing ET, which indicates that plants were well-watered at the 0 LF level.

Table 4.9. Greenhouse model outputs for water. Ku and Hershey (1997a, 1997b) did not report values for water, so no comparison could be made. Results based on six different runs, with three different leaching factions (LF) (0, 0.2, 0.4) and two different rates of P_2O_5 (53 mg/L and 18 mg/L).

LF P_2O_5 rate (mg/L)	**Water applied (L)**	**Evapotranspiration (L)**	**Water leached(L)**
0 : 53	8.4	6.8	1.6
0.2 : 53	11.3	6.9	4.5
0.4 : 53	16.2	6.9	9.4
0 : 18	8.4	6.8	1.6
0.2 : 18	11.3	6.9	4.5
0.4 : 18	16.2	6.9	9.4

ii. Ristvey et al., (2007)

Since the Ku and Hershey dataset was used for model calibration, a second dataset was run through the model to validate the model outputs without changing any variables in the model that were not changed between the two datasets. If model outputs for the second data set are similar to published results, this would increase our confidence that the model is adequately accounting for the various processes occurring during greenhouse production. Data from Ristvey et al. (2007) was chosen to run through the model as the second dataset. This specific data was chosen because I had access to the original authors and the data required to accurately assess inputs and compare model output results. This specific greenhouse study was part of a larger research project (Ristvey, 2004), focusing on how N and P rate influenced partitioning and uptake efficiency in greenhouse-grown azalea. Three N (250, 100 and 25 mg/week) and P (25, 5, 0 mg/week) rates were used in factorial combinations producing nine different nutrient levels. Five destructive harvests were performed over the ten-week growing period, and the experiment was repeated during two consecutive years, increasing the confidence in the data (the 100 mg rate was only included in the second study).

Table 4.10 provides rate information for fertilizer applied over the nine model runs that were used in the validation of the model. Note that the highest rate of N used 240.1 lb/acre is lower than many of the rates reported in greenhouse operations in Maryland reported in Chapter 3. This is especially true for the recommended rate of 100 mg/week, which corresponds to 96 lb/acre, for the 10-week study. If this rate is multiplied by 4 for a typical 40-week growing season, it is still a rate of less than 400 lb/acre, which is relatively low compared to the typical rates for 7.6 L container-grown plants. Azalea is a low nutrient using (ericaceous) species, so rates for higher nutrient using plants might need to be adjusted accordingly (Ristvey et al. 2007).

iii. Model Validation Results – Nitrogen

Fertilizer in the model was added weekly at the appropriate rate for 10 weeks (Table 4.11), which led to the model applying the identical rate to that reported by Ristvey et al. (2007). Plant N uptake rates were set for the nine runs at 278 mg over the course of the 10-week run. This was based on the N uptake from the 250 mg/week treatment (5 mg/week P). N uptake was at its maximum level for both the 250 and 100 mg/week N rates, indicating that under these model conditions, there was no N limitation on plant growth. This is reasonable since, as mentioned previously, deficiencies in one nutrient or water do not impact the uptake of the other factors by the model. Ristvey et al. (2007)

Table 4.10. Summary values from greenhouse model runs including fertilizer applied per cycle, and N and P pounds per acre per cycle, based on input information from Ristvey et al. (2007). Results based on nine different runs, with three different N rates (250, 100, and 25 mg/week) and three different rates of P (25, 5 and 0 mg/week).

N mg/week	P mg/week	Fertilizer applied/ cycle (pounds)	N/ acre/ cycle (pounds)	P_2O_5/ acre/ cycle (pounds)
250	25	27.6	240.1	55.5
250	5	27.6	240.1	22.3
250	0	27.6	240.1	0.0
100	25	22.0	96.0	55.5
100	5	22.0	96.0	22.3
100	0	22.0	96.0	0.0
25	25	11.0	24.0	55.5
25	5	11.0	24.0	22.3
25	0	11.0	24.0	0.0

reported that N uptake was significantly different for 250:25 and 100:5, with all 25 mg/week N being similar and 250:5, 250:0, 100:25, and 100:0 being similar, using a Least Significant Difference (LSD) test at an $\alpha = 0.05$. Using this information, the model correctly predicted that the 25 mg/week N rate being different from the higher rates,but did not show the 100:5 rate being lower than the rest of the rates. The model results did not indicate that the 250:25 rate had a higher N uptake rate, since this was limited by the inputs. The N uptake could have been changed to increase N uptake for the 250:25 run, but as mentioned previously, it was decided to leave this input constant for all nine model runs.

Table 4.11. Model outputs for Nitrogen compared to published results from Ristvey et al. (2007), with published results shaded. Results based on nine different runs, with three different N rates (250, 100, and 25 mg/week) and three different rates of P (25, 5 and 0 mg/week). The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value. (Note: Value reported for published data is N that is unaccounted for in the results, while model results report denitrification value.)

N mg/ week	P mg/ week	N applied per plant (mg)		Deviation	Unaccounted/ Denitrified N (mg)		Deviation	N uptake (mg)		Deviation
250	25	2500	2500	0	1295.4	1766	0.363	324.9	278	0.144
250	5	2500	2500	0	1451.1	1766	0.217	276.3	278	0.006
250	0	2500	2500	0	1141.9	1766	0.547	313.4	278	0.113
100	25	1000	1000	0	543.9	667	0.226	251.3	278	0.106
100	5	1000	1000	0	640.7	667	0.041	222.2	278	0.251
100	0	1000	1000	0	537.9	667	0.240	242.2	278	0.148
25	25	250	250	0	152.1	219	0.440	84	107	0.274
25	5	250	250	0	156.9	219	0.396	82.8	107	0.292
25	0	250	250	0	160	219	0.369	73.9	107	0.448
Avg. Deviation				**0**			**0.315**			**0.198**

Table 4.11 (Continued)

N mg/ week	P mg/ week	N leached (mg)		Deviation	Container N (mg)		Deviation
250	25	117.1	93	0.206	762.6	438	0.426
250	5	152.3	93	0.389	620.3	438	0.294
250	0	147.6	93	0.370	897.1	438	0.512
100	25	35.6	0	1.0	169.2	132	0.220
100	5	44.2	0	1.0	92.9	132	0.421
100	0	41.9	0	1.0	178	132	0.258
25	25	5.3	0	1.0	8.6	0	1.0
25	5	3.6	0	1.0	6.7	0	1.0
25	0	3.8	0	1.0	12.3	0	1.0
Avg. Deviation				**0.774**			**0.5701**

N leaching results reported in Table 4.11 are similar for the model run and the reported data, with Ristvey et al. (2007) reporting slightly more leaching than the models. This indicates that the N holding capacity of the substrate is appropriate, since similar levels of leaching occurred. Levels of container N are also similar, at least for the 25 mg/week and 100 mg/week rates, with the 250 mg/week rates being lower than the published values. As mentioned previously, the container N value is a point measurement taken at the end of the run/study. The denitrification rates reported by the model are similar to, but slightly higher than the amount of unaccounted for N reported by Ristvey et al., (2007) but the model showed a relatively good sensitivity to this parameter. Considering the limited information available for denitrification rates in soilless substrates, the values in the model appear to be a good approximation of denitrification rates, but as previously mentioned, would benefit from increased research in this area.

iv. Model Validation Results – Phosphorus

Table 4.12 provides P values from model runs compared to those reported by Ristvey et al (2007). The amount of P applied by the model was very similar to the amount reported, with slight variation due to P being inputted as P_2O_5, and being converted by the model. Plant P uptake rates were set to 26.6 mg over the course of the 10-week run, based on the average of 250:25 and 250:5 plant uptake rate. P uptake was not limited at either the 25 mg/week or 5 mg/week rate, as indicated by the 26.6 mg P uptake, which

Table 4.12. Model outputs for Phosphorus compared to published results from Ristvey et al. (2007), with published results shaded. Results based on nine different runs, with three different N rates (250, 100, and 25 mg/week) and three different rates of P (25, 5 and 0 mg/week). The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value. (Note Ristvey et al. (2007) reported substrates had an average of 29 mg of P in the substrates before experiments began, so this was added to unaccounted P column.)

N mg/ week	P mg/ week	P applied (mg)		Deviation	Plant uptake (mg)		Deviation	P leached (mg)		Deviation
250	25	250	250	0	31.5	27	0.143	8.3	164	18.76
250	5	100	100	0	21.8	27	0.239	2.4	22	8.17
250	0	0	0	0	12.4	11	0.113	2	0	1.00
100	25	250	250	0	33.7	27	0.199	13.8	164	10.88
100	5	100	100	0	22.1	27	0.222	2.7	22	7.15
100	0	0	0	0	17.6	11	0.375	1.5	0.0	1.00
25	25	250	250	0	24.3	27	0.111	16.3	164	9.06
25	5	100	100	0	18	27	0.500	5.1	22	3.31
25	0	0	0	0	13	11	0.154	2.5	0	1.00
Avg. Deviation				**0**			**0.228**			**6.70**

Table 4.12 (Continued)

N mg/ week	P mg/ week	P in container (mg)		Deviation	Unaccounted/ microbial P (mg)		Deviation
250	25	83.1	42	0.495	156.1	33	0.789
250	5	15.9	42	1.642	88.9	25	0.719
250	0	9.9	0	1.000	4.7	4	0.149
100	25	64.4	42	0.348	167.1	33	0.803
100	5	16.4	42	1.561	87.8	25	0.715
100	0	10.6	0	1.000	-0.7	4	6.714
25	25	66.6	42	0.369	171.8	33	0.808
25	5	24.1	42	0.743	81.8	25	0.694
25	0	10.8	0	1.000	-2.7	4	2.481
Avg. Deviation				**0.906**			**0.502**

was the maximum allowed amount, indicating that the lower limit of 5 mg/week is sufficient for maximum plant growth, a conclusion that was also reached by the authors. The 0 mg/week rate resulted in reduced plant P uptake indicated by the 11.3 mg P uptake over the 10-week run.

Unaccounted P was determined by adding the amount of P applied plus 29 mg as the initial P reported to be in the substrate at the start of the experiment, minus plant uptake, P leached and P in the container at the end of the study. The unaccounted P was greatest at the highest rate of P application (25 mg/week), but was also high for 5 mg/week P rate at 100 mg/week N and 25 mg/week N. The model included 15 mg of initial P, even at the 0 mg rate, which allowed for similar plant P uptake, and unaccounted P, with a lower amount of P left in the container compared with published results. The largest differences between the unaccounted P were for the 25 mg/week P rates, with the model reporting high leaching, and the research reporting high unaccounted P. It is unclear why Ristvey et al. (2007) reported so much unaccounted P at the 25 mg/week rate. Microbial P use was similar for the 25 and 5 mg/week P rates with the 5 mg/week rate being lower, while the 0 mg/week rate showed low levels of microbial P accumulation. The microbial P rates are much lower than the amount of unaccounted P reported, but since this value requires research to better define it, it is beneficial that the model is conservative in this respect.

v. Model Validation Results – Water Use

Results for water applied, ET, and leaching are provided in Table 4.13. Since the same amount of water was applied across all model runs, all values were the same. Model results could not be compared to published results because irrigation water additions between the 10 weekly leaching events were not published by Ristvey et al. (2007). The amount of water applied is either higher than the actual volume applied, or the ET values used in the model for the run were too low, considering that the plants were deficit irrigated except for a weekly leaching with 1.0 liter of water before the next fertigation; the models reported 7.6 L of leachate, which seems reasonable. The greenhouse model is not able to apply different irrigation volumes during the same week. Since plants were deficit irrigated twice a week (once with 250 ml and once with an unspecified volume), and leached once a week using 1 L of water, 250 ml of water was used as the amount of water added at each fertigation. Since this value resulted in no leaching during the experiment, the models also should have reported minimal or no leaching during the run, but leaching was reported by the model (Table 4.13). This indicates that either ET levels were too low, or the water holding capacity of the substrate is too low. Neither evapotranspiration nor water holding capacity levels were adjusted during model runs, since it would only impact water leached, and there were no reported values to compare the model runs with.

Table 4.13. Model results for water application, ET, leachate, and container water, based on model outputs. Values shown were the same for each model run, since the same volume of water was applied at each irrigation over the same 10-week period, so only one value is shown below.

Water applied (L)	Evapotranspiration (L)	Water leached (L)	Water in container (L)
14.9	7.0	7.6	0.1

F. Greenhouse Hypotheses

After the models were developed, calibrated and validated, a number of hypotheses were developed from the results of Chapter 3 and from conversations with growers, that are important from an industry perspective, and which are hard or impossible to test without extensive research. The scenarios discussed below represent only a small number of possible scenarios that could be run using these models. The six scenarios discussed below are fertilizer rate, fertilizer N: P ratio, substrate holding capacity (N, P and water), number of days fertigated per week, interception efficiency, and volume of irrigation per application. Each of the six scenarios were run through the greenhouse model, with three runs for each scenario (except for irrigation volume (Hypothesis #10) which had four runs), representing a range of values for each scenario. These hypotheses are only a few of the interesting questions that can be answered using this greenhouse model. For each hypothesis listed below, only the variable being tested was changed, with all other variables remaining at set levels, unless otherwise noted. Most of these greenhouse production hypotheses are equally valid for container-nursery operations, since similar substrates and cultural methods are used.

The constant variables, and their corresponding values for each model run are listed in Table 4.14. For each run these values were not changed, unless that variable was being assessed. Four graphical variables, which were held constant during all the runs (except where noted), are also included in Table 4.14.

Table 4.15 provides the values for the graphical variables that varied in the model runs. Plant uptake and water use values were the same as the values used for the Ku and Hershey poinsettia data, since this is a greenhouse crop that has a high nutrient requirement, and is grown throughout the United States. These values were also not changed for any of the model scenarios, which allowed for comparison between model runs. The only graphical values that were changed during all of the runs were days irrigated per week, while evaluating that scenario, and time of irrigation (minutes), which were varied in an "ideal" scenario. That is, after running the six different scenarios, the results were used to create an additional model run, which combined the information from the individual scenarios into what could be described as a "best management practice" under these particular conditions. This "ideal" scenario was included to show the impact that the results from these models can have on grower decisions.

Table 4.14. Constant values for all what-if scenarios. Unless specified in the text for each scenario, values were not changed between runs. Graphical values listed in the lower half of the table were held constant for the entire run.

Variable	**Value**
Number of weeks in cycle	13
Emitters/ MU	10000
# of plants in MU	10000
Sq ft of MU	1000
Liters per hour/ emitter	0.5
Container size (L)	0.5
N holding capacity (mg/L)	100
P holding capacity (mg/L)	50
Water holding capacity (%)	30
Fertilizer price per lb ($)	1
N mg/ L	200
Fertilizer N (%)	20
Fertilizer P_2O_5 (%)	10
Percent of runoff recycled	0
Interception efficiency	0.9
Graphical values that were held constant	
Temperature effect	1
Minutes of irrigation/ application	30
Days fertigated per week	5
Days irrigated per week	0

Table 4.15. Graphical value inputs for what-if scenarios for the 13 weeks of the model run. These values were not changed during any of the model runs, in order to be able to compare model outputs between runs.

Week	N uptake (mg/week)	P uptake (mg/week)	Plant ET (L/week)
0	10	1.0	0.20
1	11	1.3	0.22
2	13	12.0	0.25
3	14	16.5	0.28
4	18	4.5	0.35
5	24	6.0	0.45
6	31	7.2	0.50
7	42	9.2	0.62
8	53	11.6	0.735
9	63	14.8	0.79
10	78	16.4	0.85
11	89	17.2	0.885
12	89	19.2	0.885

i. Nutrient application rates for N and P are very important for both plant growth and controlling leaching. How does the rate of N applied at 20, 200, and 600 mg/L (ppm) effect plant N uptake and leaching?

Hypothesis #5: A continuous rate of 200 and 600 mg/L will exceed plant uptake requirements and result in high N and P leaching, while a rate of 20 mg/L will be insufficient to meet plant growth requirements for N. A continuous rate of 50-100 mg/L will be sufficient to maintain optimal plant growth (N uptake), but have substantially lower N and P leaching compared to the 200 mg/L rate.

The three different rates of fertilizer used (20 mg/L, 200 mg/L, and 600 mg/L), represent insufficient, sufficient, and excess rates (respectively) of N applied in a typical greenhouse grown poinsettia. Table 4.16 shows that plant uptake values are insufficient at 20 mg/L, but are maximized at 200mg/L and above. Under these conditions, it is therefore likely that fertilizer rate can be reduced somewhere between 20 and 200 mg/ for optimal plant growth, while minimizing leaching. It can also been seen that denitrification and leaching rates are much higher at the 600 mg/L level compared to 200 mg/L, indicating excess N applications above 200 mg N / L for poinsettia production.

When these rates are extrapolated to a per acre basis, 200 mg/L equates to 350 kg of N applied per hectare, growing plants at a 11 plants/m^2 (1 ft) spacing in 0.5 L (1.09 pt) containers. Ku and Hershey (1997a) grew plants at 640/1000 sq ft, while for this example, plants were placed at a density of 1000/ 1000 sq ft, but similar amounts of N and P were applied to each plant. The ideal scenario applied N at 40 mg/L, 4 days a week, and showed slightly lower N uptake (504.2 vs. 540.6 mg) but improved denitrification rates, leaching and total amount of N applied compared to the 200 mg/L rate. Fertigation for the ideal scenario was applied for 15 minutes the first four weeks, 20 minutes weeks 5-8, and 30 minutes weeks 9-13. It is likely that a slightly higher rate (e.g. 50-100 mg N /L) would provide maximum growth, while reducing leaching and denitrification losses. This information supports hypothesis #5, which stated that a rate of 200 mg N / L would produce excess leaching (assuming there is water leaching), while a rate between 50-100 mg N / L would support maximum plant growth, and minimize N leaching and denitrification losses (if sufficient water is applied for leaching). A rate of 50-100 mg N / L should be sufficient to meet maximum plant growth under these conditions, considering a rate of 40 mg / L allowed for near maximum growth while reducing leaching losses (Table 4.16).

Similar results were seen for P application as N application (Table 4.17), with 20 mg/L (at a 20:10 N : P_2O_5 ratio) predicted to have reduced P uptake compared to 200 mg/L, but no higher uptake above 200 mg/L. The 600 mg/L rate was predicted to have a significantly higher rate of leaching, indicating excessive P application. The ideal scenario showed slightly lower P uptake (110.1 vs. 114.3 mg) suggesting that P levels were sufficient for maximum plant growth at 10 mg/L.

ii. A variety of different N: P_2O_5 : K_2O fertilizer ratios are sold commercially, even though most ornamental plants would benefit from a ratio similar to the 4:1:3 recommended by Sammons (2008). It is likely that fertilizers with P ratios higher than those recommended lead to higher P leaching in these operations.

Hypothesis #6: A comparison of 20N: 20P_2O_5 vs. 20N: 10P_2O_5 vs. 20N:5 P_2O_5 fertilizer ratios will result in no difference in plant P uptake rates, but will significantly reduce P leaching at the 20:10 and 20:5 rate.

Ristvey et al. (2007) showed that a 20:1 ratio of N:P was sufficient for maximum growth of greenhouse-grown azalea, which agrees with plant nutrient analysis from a number of other researchers (Cabrera and Devereaux 1998; Griffin et al. 1999; Cabrera 2003). This suggests current fertilizers ratios often contain excessive amounts of P. Thus, to test hypothesis #6, i.e. that 20N: 20P_2O_5 vs. 20N: 10P_2O_5 vs. 20N:5 P_2O_5 fertilizer ratios will result in no difference in plant P uptake rates, but will significantly reduce P leaching at the 20:10 and 20:5 rate. These three different N: P ratios were run through the model. Nitrogen application did not change for the three runs (as equivalent amounts were applied), while P_2O_5 application increased from 316 to 1265 mg applied per plant

Table 4.16. Model results for nitrogen under six different what-if scenarios, and an "ideal" scenario, which combines information from the six scenarios.

Variable	Value	N kg/ ha/ cycle	N kg/ cycle	N/ plant/ application (mg)	N applied/ plant (mg)	Denitri-fication (mg)	Plant N uptake (mg)	N leached (mg)	N in container (mg)
Fertilizer mg/ L	20	35	0.3	5	293	35	248	6	5
	200	350	3.3	50	2925	351	541	1935	59
	600	1049	9.8	150	8775	789	540	7177	139
N:P ratio	20:05	350	3.3	50	2925	429	540	1857	59
	20:10	350	3.3	50	2925	429	540	1857	59
	20:20	350	3.3	50	2925	429	540	1857	59
N, P, and Water capacity (mg/L, mg/L, %)	30, 10, 10	350	3.3	50	2925	484	405	1951	45
	100, 50, 30	350	3.3	50	2925	429	540	1857	59
	300, 100, 50	350	3.3	50	2925	369	540	1817	159
Days fertigated per week (same vol./ wk)	1	350	3.3	250	2925	356	193	2381	0
	4	350	3.3	62.5	2869	377	540	1925	31
	7	350	3.3	35.7	2924	325	542	1966	65
Interception efficiency	0.7	350	3.3	50	2275	326	540	1331	48
	0.85	350	3.3	50	2763	345	540	1784	56
	1	350	3.3	50	3250	363	542	2236	64
Irrigation volume (L/irrigation)	0.05	69	0.6	10	585	114	396	62	9
	0.188	262	2.4	37.5	2194	307	256	1538	65
	0.25	350	3.3	50	2925	351	541	1935	59
	1	1399	13.0	200	11700	1005	540	9800	180
"Ideal"		**78**	**0.7**	**11.2**	**730**	**151**	**504**	**50**	**15**

Table 4.17. Model results for phosphorus value results for six different what-if scenarios, and an "ideal" scenario, which combines information from the six scenarios.

Variable	Value	P_2O_5 kg/ ha/ cycle	P_2O_5 kg per cycle	Total mg P applied per plant	Plant mg P uptake	mg P leached	P mg microbial accumulation	P in container
Fertilizer mg/ L	20	17	0.2	63	56	3	3	1
	200	175	1.6	632	114	453	28	28
	600	525	4.9	1897	114	1667	41	47
N:P ratio	20:05	87	0.8	316	114	150	24	24
	20:10	175	1.6	632	114	453	28	28
	20:20	350	3.3	1265	114	1060	34	38
N, P, and Water capacity (mg/L, mg/L, %)	30, 10, 10	175	1.6	632	111	493	9	10
	100, 50, 30	175	1.6	632	114	453	28	28
	300, 100, 50	175	1.6	632	114	407	50	53
Days fertigated per week (same vol./ week)	1	175	1.6	632	107	504	20	3
	4	175	1.6	620	114	458	28	22
	7	175	1.6	632	114	455	28	29
Interception efficiency	0.7	175	1.6	492	114	320	26	26
	0.85	175	1.6	597	114	420	27	28
	1	175	1.6	703	114	520	29	30
Irrigation volume (L/irrigation)	0.05	35	0.3	126	99	10	15	2
	0.188	131	1.2	474	114	302	26	26
	0.25	175	1.6	632	114	453	28	28
	1	700	6.5	2530	114	2274	47	56
"Ideal" scenario		**31**	**0.3**	**126**	**110**	**0**	**12**	**3**

(Table 4.17). Phosphorus uptake rates were the same for all three runs, indicating that plants at the lowest rate (20:5) received sufficient P for maximal growth. Leaching was reduced from 1060 to 150 mg between the 20:20 and 20:5 runs, a factor of over seven times less leaching. This information supports hypothesis six, which states that leaching will be reduced at the 20:5 N:P_2O_5 ratio, while plant P uptake will not be affected, compared to the 20:20 N:P_2O_5 ratio.

iii. It is known that most soilless substrates have a poor anion exchange capacity, which means most substrates have a poor ability to store nitrate and phosphate in the root zone where they are available for plant uptake (Handreck and Black 2002). There has been some research that show reduced nutrient runoff by amending soils with a variety of materials to increase their nutrient holding capacity such as calcined clay (Ruter 2003a), brick chips (Williams and Nelson 2000), rockwool and compost (Bilderback and Fonteno 1993), and phosphorus charged alumina (Lin et al. 1996). Nitrogen holding capacities were set to 30, 100, or 300 mg/L and P holding capacities were set to 10, 50, and 100 mg/L to represent different substrate types, and potentially adding soil amendments to increase ion exchange capacity.

Hypothesis #7: Higher anion-exchange (substrate) capacities will result in reduced N and P leaching.

The type of soilless substrate used impacts substrate properties such as water holding capacity, air-filled porosity, and the ion and cation exchange capacity. Three different values were used to test hypothesis #7, i.e. that higher anion-exchange (substrate) capacities will result in reduced N and P leaching (Table 4.17). In these model runs, combinations of N holding capacity (30, 100 and 300 mg/L), P holding capacity (10 mg/L, 50 mg/L and 100 mg/L) and water holding capacity (10, 30 and 50 %) were tested. Since the model processes these variables independently, these factors can be changed without impacting the other values. At the lowest values, N, P and water uptake rates were reduced, indicating that plant nutrient uptake and ET are limiting to plant growth, compared to the medium and higher holding capacities tested. Medium and higher capacities produced maximum nutrient and water retention, while the highest capacity had the lowest N and P leaching amounts, indicating that more nutrients were held by the substrate. Higher holding capacities could be shown to be even more beneficial if fertilizer was applied less frequently (every 5 or 7 days), or at a lower rate (<200 mg/ L), so the substrate would be able to hold nutrients and water more effectively between fertilizations or at lower rates of nutrient addition. Higher exchange capacities did reduce N and P leaching, which supports hypothesis 7. More compelling results are most likely possible if fertilizer is applied less frequently, or at a lower rate, as described above. It should be noted that N is not bound by the substrate very well, so it is unlikely that N retention could be increased at present. If N is able to be bound by the substrate, the model would be able to correctly model that.

iv. The frequency of fertilizer applications will have an effect on N and P leaching. If more fertilizer is applied than the substrate can retain, then leaching will occur. This is more likely to happen in operations that apply larger amounts of fertilizer less frequently.

Hypothesis #8: A comparison of equivalent amounts of nutrients applied in 1, 4, or 7 weekly (split) applications will incrementally reduce nutrient leaching.

To test hypothesis #8 (i.e. that equivalent amounts of nutrients applied in 1, 4, or 7 weekly (split) applications will incrementally reduce nutrient leaching) the number of fertigations per week was changed, keeping the volume of water and nutrients constant. A single fertigation per week applied more fertilizer and nutrients than the container could hold, which exceeded the container capacity, especially for N content. Plant N uptake rates were lower (193.2 mg vs. 540.3 mg) and N leaching rates higher (2381 mg vs. 1925 mg) compared to plants fertigated 4 days per week (Table 4.17). The same trend was seen with P uptake and leaching (Table 4.17), ET and water leaching through the container (Table 4.18). There was little difference seen between irrigation applied 4 days per week vs. 7 days per week, but this would most likely change at lower water volumes or fertilizer rates. Nutrient and water leaching was reduced between 1 and 4 applications per week, supporting hypothesis 8, but no difference was seen between 4 and 7 irrigations per week (Table 4.18). Under the conditions described here, I would reject hypothesis 8, but the hypothesis would likely be accepted under conditions of lower water or nutrient application rates. The rates of water and nutrients applied and the container capacities used in this scenario were sufficient to keep the plants well irrigated and fertilized between applications when water and nutrients were added every other day.

v. Interception efficiency (IE), or the percentage of applied irrigation and fertigation that reaches the substrate surface, has an impact on water leaching, N and P leaching, and plant growth, since unintercepted water and nutrients cannot be used for plant growth and evapotranspiration. Interception efficiencies of 70%, 85% and 100% were used in model simulations, with 70% representing a poorly managed greenhouse irrigation system, 85% an average system, and 100% an ideal system.

Hypothesis #9: Increasing IE will increase the amount of water and nutrients entering the container for fertigated material, which incrementally decreases N, P and water runoff, and increases leaching through the container.

Interception efficiencies in greenhouse operations are typically high compared to overhead outdoor container irrigation. Interception efficiencies of 0.70, 0.85 and 1.0 were used to represent a poor, well maintained, and ideal irrigation system respectively and test hypothesis #9, i.e. that increasing IE will increase the amount of water and nutrients entering the container, incrementally decreasing N, P and water runoff. N and P uptake did not change, indicating that sufficient nutrients were available to plants at all levels (Table 4.16 and Table 4.17). Leaching was lowest at 0.70, and 0.85 was intermediate to 1.0, indicating that some nutrients were not entering the container at interception efficiencies below 1.0 (Table 4.17). Plant ET was reduced at 0.70 compared to 0.85 (5.3 vs. 7.0 L respectively), suggesting that plants were water stressed at some point during the run. Higher IE rates did have a positive impact on water entering the container, but a neutral impact on N and P, since N and P were available in excess under these conditions. The values presented in Table 4.16, 4.17 and 4.18 only account for the N, P and water that leached out the container, and do not account for the portion that never reached the container (which is accounted for elsewhere in the model). In these scenarios excess irrigation and fertilizer was applied over plant requirements, which provided adequate nutrients even at the lowest IE of 0.7. Therefore, hypothesis 9 is accepted for water under these conditions, but rejected for N and P. Further analysis would likely lead to acceptance of this hypothesis for N and P under different conditions not analyzed here.

vi. Cyclic irrigation is considered a best management practice (BMP), and applies irrigation over a number of shorter cycles, instead of one longer event. For example, instead of irrigating for 45 minutes, a grower might irrigate three times at 10 minutes each, with 20 minutes between irrigation cycles. This type of irrigation has been found to require about 25% less water when applied overhead, or 15% less water when using microirrigation (spray stakes) (Tyler et al. 1996a; Mathers et al. 2005). Although the models are not refined enough to be able to input information on cyclic irrigation, the models can be run using 15% or 25% less water to simulate the water savings of cyclic irrigation in microirrigation and overhead irrigation respectively. The volume of irrigation applied per single event has an impact on total water applied (and N and P for fertigation systems), which in turn impacts nutrient and water runoff. Volumes of 0.05 L/application, 0.1875 L/application, 0.25 L/application and 1.0 L/application were investigated with the model.

Hypothesis #10: Lower applied water volumes will lead to less leaching and water runoff from a management unit. The 0.05 L/application rate will be insufficient for optimal plant growth (ET will be reduced) while the other three rates will be sufficient for optimal plant growth.

Table 4.18. Model results for water value results for six different what-if scenarios, and an "ideal" scenario, which combines information from the six scenarios.

Variable	Value	Water applied (L)	Evapo-transpiration (L)	Water leached (L)	Water in container (L)
Fertilizer mg/ L	20	14.9	7.0	7.6	0.1
	200	14.9	7.0	7.6	0.1
	600	14.9	7.0	7.6	0.1
N:P ratio	20:05	14.9	7.0	7.6	0.1
	20:10	14.9	7.0	7.6	0.1
	20:20	14.9	7.0	7.6	0.1
N, P, and Water Capacity (mg/L, mg/L, %)	30, 10, 10	14.9	6.2	8.4	0.1
	100, 50, 30	14.9	7.0	7.6	0.1
	300, 100, 50	14.9	7.0	7.5	0.2
Days fertigated per week (same vol./ wk)	1	14.6	2.9	11.7	0.0
	4	14.9	7.0	7.9	0.0
	7	14.8	7.0	7.5	0.2
Interception efficiency	0.7	11.6	5.3	6.1	0.0
	0.85	14.0	7.0	6.8	0.0
	1	16.5	7.0	9.1	0.1
Irrigation volume (L/irrigation)	0.05	3.0	2.7	0.3	0.0
	0.1875	11.1	4.6	6.3	0.1
	0.25	14.9	7.0	7.6	0.1
	1	59.4	7.0	50.8	0.7
"Ideal" scenario		**12.3**	**7.0**	**4.9**	**0.1**

To test hypothesis #10, i.e. that lower water application volumes will lead to less leaching and water runoff from a management unit, four volumes were tested for this particular size of container. Volumes of 0.05 L, 0.188 L, 0.25, and 1 L per application, with plants fertigated 5 times a week. The rate of 0.25 represented a "typical" irrigation rate, while the 0.188 rate represented a cyclic irrigation rate, applying about 25% less water compared to irrigation applied continuously (Beeson and Haydu 1995; Tyler et al. 1996a; Mathers et al. 2005). Although the model does not currently have a setting for cyclic irrigation, all irrigation is applied based on interception efficiency and volume applied, so a 25% reduction would simulate the efficiency gains seen by cyclic irrigation. Rates of 0.05 and 0.188 L/application did not provide adequate water to the container, with ET levels of 2.7 L and 4.6 L respectively, compared to a 0.25 L/application ET rate of 7.0 L (Table 4.18). A lower rate of N uptake was also observed, indicating that application levels were most likely insufficient. It is possible that the 0.25 L/application rate is a reduction of the typical rate applied to 0.5 L containers, and would be considered the best management rate, but further scenarios were not run. Based on this information, hypothesis #10 is accepted that reduced application rates yield reduced runoff values, but rates below 0.25 L/application are not recommended unless further model runs are completed.

Compared to the medium rates applied for the six different scenarios, the ideal scenario showed lower N, P and water inputs (Table 4.16, 4.17 and 4.18). The ideal scenario was also able to reduce N, P and water leaching, while maintaining optimal plant growth. By being able to easily adjust different variables users should be able to quickly assess current management practices, and identify areas of potential nutrient and irrigation savings, which could translate into increased profit margins, and reduced water and nutrient losses through leaching.

G. Conclusions

Greenhouse model calibration and validation produced a model that can accurately predict N and P uptake, leaching, microbial loss, and container-holding mechanisms reported in two independent greenhouse research papers. Results from 15 different model runs were compared with published results, demonstrating the ability of the models to return accurate results under a variety of conditions. Applied N and P and uptake values were similar in model outputs compared to published results, while values for N and P in the container, denitrification loss and leaching values tended to have more variability in model results.

In addition, six hypotheses were generated and tested using information from the production practices of 27 greenhouse operations, with 169 different management units along with current issues in greenhouse production, which illustrates the usefulness of these models for testing real-world scenarios. For example in Chapter 3, the average rate of N and P_2O_5 that was applied to 8-18 cm poinsettias was 618 kg/ ha and 243 kg/ha respectively. For the "ideal" scenario listed above using information for poinsettia, it was shown that 78 kg/ ha was sufficient for maximum N uptake, and 31 kg/ ha was sufficient for maximum P uptake. These rates are almost 8 times lower for both N and P compared to the average rates, which would represent a huge cost savings and environmental benefit to growers that implemented these rates. It is likely that similar reductions can be realized with a variety of different species grown in greenhouse operations. These models were also designed to incorporate information for different climates so they could be used across the United States, and potentially in other parts of the world.

The what if scenarios tested above, show the sensitivity of the model to a variety of inputs. For example, changing the fertilizer rate from 20 mg/ L to 40 mg/ L showed that plant uptake went from insufficient to sufficient, while increasing the rate to 200 mg/ L increased plant N uptake slightly, but also increased N denitrification and leaching. An

$N:P_2O_5$ ratio that was reduced from 20:10 to 20:5 reduced P leaching from 453 mg to 150 mg per plant, without negatively impacting plant P uptake. Additional testing and model development should continue to improve the usefulness of the greenhouse model as a valuable tool for both growers and researchers in this field, which has been shown to provide an accurate analysis of current practices, and their impact on plant uptake, microbial losses, and nutrient and irrigation runoff.

Chapter 5: Container-Nursery model

A. Introduction

Container-nursery operations are similar to greenhouse operations in that they both grow plants above ground in soilless substrates in plastic containers. There is also some overlap in the species that are grown in greenhouse and container operations, but there are also large numbers of plants that are unique to each type of operation. In container operations, the grower has less control over environmental conditions such as wind, rainfall, and temperature compared to greenhouse operations. The majority of container operations in the U. S. grow shrubs and small trees in container sizes ranging from 4 – 175 L (1 - 45 gal), while greenhouse operations typically grow plants in much smaller containers (< 1 - 8L) (0.25 - 2 gal). Use of overhead sprinkler irrigation, which allows for flexibility in the types and sizes of plants that are grown in any given area, can be much more variable in terms of efficiency, compared to greenhouse irrigation systems. Another major difference is that container operations tend to use slow release fertilizers (SRF, also called controlled release fertilizer), although some operations use solid or soluble fertilizers (Chapter 3 includes information regarding fertilizer types and rates used in Maryland). Although the greenhouse and container models share many of the same aspects, there are also some major differences between the two models, enough to warrant a separate model and analysis, as described in this chapter.

B. Materials and Methods - Model development

General model development was discussed in Chapter 2. In addition, the materials and methods section in Chapter 4 covered specific information about the processes used to model irrigation, nitrogen (N) and phosphorus (P) flow into and out of the container, which are also used in the container model, and which will be noted were appropriate, but not discussed in detail.

i. Nitrogen

The greenhouse model only allows for the use of soluble fertilizer, while the container model allows for three different types of fertilizer; soluble, slow release, and biosolid (compost, manure etc.), all of which are handled differently by the model. It is likely that most growers only use one type of fertilization on their container plants, but the model is able to integrate fertilization from all three types of fertilizer inputs. The biggest concern is to ensure that the user places their fertilizer parameters in the proper location in the model, so it is processed correctly during the run. Nitrogen is treated as the primary input, since growers most typically focus on this one nutrient in their fertilization program, followed closely by P. Figure 5.1 shows the container model layer, with the inputs and outputs for N.

Soluble fertilizer is processed similarly to that described for the greenhouse model, with fertilizer addition determined by the rate (mg/L or parts per million; ppm) and volume of irrigation applied, with the fertilizer then added to the container. The container model is able to process fertigation using either an overhead or drip system.

Interception efficiency is also included in this model to differentiate between water and nutrients that are intercepted by the container (and can later leach out of the container) and the unintercepted water and nutrients that do not enter the container and, go directly to runoff. The model takes both unintercepted N, P and water (the water that falls to the ground), and any N, P or water that comes out of the bottom of the container as leachate, and adds them to the same "leachate" (leachate/ground accumulation) stock. This becomes runoff from an operation, when there is sufficient water to carry it away.

The user is able to vary the number of fertigations using soluble N and P on a weekly basis in the appropriate graphs in the interface layer (Fig. 5.2), if either overhead or drip irrigation is used for fertigation. Although there is more input information in the interface layer compared to the greenhouse model, growers are most likely using one type of fertilizer (soluble, solid or SRF), and one type of irrigation system (overhead or drip) simplifying the input process. It is likely that most users will not have to change many of the other parameters to get sufficient results. For example, if a grower uses slow release fertilizer, these numbers would need to be changed, since the default application value for all fertilizer amounts are set to 0, so extra fertilizer is not inadvertently applied. Similarly if overhead irrigation is used, no information for drip irrigation needs to be entered. This simplifies the use of the container model, although there are still more values that require user inputs, compared to the greenhouse model. As for the greenhouse model, the grower should know most of the important variables for their operation, and can use default values for the remainder of the information they are unsure about.

The majority of management units that were surveyed in Maryland (86%) used SRF as the main or only source of fertilizer used in container-nurseries. As discussed in

Chapter 1, SRF are considered a best management practice, but their release patterns are mainly dependent on temperature, with higher release rates occurring at higher temperatures, which do not typically coincide with maximum plant nutrient uptake. Warren and Bilderback (2004) showed substrate (root) temperatures reaching 45 °C (120 °F) or more, in outdoor containers in the summer. These high temperatures lead to high nutrient release rates in the container, which can lead to nutrient leaching and runoff into surface and groundwater. The model processes the SRF as follows. The amount of fertilizer applied per container (in grams) is multiplied by the percent N of the fertilizer, giving total grams of N added to the container. This N is added to an "Initial CRF" stock (holding tank) at the beginning of the run. Each week, the amount of fertilizer that is removed from the stock (and applied to the container) is dependent on the release rate of the fertilizer (in weeks) and the air temperature.

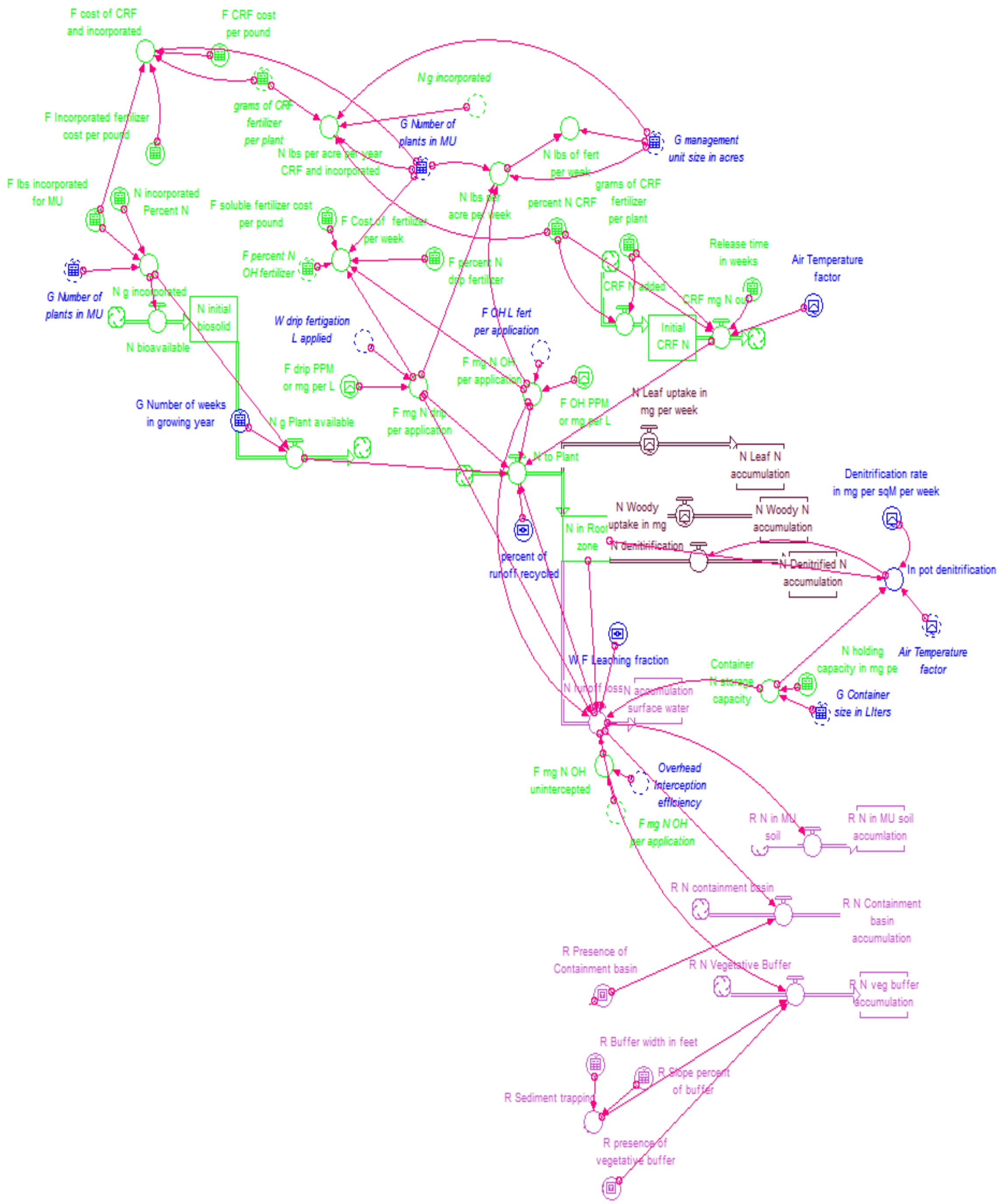

Figure 5.1. Container model interface layer showing nitrogen inputs and outputs from Stella. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Fertilization variables are noted in green, general management variables in blue, plant uptake and denitrification loss mechanisms in dark purple, leaching and nutrient removal variables in purple.

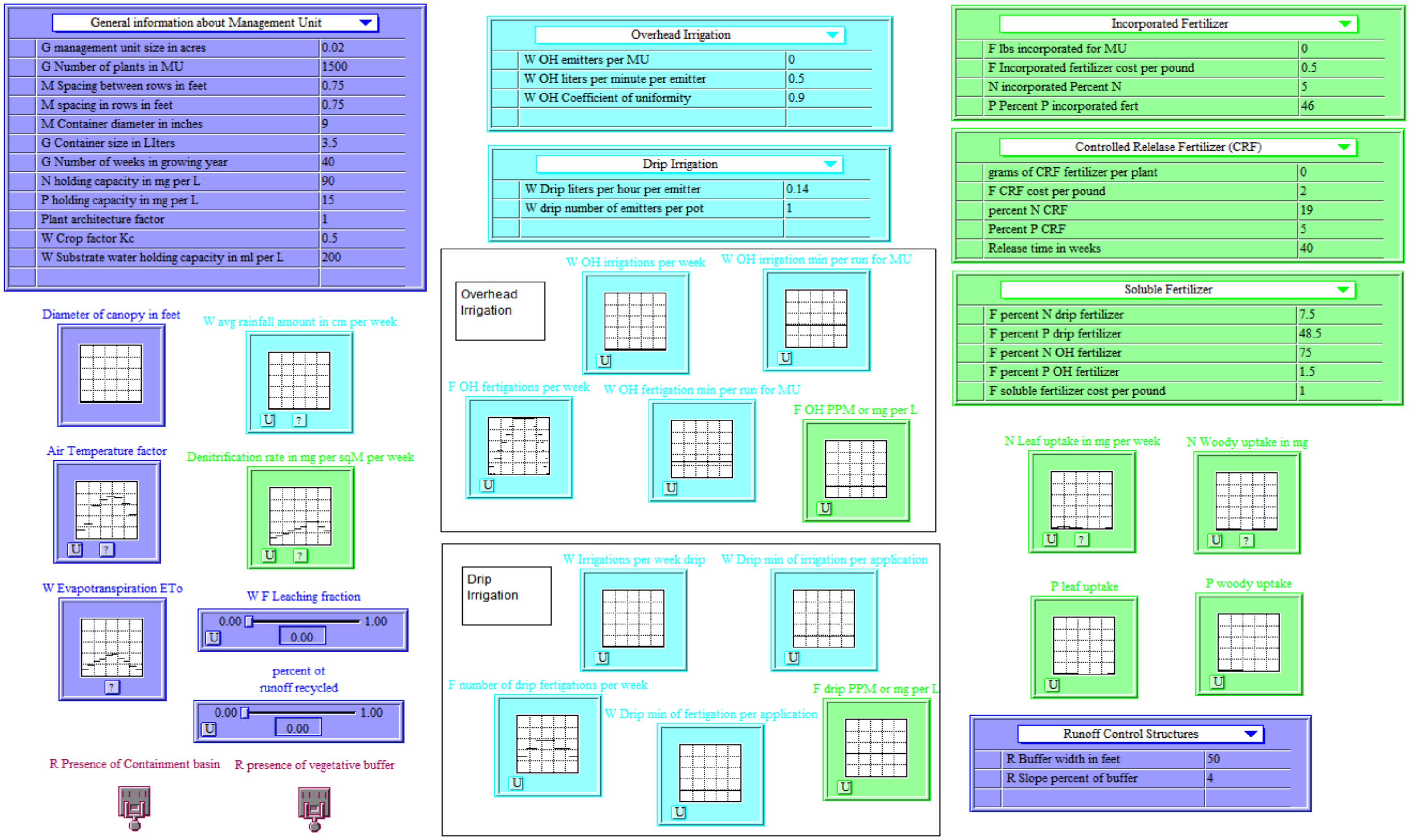

Figure 5.2. Interface layer of container model showing graphical inputs that can be changed on a weekly basis (i.e. diameter of canopy, average rainfall in cm/week), variables that can be controlled via sliders (Leaching fraction and percent runoff recycled), and table inputs that are constant for the model run (general management unit information table, irrigation tables etc.).

Slow release fertilizer release rates are often based on air/ substrate temperatures of 21 °C (70 °F). Substrate temperature for SRF release time was shown to have a Q_{10} close to 2 for a number of different commercially available formulations (Cabrera 1997; Huett and Gogel 2000; Du et al. 2006). The model uses air temperature (since most users will typically not have substrate temperature readings available) to determine the release patterns over the growing season. Container root temperatures are known to closely track ambient air temperatures (Ruter 1999). The excel spreadsheet that will be made available with the model interface has a calculation where the user can input monthly average temperatures for March through October for their geographic area, which is converted automatically to °C and to temperature factor, so temperature factor can then be copied and pasted into the appropriate graphical input in the model interface layer. For example, if a SRF with a 40-week release rate is used with 10 g of N, the release pattern for any given week is 10/40 x (temperature factor). Lower temperatures theoretically slow nutrient release, while higher temperatures will increase release rates. Once all of the nutrients in the stock are used, the SRF no longer contributes nutrients to the container.

There are a number of different biosolid substrate amendments that can be used in the nursery industry. Increasing fertilizer and substrate costs will most likely lead to increased use of organic fertilizers and amendments, which can increase nutrient holding capacity, and stretch supplies of limited substrates such as peat and pine bark. Amendments such as compost, manure, wulpak, and rice hulls have been shown to be beneficial in reducing fertilizer, irrigation, and/or disease loads and have the potential to become more widely used in soilless substrate mixes (Lin et al. 1996; Hoitink and Boehm 1999; Handreck and Black 2002; Hoitink et al. 2003; Ruter 2003b; Holman et al. 2005;

Bilderback et al. 2007; Raviv and Lieth 2008). As such, differences in nutrient holding capacity would be reflected in the inputs for N, P and water holding capacity.

For the model, a similar approach was used for biosolid fertilizer addition as the SRF process discussed above. Compost is added as lbs per management unit, and percent N of fertilizer, which is converted by the program to grams of N per plant, based on the number of plants in the management unit (MU). This N is added to a stock, and is released equally over the course of the model run (currently set to 40), without regard to temperature. Summary (i.e. lbs N/ acre) values for fertilizer application rates can be seen in Figure 5.1. These values are calculated based on the total amount of fertilizer added over the growing season for each different fertilizer type, similar to the process described for the greenhouse model.

Once nutrients enter the container, there are two different plant N removal mechanisms compared to only one for greenhouse operations. In the greenhouse model, most plants are grown for short cycles (typically 4-12 week), with the goal being maximum growth with minimal pruning of the canopy. Container operations typically grow plants for 20 weeks or more, often with one or several prunings during this time to maintain plant shape during growth. Each pruning event removes N that has been taken up by the plant, the majority of which is stored in the leaves (Ristvey, 2004). For this reason, plant N is differentiated between woody N (both root and shoot) which is less likely to be removed during pruning, and leaf or new growth N, which is likely to be removed during pruning.

Denitrification loss is calculated similar to the greenhouse model, except the rate is determined by surface area instead of container volume. This is a common way of reporting denitrification losses in native field soils, which is the method used in the field model discussed in the next chapter. There is a relatively large amount of information available for denitrification rates in native soils, compared to greenhouse operations, while no information was found for denitrification rates in outdoor container operations, increasing our confidence in the field values compared to the greenhouse values (Smith and Tiedje 1979; Rolston 1982; Olson and Swallow 1984; Sexstone 1985; Nieder et al. 1989; Nommik and Larsson 1989; Prade and Trolldenier 1989; Christensen et al. 1990a; Christensen et al. 1990b; De Klein 1996; Martin et al. 1999; Delgado 2002).

The container model was developed after the greenhouse and field model, due to its complexity, and the same mechanism was used initially in the container model as the field model for N loss. When the model was run, there was good agreement between the denitrification rates reported by the model (see validation results below). For the model, denitrification rates are based on information from Deklein (1996). Rates varied from 3 mg/m^2/day to 360 mg/m^2/day, depending largely on soil moisture (which explained 60% of the variability). The maximum rate of 300 mg/ m^2/day was used since substrate temperatures are higher in containers compared to native soils, and there is often a perched water table at the bottom of containers, which should provide optimal conditions for denitrification for extended periods of time. The highest rate was used in summer since temperatures and irrigation frequencies are higher which increases denitrification rates, with lower rates in the spring and fall. Since the model uses a weekly time step, daily rates were multiplied by 7 to give final numbers. The amount of N in the container also has an impact on denitrification rate, which is higher when the container is closer to its maximum N holding capacity, since there should be less competition between the plant and the microbes for the same resource.

Nitrogen runoff and leaching are calculated similarly to that described for the greenhouse model. Any N that is not intercepted by the container, as well as any that is applied above the container capacity goes to the “N accumulation surface water” stock, which indicates that this N is able to be conveyed to surface waters (Fig. 5.1). The greenhouse model “leaching” (and unintercepted) stock works similarly, since it includes both the N that comes out of the container due to over application, and the N that was not intercepted by the container if overhead fertigation is used. The container model includes additional factors for controlling the fate of N, P, and water runoff, if certain best management practices are used. The models include switches on the interface layer for containment basin and vegetative buffers, which are effective methods for reducing nutrient, sediment and water runoff from an operation. If a containment basin is present, 10% of the N that has runoff from the operation is captured by the basin. Nitrogen removal values are lower than P values (since P is mostly sediment bound), since P is much more efficiently trapped in sediment basins placed before containment basins compared to N. No numbers were found for N removal from containment basins, so this analysis would certainly benefit from future research. Vegetative buffers are also a best management practice that are often used to trap sediment and increase infiltration rates of water, in order to reduce sediment and nutrient loading to surface waters. The container model uses an equation from Liu et al. (2008) (Eq. 5.1) which incorporates buffer width and slope to determine sediment removal effectiveness. Although this equation does not take several important factors such as soil type, vegetation type, buffer maintenance, or rainfall intensity in account, the equation is based on 79 published research papers, which do take these values into account, and should increase the confidence that this equation is accurate under a variety of buffer conditions.

$$Y_{sediment} = 53.77 + 1.58\, X_{width} + 5.67\, X_{slope} - .0314\, X_{slope}^{2} \quad \text{......................Eq. 5.1}$$

Equation 5.1. Buffer sediment removal efficiency calculation (from Liu et al., 2008)

Regardless of whether containment basins or vegetative buffers are used, the model also accounts for runoff water that can infiltrate into soil. Beeson and Knox (1991) noted that approximately 10% of the irrigation water that is applied to a container operation infiltrates into the ground under typical conditions, with higher rates in sandy soils. A value of 10% of the N that leaches out of the container goes into ground infiltration, which represents 10% of the water that runs off (since N is typically water soluble). This value can be changed by the user, in the model layer. This value could be updated in the future to take different soils and conditions into account for more accurate results. Since the main focus of these models is to ensure water and nutrient application rates and timings are adjusted to more closely match plant requirements, there are some values for leaching and runoff factors that could be modified to be more comprehensive in future model iterations, especially since runoff factors have an impact on the environment.

ii. Phosphorus

Phosphorus inputs into the model is similar to the N inputs discussed above. Phosphorus can be added to the container from SRF, as soluble fertilizer through drip or overhead irrigation, or through biosolid application from compost or other similar sources. The amount of phosphorus added is based on the percent of P of the fertilizer (SRF) or on the ratio of P/N (soluble and bio-available). Figure 5.3 provides the input and output variables for the P portion of the model. Similar to nitrogen, P is broken into woody and leaf accumulation, to account for the P that can be lost during pruning. Interception efficiency also factors into P leaching/ runoff, similar to that described for N above. Interception efficiencies below 1.0 causes a portion of the applied P to be transferred to runoff, before it is intercepted by the container.

Similar nutrient runoff practices are used compared to the N portion of the model described above. The major difference between N and P runoff is in the ‘trapping’ or binding efficiency of the management practice. Phosphorus is more often soil-bound compared to N, with up to 90% of P from cultivated fields adsorbed to soil clays and organic matter following rain events (Havlin 2004). Both containment basins and vegetative buffers are more efficient at sediment removal, which should favor P removal over N removal in runoff water. Since containment basins are designed to overflow during times of heavy rains, P theoretically should be removed more effectively than nitrogen. A P removal efficiency of 90% is used in the model, although this can be easily adjusted. Although it is likely that vegetative buffers are more efficient at removing P than N, the same formula was used, since Equation 5.1 took a large amount of research into account, which included differences in N input values. As mentioned before, the values for N and P removal could be improved with additional research, when it becomes available.

iii. Water

The container model takes into account water inputs from three different sources, overhead irrigation, drip irrigation, and rainfall. Irrigation water is added to the container similarly to that described for the greenhouse model in Chapter 4. Briefly, water is added when either irrigation or fertigation occurs by either overhead or using drip emitters. The same "pulse" function is used to deliver a set amount of water a particular number of times in a given week (based on user inputs). There is the same concern that if irrigation and fertigation (regardless of the type of system used) are added on an even or odd number of times a week, twice the amount of irrigation will be added on days when irrigation and fertigation are occurring simultaneously, as was described for greenhouse irrigation in Chapter 4. Few container operations that were surveyed in Maryland used soluble fertilizer, so this is likely less of an issue than in the greenhouse model. The user model interface will clearly illustrate and highlight this fact, when published.

Since containers are typically more widely spaced in container operations compared to greenhouse operations, container spacing should also have a greater impact on irrigation interception and runoff, especially with overhead irrigation. Overhead irrigation was reported in 116 of the 155 management units (75%) for the 27 container operations that were visited (Chapter 2), compared to 10 using drip (6%) and 29 (19%)

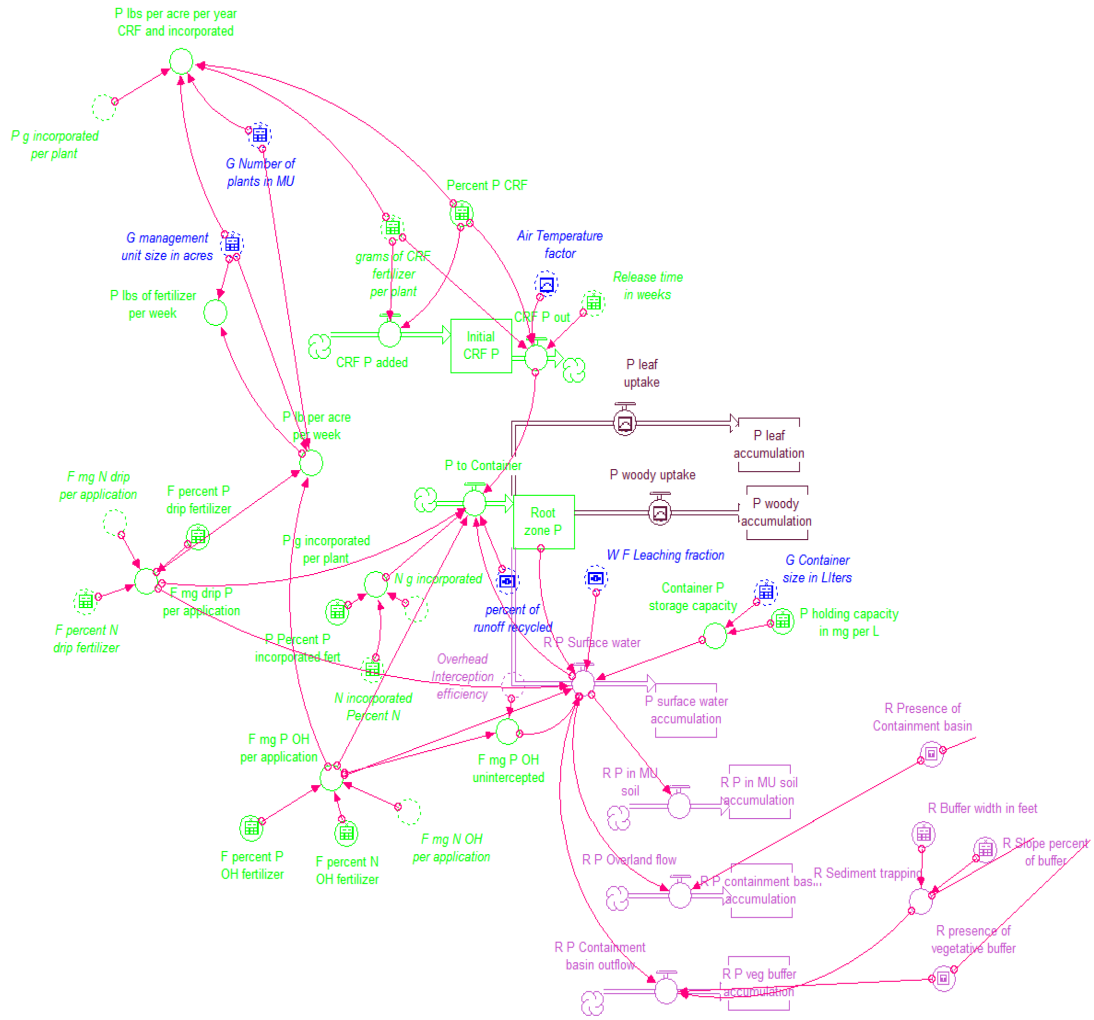

Figure 5.3. Container model interface layer showing phosphorus inputs and outputs from Stella model. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Fertilization variables are noted in green, general management variables in blue, plant uptake mechanisms in dark purple leaching and nutrient removal variables in purple.

using hand irrigation (data not shown). The model differentiates between water that is added to the container (which can leach nutrients if applied in excess) and water that is not intercepted by the container (which will not have nutrients unless fertigation is used) for both irrigation and rainfall (Fig. 5.4). Interception efficiency is calculated automatically in the model using width and length between container centers, which is provided by the user. These two factors, along with container diameter (also a user input) are used to determine the percentage of the area assigned to each container that is taken up by the container itself (interception efficiency) vs. the area that is not taken up by the container (1- interception efficiency). The interception efficiency is then a ratio for dividing the irrigation or fertigation application onto the container or open ground areas. Plant architecture also impacts this value, since an architecture value below 1 reduces the amount of water entering the container (water shedding), while a value above 1 increases the volume of water entering the container (water capturing) at each overhead irrigation or rainfall event. This value can be changed on the interface layer, but it will be recommended that this value not be changed, except by experienced users, since as discussed in the what if scenarios below, the model is sensitive to this variable, meaning that a small change in this value has a larger impact, compared to many of the other variables tested.

Evapotranspiration (ET) is determined differently in the container and field model compared to the greenhouse model. Greenhouse plants tend to be smaller in size, and most are grown either as seedlings or small plugs, which should have less variability in ET compared with field and container plants which are grown to a variety of different sizes, and various species have a large variation in water use. Values for ET (Eq. 5.2) for the container model are based on ET (evapotranspiration in mm/ day) and is determined by the reference evapotranspiration (ET_o) multiplied by the crop constant (K_c), which is crop specific (Pardossi et al. 2008).

$$ET = K_c \times ET_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 5.2}$$

Equation 5.2. Evapotranspiration equation used in the container model.

For the model, ET_o was multiplied by 7 for the weekly time-step, and divided by 10 to convert to cm. The ET_o was then multiplied by the crop factor and the surface area of the canopy (in cm^2), since ET is dependent on plant size. Table 5.1 provides a list of K_c values reported from the literature for 33 ornamental species (modified from (Niu et al. 2006; Pardossi et al. 2008; Warsaw et al. 2009). Users should be able to find either the species they grow or one similar to it, to input a K_c value into the model. It would also be beneficial for additional K_c values to be determined through research for the most popular container-grown plants.

The value for ET_o is specific to a geographic region, so this value was determined as follows for Maryland and the surrounding area. Agroclimactic data was downloaded using the program CLIMWAT 2.0 (Grieser 2006), for the closest reporting station (Baltimore Washington International Airport). Climwat provides long-term mean monthly values on max and min temperatures (°C), relative humidity, wind speed (km/day), hours of sunshine per day, solar radiation (MJ/m2/day), monthly rainfall, and monthly effective rainfall. This information was then uploaded into the program EToCalc (Raes 2009) to calculate the ET_o for Baltimore, Maryland and the surrounding area. The output of the ET_o calculations were then used as inputs for the Stella model (Appendix E Table E 5.1). Evapotranspiration is the only variable in the model that actively removes water from the container, which drives water loss in the model, similar to that described for the greenhouse model, although the mechanism is different. Excess water that is applied either through irrigation or rainfall goes into the leaching portion in the model. Container water volume is determined by container size in liters, and substrate water holding capacity in ml/ L, like that described for the greenhouse model in Chapter 4.

Since container operations are open to rainfall, this factor is included in the container model, unlike the greenhouse model (Fig. 5.4). The model generates the number of rainfall events per month, by using a normal curve with a standard deviation of 2 and a mean of 3. Only whole numbers are used for rainfall events per month. For that month, the average rainfall is divided by the number of rainfall events. The difficulty in modeling rainfall is that is an inherently random process as far as intensity, duration and frequency are concerned. In order to be better able to model this factor, some of the variability had to be removed. For the average rainfall amount (cm/week), the average rainfall per month is used as an input graph on the interface layer. This information is readily available to a user for their specific area from the internet at sites such as weather.com (www.weather.com). If this information is placed into the proper column in the excel spreadsheet (that will be provided with the model interface), the average weekly irrigation (cm) will be calculated automatically. Instead of adding the same amount of irrigation every week, the program has some stochasticity built in.

The model was designed to use a normal (Gaussian) rainfall intensity curve, with a mean of 0.75 cm/hr, and a standard deviation of 0.76 cm/ hr, which are average values derived from the American Meteorological Society (2010) for the Maryland area. For model calibration and validation, rainfall intensity was maintained at 0.75 cm/ hr in order to have the same rainfall values to be able to compare values among runs.

In the model, rainfall duration is determined by rainfall intensity, and depth of precipitation, which varies by month. For example, if there were five storms in a month, each delivering 1 cm of rain, with an intensity of 0.75 cm/hr, each of the five storms would last 1.33 hours. This irrigation is converted into a depth, which is then delivered to the container using surface area of the container (in cm^2) to determine volume of water applied to the container. Any excess water applied over container capacity is leached. Water that is not intercepted by the container either goes into infiltration or unintercepted runoff (runoff water that does not have nutrients, since it never came into contact with the container). Infiltration is set to 10% of the unintercepted rainfall and runoff water, since this has been shown to be a good estimation of infiltration losses for container operations (Beeson and Knox 1991).

It was decided not to use rainfall intensity, duration, frequency information in the model. Rainfall intensity, frequency duration graphs only report the largest storms in a given time period, which are beneficial for engineering designs. For the models, we are interested in all storms, since we are interested in total rainfall, not just the largest events. Rainfall intensity, duration, frequency information would incorporate higher values into the models compared to average rates, which would produce higher levels of runoff, since these data represent only the largest storms in a given area during the year.

Table 5.1. Crop coefficient (K_c) values reported for 32 species/cultivars modified from (Niu et al. 2006; Pardossi et al. 2008; Warsaw et al. 2009). The crop coefficient is determined empirically, and represents whether a plant transpires more (K_c >1) or less (K_c<1) than a reference crop under the same conditions.

Species	**K_C**
Abelia grandiflora 'Edward Goucher'	0.93
Buddleia davidii ' Burgundy'	1.29
Buddleja davidii 'Guinevere'	6.80
Callicarpa dichotoma 'Early Amethyst'	3.80
Caryopteris xclandonensis 'Dark Knight'	3.70
Cornus sericea 'Farrow'	3.40
Cotinus coggygria 'Young Lady'	2.20
Deutzia gracilis 'Duncan'	1.60
Euonymus japonica	1.29
Forsythia xintermedia	0.81
Forsythia xintermedia 'New Hampshire Gold'	3.60
Hydrangea arborescens 'Dardom'	3.00
Hydrangea paniculata 'Unique'	3.60
Hydrangea serrata 'Blue Billow'	3.10
Ilex vomitoria Pride of Houston'	1.30
Kerria japonica 'Albiflora'	1.90
Lonicera korolkowii 'Honey Rose'	3.30
Nerium oleander 'Hardy pink'	1.74
Photinia xfraseri	0.53
Prunus laurocerasus	0.24
Rosa 'Winnipeg Parks'	2.60
Spiraea fritschiana 'Wilma'	3.60
Spiraea japonica 'Flaming Mound'	5.00
Symphoricarpos xdoorenbosii 'Kordes'	2.10
Syringa xhyacinthiflora 'Asessippi'	1.90
Thuja occidentalis 'Techny'	2.60
Thuja plicata 'Atrovirens	1.70
Viburnum xburkwoodii 'Chenaultii'	1.60
Viburnum dentatum 'Ralph Senior'	1.60
Viburnum nudum 'Bulk'	3.40
Viburnum opulus 'Roseum'	2.20
Viburnum tinus	0.33
Weigela florida 'Alexandra'	3.60

iv. Additional calculations

Similar additional values are calculated for the container model compared to the greenhouse model. Total amount of fertilizer in pounds per acre for N and P are calculated for each run. In addition, fertilizer cost for the cycle is determined for the different types of fertilizers applied (SRF and soluble) for the management unit being analyzed (Fig. 5.5). All calculations that are performed in the container model are shown in Appendix E. As discussed for the greenhouse model, it was decided to calculate summary values in Imperial or avoirdupois units, since these models were designed to be used for growers in the United States.

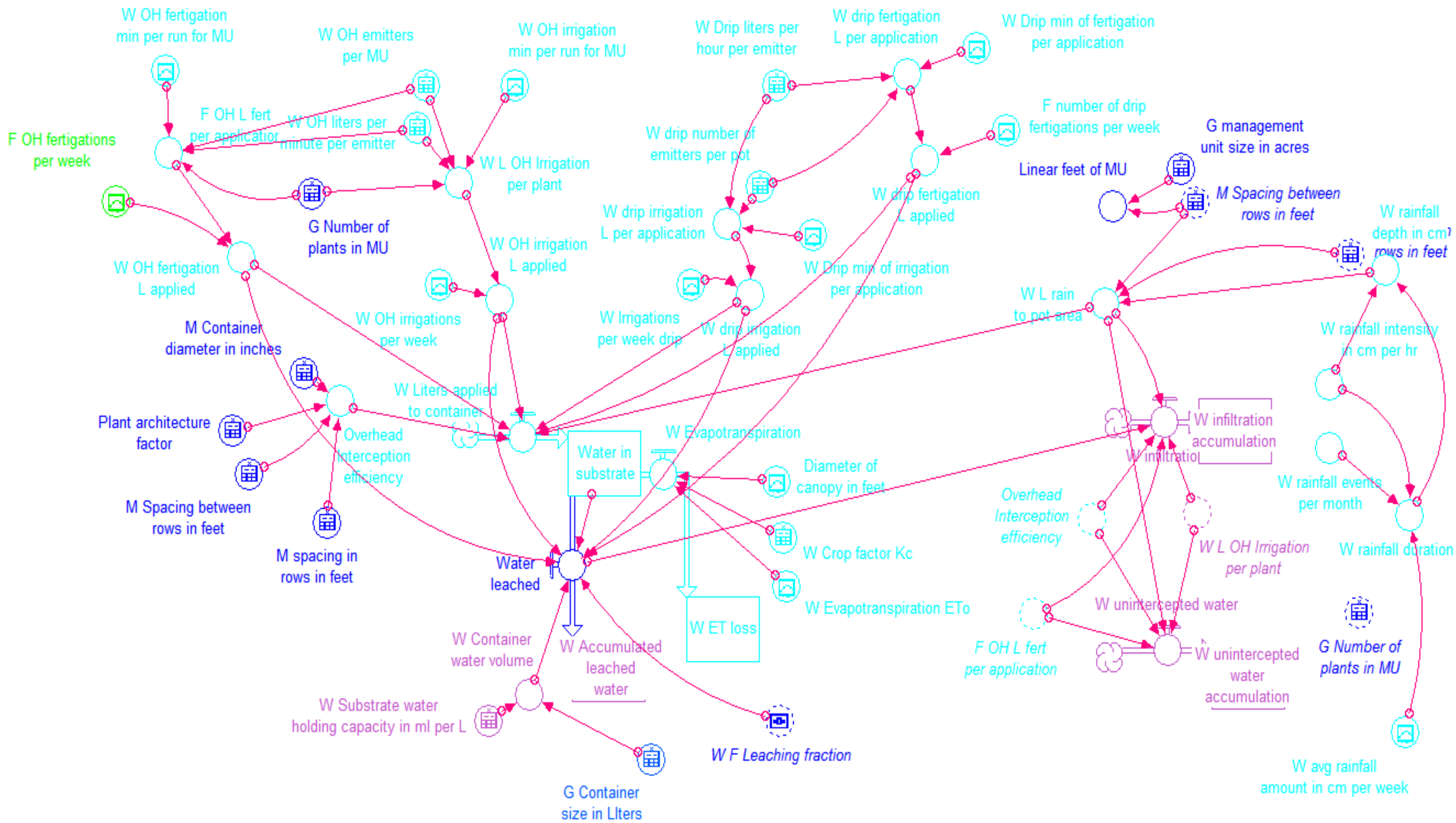

Figure 5.4. Container model modeling layer showing water inputs and outputs from Stella model. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Green variables indicate fertilizer variables, dark blue are general management variables, light blue variables are water variables, and purple are leaching and nutrient removal variables.

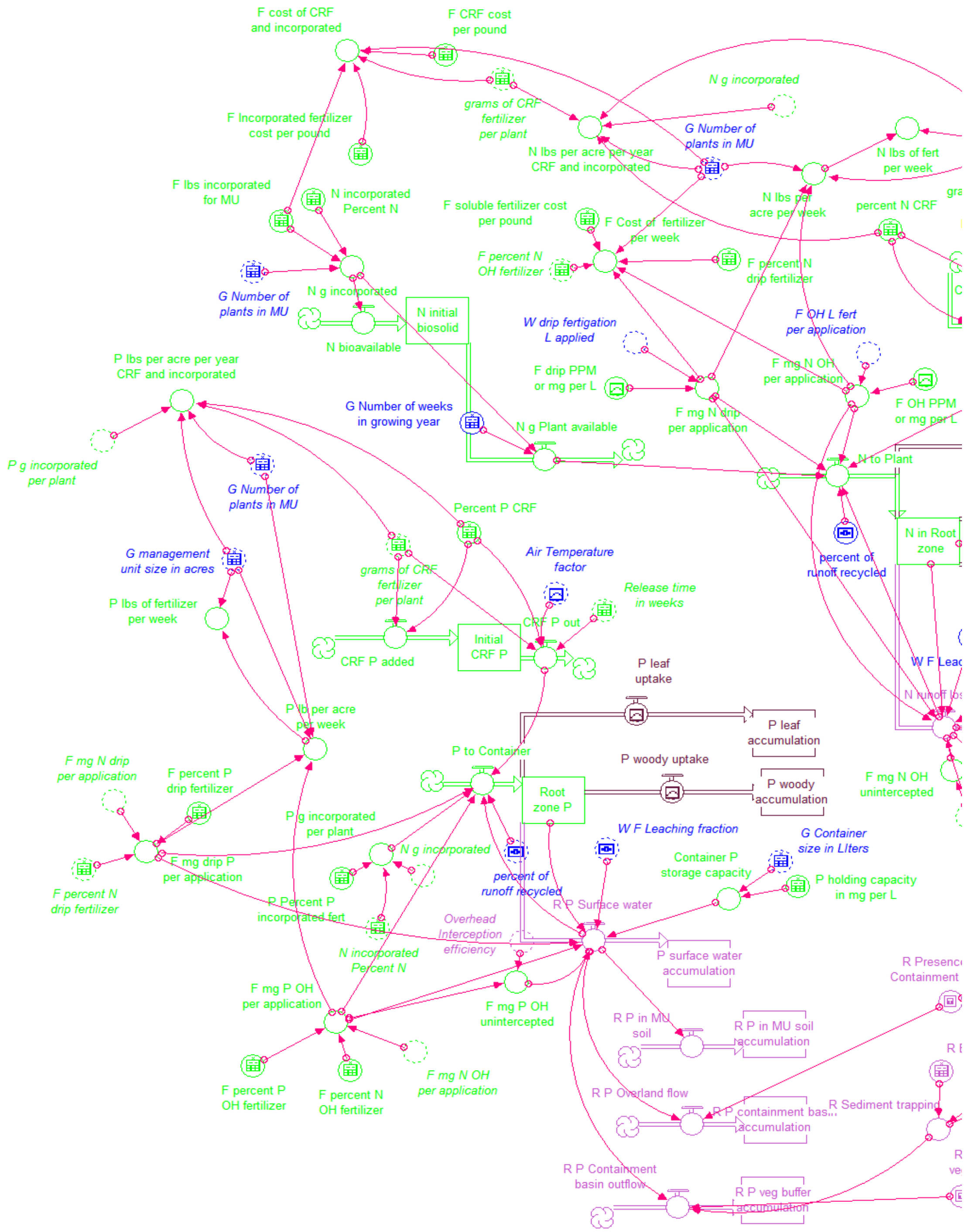

Figure 5.5a. Container model showing variables used for both N and P inputs and outputs. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Fertilization variables are noted in green, general management variables in blue, plant uptake and microbial mechanisms in dark purple, leaching and nutrient removal variables in purple. The complete water portion of the model is shown in Fig. 5.4.

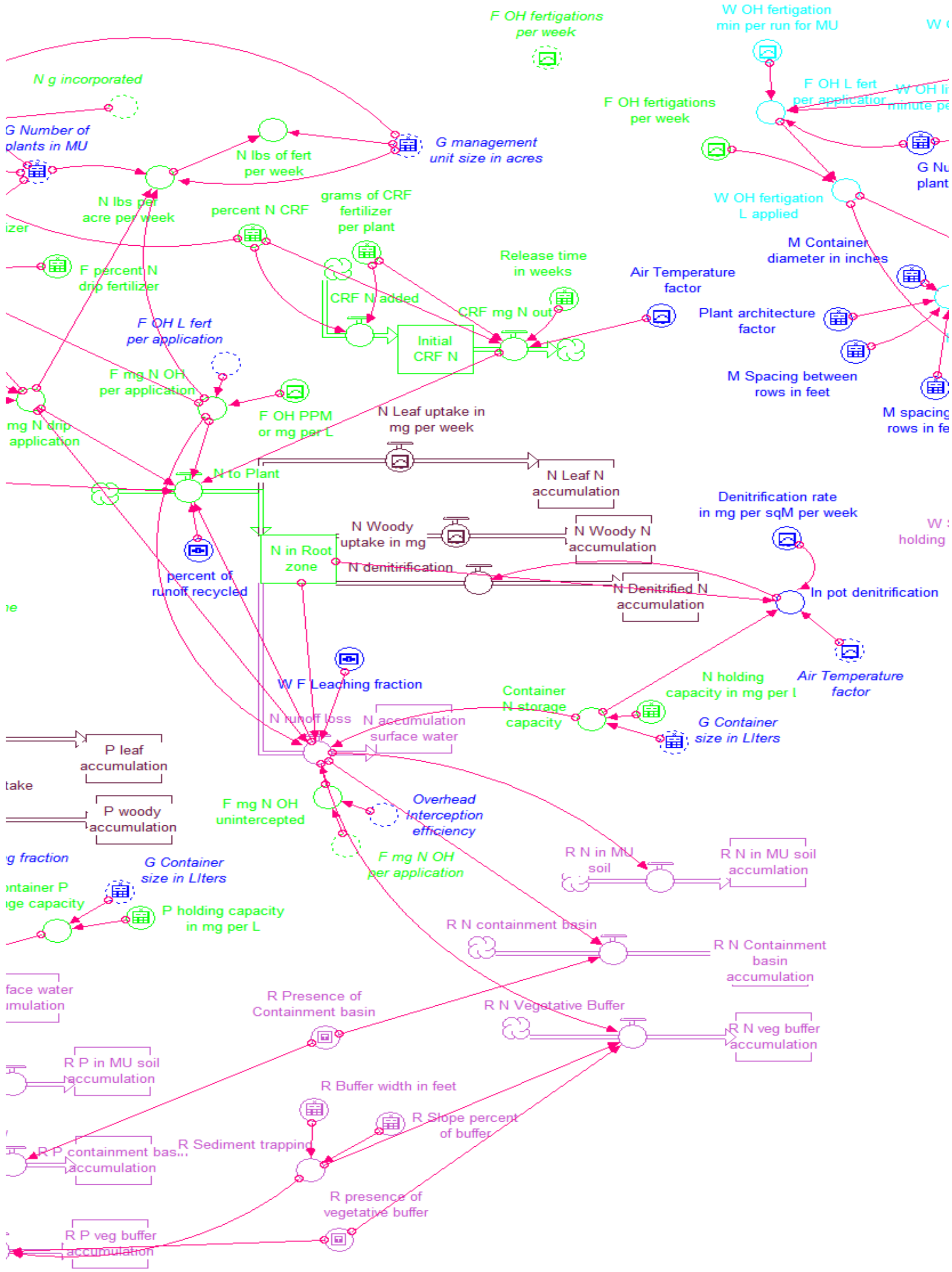

Figure 5.5b. Container model showing variables used for both N and P inputs and outputs. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Fertilization variables are noted in green, general management variables in blue, plant uptake and microbial mechanisms in dark purple, leaching and nutrient removal variables in purple. The complete water portion of the model is shown in Fig. 5.4.

C. Model Calibration – Ristvey (2004)

Calibration of the container model was completed in a similar fashion to that described for the greenhouse model (Chapter 4). Data from Ristvey (2004) were used as model inputs, with constant values used in the model provided in Table 5.2. Graphical input values are included in Appendix E (App. Table E.1, E.2, and E.3), due to the large amount of space required to report input values. Data set 1 for drip irrigation was used for model calibration (Table 5.3, 5.4, 5.5). Any model variables that were not reporting appropriate values were either corrected, by adjusting the formula or internal logic, if doing so could be justified. For example, values for denitrification were increased slightly compared to the values reported for the field model (see Chapter 6), since it is likely that denitrification rates are higher in soilless substrates due to higher temperatures, more carbon availability (higher organic matter content), and more frequent irrigation leading to more frequent anoxic conditions. The values used in the greenhouse model, are approximately similar to the values reported for the field. To compare the rate used in the greenhouse to the rate used in the container model, I assumed the 350 ml container used in Agner (2003) is a square with sides 3 inches (based on information from Maryland Plants and Supplies Catalog). The surface area of this container would be 58.1 cm^2, which is then converted to m^2 (0.0581) and multiplied by the lower end of the rates used in the container model of 150 mg/m^2/week (range is 100 to 300 mg/m^2/week) that gives 8.7 mg/week, which is similar to the low rate used in the greenhouse model of 5.1 mg/L/week.

Table 5.2. Constant input values used for model calibration, from Ristvey (2004).

Variable	Value
MU size (acres)	0.26
# of plants in MU	1792
Between row spacing (ft)	0.75
In row spacing (ft)	0.75
Container diameter (in)	9.0
Container size (L)	11.7
# of weeks in growing year	40
N holding capacity (mg/ L)	75
P holding capacity (mg/ L)	10
Plant architecture factor	1.0
Crop factor Kc	0.8
Substrate water holding cap. (ml/ L)	200
OH emitters per MU	0
OH L/ min per emitter	0.5
OH Coefficient of uniformity	0.9
Drip L/ hr per emitter	1.2
Drip # of emitters per pot	1
grams of SRF fertilizer per plant	51.7
SRF cost per lb	2.00
SRF N %	19.0
SRF P %	5.0
SRF release time in weeks	40
Drip fertilizer % N	75
Drip fertilizer % P	1.5
OH fertilizer % N	75
OH fertilizer %P	1.5
Soluble fert. $/ pound	1.00
Buffer width (ft)	50
Slope of buffer (%)	4.0

D. Results and Discussion

i. Model Calibration/ Validation - Ristvey (2004)

Ristvey (2004) examined the impact of several different cultural practices on azalea (*Rhododendron* 'Karen') and holly (*Ilex cornuta xregosa* 'China girl') N and P uptake during a comprehensive 40-month study that compared water and nutrient runoff dynamics from drip vs. overhead irrigation, cyclic irrigation and time-domain reflectometry (sensor) scheduling. Dataset 1 drip irrigation was used for model calibration, while dataset 1 overhead irrigation, and datasets 2 and 3 were used for model validation. For dataset 1 plants had SRF incorporated at planting (July) and were top dressed with SRF in January. In addition, 2 fertigations/ week were applied from August to November, and then May to September with either 75 mg N/L or 150 mg N/L, with P applied at a constant 1.5 mg P/L. In dataset 2, plants were top-dressed with SRF in January (dataset ran from September to September), with either 75 mg N/L or 150 mg N/L and 1.5 mg P/L. Plants were fertigated twice a week from April to September. Dataset 3 used continuous fertigation (no SRF) at 50, 75 or 100 mg N/L and P applied at either 1.5 or 4.5 mg P/L.

The container model was validated simulating March to November conditions for each run, with the total amount of SRF applied at the beginning of the run (for dataset 1), and fertigation starting at week 5, and ending at week 32. Although this does not exactly match the reported conditions, the changes made for the model run should not have had a large impact on the results. The azalea data was used for validation, to compare model outputs to a low nutrient-using plant.

Plant N and P uptake were changed for each dataset (comparing overhead vs. drip; Table 5.3), since there was such a large difference seen in plant uptake between datasets. Total N application rates were similar between published results and model runs for five of the six runs (Table 5.3). Dataset 3, drip irrigation Ristvey (2004) reported 21.51 g of N applied, while the model reported 34 g of N applied. This difference is likely partially due the higher volume of fertigation applied (Table 5.5), and it is possible that the models application rates in mg/L did not exactly match those reported. Plant N uptake rates were similar between published and model results for all runs although the value for N uptake in the model is slightly higher than that reported for dataset 2 overhead irrigation (Table 5.3).

Model runoff rates were higher than all published rates, except for dataset 3 overhead irrigation. It is likely that the model rates are higher, since the denitrification rates are lower in the model compared to the unaccounted N amount that was published. It makes sense that denitrification and runoff values are linked, since plant uptake values closely matched published results, so if denitrification is not occurring, then more N is left in the substrate, which is going to leach when additional N is added. For all model results, the columns for surface water and ground water (leaching into soil) runoff were combined to simplify reporting, and to match how the results were reported in the published research. For both the Ristvey and Cabrera datasets that were run, the model underestimated the amount of denitrification, especially at higher rates of N addition. After reviewing the published information and comparing it to model results, it is possible that denitrification rates are exponential with increasing N in the substrate, while the model is using a linear relationship. If this is true, it would explain why

Table 5.3. Data comparison of Nitrogen values for Ristvey (2004) compared to model outputs. The values for unintercepted N are reported for model results, while these values were included in runoff values reported in Ristvey (2004). Unintercepted N values for the model are included in the runoff values column, but are also shown separated out to highlight the inefficiency of overhead fertigation. Shaded values represent published results, while unshaded values represent model outputs. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Dataset		N applied (g)		Deviation	Plant N (g)		Deviation	Runoff N (g)		Deviation
1	Drip	11.87	14.5	0.22	2.46	2.5	0.016	0.69	6.8	8.86
	OH	11.84	13.3	0.12	2.46	2.5	0.016	2.41	5.5	1.28
2	Drip	13.81	16.3	0.18	4.87	4.4	0.097	1.4	6.0	3.29
	OH	33.55	34.1	0.017	6.2	7.4	0.19	7.53	12.1	0.61
3	Drip	21.51	34.0	0.58	6.63	6.7	0.011	11.12	18.2	0.64
	OH	94.47	93.3	0.012	7.16	7.2	0.006	56.49	49.1	0.13
Avg. Deviation				**0.19**			**0.056**			**2.47**

Table 5.3. (Continued)

Dataset		Unaccounted/ denitrified N (g)		Deviation	Substrate N (g)		Deviation	Unintercepted N (g)
1	Drip	9.2	6.2	0.33	0.02	0	1.0	0
	OH	7.5	5.6	0.25	0	0	0	0.6
2	Drip	8.4	6.8	0.19	0.87	0	1.0	0
	OH	21.0	5.1	0.76	0.87	0.01	0.99	10.6
3	Drip	5.7	9.2	0.61	0.1	1.51	14.1	0
	OH	30.3	9.2	0.70	0.49	1.51	2.08	30.7
Avg. Deviation				**0.47**			**3.20**	

Table 5.4. Data comparison of Phosphorus values for Ristvey (2004) compared to model outputs. The values for unintercepted P are reported for model results, while these values were included in runoff values reported in Ristvey (2004). Unintercepted P values for the model are included in the runoff values column, but are also shown separated out to highlight the inefficiency of overhead fertigation. The column recovered P was included, since this value was relatively low, and potentially accounts for the differences in P runoff between the model and published results. Shaded values represent published results, while unshaded values represent model outputs. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Dataset		**Applied P (mg)**		**Deviation**	**Plant P (mg)**		**Deviation**	**Runoff P (mg)**		**Deviation**
1	Drip	1408	2625	0.86	343	353	0.029	59	2249	37.1
	OH	1304	2615	1.01	429	431	0.005	89	2183	23.5
2	Drip	1150	1742	0.51	418	421	0.007	100	1287	11.9
	OH	1480	1913	0.29	571	573	0.004	220	1247	4.7
3	Drip	1450	1765	0.22	632	637	0.008	140	946	5.8
	OH	6710	4842	0.28	786	569	0.28	840	1823	1.2
Avg. Deviation				**0.53**			**0.055**			**14.0**

Table 5.4. Continued

Dataset		**Root zone P (mg)**		**Deviation**	**Unintercepted P (mg)**	**Recovered P (%)**
1	Drip	15	35	1.3	0	24.9
	OH	4	7	0.75	54	35.6
2	Drip	69	46	0.33	0	35.1
	OH	61	0	1.0	215	41.2
3	Drip	60	197	2.3	0	48.2
	OH	60	197	2.3	1595	22.9
Avg. Deviation				**1.3**		

denitrification rates are lower in the model compared to published result for both Ristvey (2004) and Cabrera (2003) at higher rates of N addition. As mentioned previously, more research into denitrification rates in soilless substrates and particularly in container operations would be beneficial to closer match model output to published results. It is worth mentioning that no published results could be found for denitrification rates in container operations, after an extensive literature search.

There is also a difference in the amount of substrate N at the end of the run in the model versus the published results. The model reported no N for the first three runs, while the published results report 0 to 0.87 g. The fourth run reported 0.01 g, while the published result was 0.87 g. The last two runs both reported 1.51 g in the container, with the published results reported to be 0.1 and 0.49g for drip and overhead respectively. Fertigation was stopped at week 32 for the first four dataset runs (datasets 1 and 2; drip and overhead), and the SRF that was added at the beginning of the run was used up by the end of the growing season (data not shown). The models were also set up to have leaf N mainly taken up during the first 20 weeks of the run, while woody N was mainly taken up during weeks 24-36. This was done to simulate spring flush and plant growth during the summer, with a reduction in growth and uptake later in the growing season. Since N addition was completed around week 32, no additional N entered the container after that time, so the N that was being removed after this time was N remaining in the container substrate (data not shown). If N fertigation had continued for another few weeks, it is likely that some additional N would have been reported to be in the container. Again, the value for N in the substrate is a point measurement taken at the end of the run, so some variability is expected from published results.

The model also calculated the amount of N that was unintercepted by the container, which was not reported separately from the container runoff in the published research. In the model, the unintercepted N value is based on interception efficiency (surface area of container/ total area for container) for overhead irrigation. Drip irrigation has 100% interception efficiency, so there was no unintercepted N. Overhead irrigation was found to have 0.6, 10.6, and 30.7 g of N unintercepted for datasets 1, 2, and 3 respectively (Table 5.3). The unintercepted N values in Table 5.3 are included as part of the runoff N column for the model runs, but were also separated out to highlight the inefficiency of overhead fertigation, especially at increasing distances between containers. The main difference between these three datasets, with regard to N interception, was in container spacing, as containers were spaced further apart between datasets, as the plants grew larger and were therefore spaced as they would have been in a commercial nursery. For this reason, more than a third of the N applied was not intercepted in datasets 2 and 3, which should be a strong incentive for growers using overhead fertigation to change practice, for anything but the closest container spacings. Based on the results from Ristvey (2004), a number of growers in Maryland switched to SRF, and discontinued the use of overhead fertigation at their operations.

Although the same rate of P was used for model runs, compared with the rates reported in Ristvey (2004), the model reported about 1.2 and 0.5 g more P applied for datasets 1 and 2 respectively, while dataset 3 slightly over-applied P for drip, but underestimated P for overhead by almost 2 grams, with deviations from 0.22 to 1.01 (Table 5.4). It is not clear why the models are reporting slightly different rates of P addition compared to published results. Plant uptake rates were similar for all data sets except overhead irrigation for dataset 3 (deviation 0.28), which reported lower P uptake compared to published results. This was perhaps due to P rates limiting plant uptake early in the run when fertigation was not being applied, and SRF release rates were still low due to low temperatures (data not shown). As stated previously, plants are able to compensate for low nutrient availability for part of the year, while the models are not able to do so, at least in their current configurations. The models are therefore limited in their ability to precisely fine-tune N and P uptake dynamics in this respect.

Runoff P rates for the model run are substantially higher than the runoff rates that were published. These results are likely linked to the low P recovery rates reported in Ristvey (2004), as indicated in the last column (Table 5.4). Since the model had close to 100% P recovery, this excess P was shown in the runoff portion of model results, whereas in the published results, it was included as unrecovered P. Typical P recovery rates reported in the literature are often in the 60-90% range, so the values reported in Table 5.4 are lower than expected (Tyler et al. 1996b; Ku and Hershey 1997b; Williams et al. 2000). It is also worth noting that the container model does not have a microbial P uptake function included, unlike the greenhouse model. It was assumed that microbial uptake was likely to have less of an impact in container compared to greenhouse operations, but this assumption may be incorrect. Future model iterations could include an analysis of microbial P use, which is likely to account at least for part of the P that is not recovered in container-nursery studies. As mentioned for the greenhouse model, there were no published microbial P uptake rates that could be found to include in the model.

Root zone P rates were similar for datasets 1 and 2 (Table 5.4), with the model predicting slightly higher P in the container versus those reported by Ristvey (2004). Even though fertilizer had not been added for approximately 8 weeks from the end of the model run, there was still sufficient P in the substrate to meet plant growth requirements, indicating the relatively low P requirements of plants compared to N, which was shown to be depleted in the containers by the end of the model run.

Table 5.5 shows the comparison of irrigation results between the model run and those published by Ristvey (2004). Overhead irrigations closely matched reported results, for datasets 1 and 2. When dataset 3 was originally run through the model, the results for N, P and water were much lower than the published values (data not shown). When irrigation time was increased to 270 minutes per irrigation, from 90 minutes per irrigation, without changing any other variables, the results (Tables 5.3, 5.4 and 5.5) closely matched the published results for N, P and water. Model estimates for drip irrigation in datasets 1 and 2 were about double the reported values, while dataset 3 was only slightly higher than the reported values (Table 5.5). It is unclear why these irrigation values were different from those reported by Ristvey (2004) since the N values reported were similar to published values, and the irrigation information that was used was based on published results.

Evapotranspiration values reported by Ristvey (2004) were higher than those reported by model outputs for all but dataset 3 drip irrigation (Table 5.5). It is likely that part of the reason why model values are lower is because the models do not take into account the water that directly evaporates from the surface of leaves, substrate and production bed area etc. during and after an irrigation or rain event. Up to 30 or 40% of

Table 5.5. Data comparison of water values for Ristvey (2004) compared to model outputs. The values for water leached are reported for model results, while these values were not reported in Ristvey (2004). Shaded values represent published results, while unshaded values represent model outputs. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Dataset		Total water Applied (L)		Deviation	ET (L)		Deviation	Runoff (L)		Deviation	Water leached (L)
1	Drip	240.3	472	0.96	182.4	67	0.63	57.9	230	3.0	190
	OH	343.2	328	0.044	216.2	67	0.69	127.0	179	0.41	95
2	Drip	451.7	978	1.2	324.2	203	0.37	127.5	416	2.3	251
	OH	788.3	585	0.26	420.4	139	0.67	367.9	424	0.15	16
3	Drip	679.0	675	0.006	278.4	358	0.29	400.6	332	0.17	140
	OH	2093.0	2313	0.11	779.2	482	0.38	1313.3	1165	0.11	1324
Avg. Deviation				**0.42**			**0.51**			**1.01**	

the overhead irrigation that is applied can be lost due to evaporation before it reaches the container substrate (Ross 2008a). It is also possible that the K_c value or the canopy diameter estimates that were used in the model were too low, resulting in reduced ET values over published results. However, given the disparate ranges of data from these six datasets that were run in this model validation, it was felt that these values provided reasonable approximations of the data over all runs.

A comparison of runoff rates are also included in Table 5.5. Runoff rates reported by the model are higher than the published runoff rates for all datasets except dataset 3 overhead irrigation, although the values for dataset 1 overhead are similar. It is likely that that higher runoff rates reported by the model would have been reduced if ET rates were similar to published results and/or similar volumes of water were applied.

In addition to the published results, the amount of water leached through the container, reported by the model, is also included in Table 5.5. This data was not reported by Ristvey (2004). For datasets 1 and 2, drip irrigation led to higher leaching rates, since all applied water was intercepted compared to overhead irrigation, which had lower interception efficiencies. Dataset 3 showed much higher leaching rates using overhead compared to drip, since much more water was applied using overhead irrigation.

ii. Validation – Cabrera (2003)

A second dataset was run through the container model, similar to the greenhouse model to test the container model using a different set of conditions. For the second set of model runs, information from Cabrera (2003) was used as model inputs (changing only the variables necessary to replicate reported conditions), and the outputs were compared to published results. For this publication, *Ilex opaca* 'Hedgeholly' and *Lagerstroemia x* 'Tonto' were grown for 9 months using six different N rates (15, 30, 60, 120, 210, 300 mg/L), to determine the impact of N rate on plant growth and leaching losses. The author notes that leaf N concentrations were 2.53% and 2.67% for *Ilex* and *Lagerstoemia* respectively, and 22.8 to 40.6 % of the N that was applied was not recovered during the experiment (presumably due to denitrification). Data for *Ilex* was run through the model, since Ristvey (2004) reported on a similar species (*Ilex cornuta xregosa*) to be a high nutrient user, so the model was therefore validated by using inputs for both high and low nutrient-using species. It was reported by Cabrera (2003) that plants were irrigated 1-2 times per week (based on gravimetric analysis) during the growing season using spray stakes, with a targeted leaching fraction of 25%. This study was chosen for validation because of the detailed methods that were reported, and because the results could be compared to model outputs. This paper did not report P analysis, so the P outputs could not be compared to published results. It should also be noted that P application rate was reported as 1 mM, which was used to calculate P in mg/L, as 1 mM = 0.001 moles/L x 96.97 g/mol (for H_2PO_4) = 0.09697 g/ L = 96.97 mg/ L. This rate was used for all six runs, which is a high rate of P even at 300 mg/L N; this is reflected in the P results, reported below.

Constant values and graphical values were based on published information, summarized in Appendix E Tables E 5.5 and E 5.6 – E 5.8, respectively. Constant values were not changed during model runs, but mg/ L N in Appendix E Table E 5.7 and N and

P uptake in Appendix E Table E 5.8 were varied to match reported values. Models were run for 40 weeks, which approximated the 9 months reported in the study. It should be noted that in the published study, plants were shielded from rainfall with a plastic sheet placed above the plant canopy, so all water was applied by irrigation. For the model, rainfall per month was set to zero to simulate no rainfall. This would also be the recommended way to model any greenhouse plants which uses SRF or a combination of SRF and fertigation (i.e. mums, hanging baskets etc).

Similar rates of N were applied for all six model runs compared to published results (Table 5.6). Values for plant N uptake were also similar for all six model runs, suggesting that N rates were not limiting at any time during the run. Leaching rates were lower for the 15, 30 and 60 mg/ L rates, similar for 120 mg/ L, and higher than published values for the 210 and 300 mg/ L runs. The lower leaching rates might be because the N holding capacity was set too high, while the higher leaching rate for the 210 and 300 mg/ L runs is likely due to the lower denitrification rate for these runs, compared to the N that was unaccounted for in the published results. For the 15 mg/ L to 120 mg/ L runs, denitrification rates are similar for the model results compared with the “unaccounted for” N in the published results.

Denitrification rates at 210 and 300 mg/ L were much lower than the published “unaccounted for” N, with the model N loss less than half the reported loss for 210 mg/ L, and almost a quarter of the reported N loss for 300 mg/ L. This suggests, as mentioned above, that is possible that denitrification rates are quadratic, while the model currently uses a linear rate, which may account for the discrepancies at the higher N rates. Model results for the amount of N left in the substrate at the end of the run were higher for the

15, 30, and 60 mg/ L rates, but were similar for the 120, 210, and 300 mg/ L rates compared to published results (Table 5.6).

As mentioned previously, results for P allocations were not published by the author, but the results for the model runs are reported in Table 5.7. Phosphorus uptake rates were assumed to be 10% of the N uptake rates for each run. These values were then split between leaf and woody tissues at a 3:1 ratio, to represent the approximate amount of P stored in leaves and root/stems respectively. All of the model runs report high rates of P leaching, which indicate that P was applied at an excessive rate in this research study. Leaf and woody P uptake are similar to input levels, indicating that P was not limiting during plant growth.

Irrigation information is reported in Table 5.8, with the amount of water applied being the only published result reported by Cabrera (2003) that could be compared to model results. The model applied a slightly higher rate of water compared to the published results, with all model runs applying the same volume of irrigation. The same volume of irrigation, and irrigation timing was used for each run, so these values are expected to be the same for each run. Evapotranspiration levels were high compared to volume of irrigation applied, with correspondingly low leaching levels compared to the target leaching fraction of 25% that was reported in the article, although no leaching or ET information was provided by Cabrera (2003).

It is likely that either the K_c value or the canopy diameter (both of which were assumed) were too high under these conditions, since no leaching was observed, although leaching was reported. It would have been possible to reduce these numbers in order to

Table 5.6. Data comparison of Nitrogen values for Cabrera (2003) compared to model outputs. Shaded values represent published results, while unshaded values represent model outputs. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

N (mg/L)	Applied N (mg)		Deviation	Plant N (mg)		Deviation	Leached N (mg)		Deviation
15	243	256	0.053	114	115	0.009	40	0	1
30	536	512	0.045	266	282	0.060	118	0	1
60	1053	1025	0.027	416	417	0.002	309	13	0.96
120	2085	2050	0.017	367	368	0.003	924	960	0.039
210	3673	3587	0.023	323	328	0.015	1888	2693	0.43
300	5276	5124	0.029	417	417	0	2385	4303	0.80
Avg. Deviation			**0.032**			**0.015**			**0.71**

Table 5.6. Continued

N (mg/L)	Unaccounted/ Denitrified N (mg)		Deviation	Substrate N		Deviation
15	87	106	0.22	2	67	33
30	134	138	0.030	1	123	122
60	273	315	0.15	56	312	4.6
20	482	527	0.093	311	312	0.003
210	1164	547	0.53	298	310	0.040
300	2142	563	0.74	332	312	0.060
Avg. Deviation			**0.29**			**27**

Table 5.7. Results of Phosphorus outputs for six model runs. Phosphorus results were not reported in Cabrera (2003) so the values could not be compared to published results.

N (mg/L)	Applied P (mg)	Leaf P (mg)	Woody P (mg)	Root zone P (mg)	Leached P (mg)
15	1755	5.5	7.9	52.3	1682
30	1755	20.1	7.9	52.4	1670
60	1755	31.4	10.3	52.4	1653
120	1755	27.7	9.1	52.4	1664
210	1755	26.5	9.9	52.4	1665
300	1755	27.7	9.1	52.4	1665

Table 5.8. Data comparison of water values for Cabrera (2003) compared to model outputs. Shaded values represent published results, while unshaded values represent model outputs.

N (mg/L)	Applied water (L)		Deviation	Evapotrans-piration (L)	Leached water (L)
15	16.2	18.1	0.12	18.4	0
30	17.9	18.1	0.011	18.4	0
60	17.6	18.1	0.028	18.4	0
120	17.4	18.1	0.040	18.4	0
210	17.5	18.1	0.034	18.4	0
300	17.6	18.1	0.028	18.4	0
Avg. Deviation			**0.043**		

produce leaching, but since there were no values to compare these numbers to, the models were not rerun.

E. What-if Scenarios

After the models were validated, a number of what-if scenarios were run to test the hypotheses below, similar to the procedure reported for the greenhouse model (Chapter 4). The general conditions for each model run were similar, with only the variables for that particular run being changed. The complete table of the constants that were used is available in App. Table E 5.9. Briefly, model conditions were as follows. Plants were spaced as closely as possible using 23 cm (9 inch) diameter containers (23 cm between and in rows). Container size was set to 6 L (1.6 gal) with an N holding capacity of 75 mg/ L and a P holding capacity of 10 mg/ L. Water holding capacity was set to 20% (200 ml/ L). The crop factor (K_c) was set to 0.8. Slow release fertilizer was added at a rate of 45 g per container, using a 20-3-8 fertilizer with a 10-12 month release time. The recommended medium rate, based on the manufacturer's recommendation (Harrell's Professional Fertilizer Solutions, Lakeland FL), was 22 g for a 1 gallon container, and 96 g for a 3 gallon container. Irrigation was applied either as overhead irrigation or with fertigation (except where indicated below). Plants were irrigated a total of 179 times over the 40 week cycle. All other conditions including plant uptake amounts were based on inputs from the Ristvey (2004) dataset 1 for overhead irrigation.

Greenhouse and container models are similar in many respects, since both types of operations grow plants above ground in containers using soilless substrates. The main differences between these two types of operations is the scale and spacing at which plants are grown, the types of fertilizer used, irrigation methods, and that container operations are exposed to rainfall during the growing season. The container and greenhouse model share a number of hypotheses, but there are also a number of different hypotheses that were tested with this model.

i. Container spacing has a large impact on interception efficiency in container operations, with spacings typically wider in container operations compared to greenhouse operations. Container operations that use overhead irrigation with containers that are closely spaced together are likely to have similar interception efficiencies to greenhouse operations. Container spacings of 23 cm (9 inch) and 46 cm (18 inches) were used for 11.6 L containers and 91 cm (36 inches)) was used for 19.4 L containers.

Hypothesis #11: When containers are more widely spaced, interception efficiencies will decrease, causing more water runoff, compared with more closely spaced containers.

In order to test hypothesis #11, i.e., that wider plant spacing decreases efficiency and produces higher rates of unintercepted water (runoff), three different container spacings were used, with two different container sizes. The same amount of water was delivered to each container, since the length of irrigation did not change for the three runs. Evapotranspiration and leaching were also very similar, since similar amounts of irrigation were applied (Table 5.9). The main difference was seen in the amount of unintercepted water, with the 23 cm spacing reporting 23.4 L unintercepted while the 46 cm and 91 cm spacing both reporting 350.3 L of water unintercepted. It was unexpected that the two larger spacings had similar amounts of unintercepted water, although container size did increase between the second and third run. The interception efficiency was determined to be 78.4 % for the 23 cm spacing, 19.6% for the 46 cm spacing, and 12.0% for the 91 cm spacing (data not shown), so the last two runs did have similar interception efficiencies. Based on this information, the hypothesis is accepted, especially for the first two runs in which wider spacing decreases interception efficiency and leads to higher rates of runoff. It is likely that running the last scenario, with the same container size as the first two runs would have a higher rate of unintercepted runoff water compared to the second run.

ii. As discussed previously, interception efficiency has a substantial impact on the amount of runoff coming off of an operation. Drip irrigation systems typically have close to 100% interception efficiencies since the drip emitter is located just above the substrate surface. Overhead irrigation systems have a variety of interception efficiencies mainly depending on container spacing. If the same volume of irrigation is delivered to the container by both drip and overhead irrigation/fertigation, what is the impact on nutrient leaching and runoff?

Hypothesis # 12: A drip system delivering similar N and P amounts to the surface of the container as an overhead system, will result in less N, P and water leaching, due to the more precise placement of nutrient and irrigation water using drip irrigation.

Drip irrigation should be able to more efficiently deliver water and nutrients compared to overhead irrigation, without decreasing plant nutrient or water uptake. Drip emitters (1 per container) were run for 30 minutes and delivered 1.2 L/ min, while overhead emitters (100/ MU) were run for 120 minutes at 7.5 L/ min to apply the same amount of fertilizer as in the drip irrigation run. Plant N uptake was slightly higher in drip irrigation compared to overhead (0.83 g vs. 0.75 g respectively), while delivering similar overall amounts of nutrients (4.82 g vs. 4.80 g respectively) (Table 5.10). Denitrification rates were higher in drip (1.74 g) vs. overhead (0.95 g), while overhead had 1.03 g of N unintercepted, compared to 0 g unintercepted with drip (Table 5.10). Phosphorus was reported to have 223 mg unintercepted using overhead, and 0 mg using drip, with all other values being similar (Table 5.11). Drip irrigation was able to apply almost 100 L less irrigation compared to overhead, to achieve the same amount of nutrient addition (224.3 vs. 313.7 respectively), together with lower leaching and unintercepted volumes (Table 5.9). It should be noted that these values are for closely spaced containers, with larger differences likely with containers that are more widely spaced. Hypothesis #12 is therefore accepted, i.e., that drip fertigation can deliver nutrients and water more efficiently, even at close spacings which would increase interception efficiency for overhead systems.

iii. Substrate N, P, and water holding capacity were studied in the container model, with similar values used in the greenhouse model. Since soilless substrates are used in both greenhouse and container operations, increasing substrate N, P, and water holding capacities were tested. Nitrogen holding capacities were set to 50, 100, or 300 mg/ L, P holding capacities were set to 25, 50, and 150 mg/L, and water holding capacities were set to 10, 20 and 40% of container volume.

Hypothesis # 13: Higher substrate holding capacities for N, P and water should result in reduced nutrient leaching, since increasing these chemical and physical properties will result in larger amounts of N, P and water reserves, per unit volume of substrates.

Hypothesis #13, which states that increasing the N, P and water-holding capacities of substrates should lead to decreased leaching was tested both in the greenhouse model (Chapter 4), and with this container model. Whereas few differences were seen for the greenhouse model, the container model does show an impact of increasing holding capacity on nutrient and water dynamics. Higher rates of denitrification were observed (4.91g for 50 mg/ L vs. 6.6 g for 300 mg/L) by increasing N-holding capacity (Table 5.10), resulting in less N runoff to surface water (5.99 g vs. 3.95 g respectively) and leachate water (0.6 g vs. 0.4 g respectively). Similar results were seen for P, with higher rates retained in the substrate for 150 mg/ L vs. 25 mg/L (153 mg vs. 903 mg) and a reduction of 675 mg of P in leach water (Table 5.11). Only a small difference was seen among water leachate values for any of the runs, indicating that water holding capacity did not have a large impact of water leaching from the container under these conditions, varying only 0.9 L from the 10% to 40% water holding capacity (Table 5.9). Based on these results, hypothesis #13 would be accepted for N and P, but rejected for water-holding capacity. It is likely that if water is more limiting, i.e. irrigation water is applied less frequently or at a lower volume, the water-holding capacity would have had a greater impact on leaching.

Table 5.9. Results for seven different what if scenarios representing 21 separate model runs applying a variety of water application rates and timings**.**

Scenario	Value	Water to container (L)	Evapo-transpiration (L)	Water leached (L)	Unintercepted water (L)
Container size and spacing	7.6 L 23cm	91.8	56.3	34.2	23.4
	46cm	91.5	56.3	33.9	350.3
	91 cm	91.5	56.3	33.9	350.3
Drip		224.3	56.3	166.6	18.9
Overhead		313.7	56.3	256.0	39.6
N and P capacity (mg/L); Water holding capacity (%)	50, 25, 10	237.3	56.3	179.9	39.6
	100, 50, 20	237.3	56.3	179.6	39.6
	300, 150, 40	237.3	56.3	179.0	39.6
Plant Architecture	0.5	118.6	56.3	62.3	112.2
	0.9	213.6	56.3	156.0	54.1
	1.1	261.0	56.3	203.2	25.1
	1.5	355.9	56.3	297.7	0.0
Crop Coefficient (K_c)	0.5	237.3	35.2	200.6	39.6
	1.0	237.3	70.3	165.6	39.6
	1.5	237.3	105.1	131.7	39.6
	2.0	237.3	138.3	98.9	39.6
	4.0	237.3	223.1	14.2	39.6
Cyclic irrigation simulation	90 min	195.3	56.3	137.7	37.0
	60 min	153.4	56.3	95.7	34.4
Irrigation decisions	Weekly	239.3	56.3	181.5	39.6
	Monthly	239.2	56.3	181.5	39.6

Table 5.10. Nitrogen results for seven different what-if scenarios, representing 21 separate model runs.

Scenario	Value	Leaf N (g)	Woody tissue N (g)	Surface water N (g)	Leach water N (g)	Denitrified N (g)	Applied N (g)	Unintercepted N (g)
Container size and spacing	7.6 L 23cm	1.84	0.46	2.60	0.26	4.15	9.00	0.00
	7.6 L 46 cm	1.84	0.46	2.60	0.26	4.15	9.00	0.00
	19.4 L 91 cm	1.84	0.46	2.60	0.26	4.15	9.00	0.00
Drip		1.87	0.83	0.00	0.00	1.74	4.80	0.00
Overhead		1.81	0.75	1.03	0.10	0.95	4.82	1.03
N and P capacity (mg/L), Water holding capacity (%)	50, 25, 10	1.87	0.83	5.99	0.60	4.91	13.82	1.03
	100, 50, 20	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	300, 150, 40	1.87	0.83	3.95	0.40	6.60	13.82	1.03
Plant Architecture	0.5	1.87	0.75	6.10	0.61	4.99	13.82	2.92
	0.9	1.87	0.83	5.40	0.54	5.47	13.82	1.41
	1.1	1.87	0.83	5.05	0.51	5.74	13.82	0.65
	1.5	1.87	0.83	4.73	0.47	6.00	13.82	0
Crop Coefficient (K_c)	0.5	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	1.0	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	1.5	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	2.0	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	4.0	1.87	0.83	5.23	0.52	5.61	13.82	1.03
Cyclic irrigation simulation	90 min	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	60 min	1.87	0.83	5.23	0.52	5.61	13.82	1.03
Irrigation decisions	Weekly	1.87	0.83	5.23	0.52	5.61	13.82	1.03
	monthly	1.87	0.83	5.23	0.52	5.61	13.82	1.03

Table 5.11. Phosphorus results for seven different what if scenarios representing 21 separate model runs**.**

Scenario	Value	Leaf P (mg)	Woody P (mg)	Surface water P (mg)	Leach water P (mg)	Root zone P (mg)	P to container (mg)	Unintercepted P (mg)
Container size and spacing	7.6 L 23cm	264	104	988	49	0	1350	0
	7.6 L 46 cm	264	104	988	49	0	1350	0
	19.4 L 91 cm	264	104	988	49	0	1350	0
Drip		265	107	395	20	300	1038	0
Overhead		265	107	392	20	303	1041	223
N and P capacity (mg/L); Water holding capacity (%)	50, 25, 10	265	107	1877	94	153	2391	223
	100, 50, 20	265	107	1742	87	303	2391	223
	300, 150, 40	265	107	1202	60	903	2391	223
Plant Architecture	0.5	265	107	1743	87	301	2391	632
	0.9	265	107	1742	87	303	2391	305
	1.1	265	107	1742	87	303	2391	141
	1.5	265	107	1741	87	304	2391	0
Crop Coefficient (K_c)	0.5	265	107	1742	87	303	2391	223
	1.0	265	107	1742	87	303	2391	223
	1.5	265	107	1742	87	303	2391	223
	2.0	265	107	1742	87	303	2391	223
	4.0	265	107	1742	87	303	2391	223
Cyclic irrigation simulation	90 min	265	107	1742	87	303	2391	223
	60 min	265	107	1742	87	303	2391	223
Irrigation decisions	Weekly	265	107	1742	87	303	2391	223
	monthly	265	107	1742	87	303	2391	223

iv. Plant architecture, or the branching structure of the plant, is important for determining whether water flows down the trunk of the plant like a funnel, or is shed by the plant like an umbrella, either increasing or decreasing irrigation interception efficiency. Plant architecture factor was input as a factor of 0.5 and 0.9, which would indicate that the plant was shedding water, 1.0 which would indicate the plant architecture had no effect, and 1.1 and 1.5, which would intercept and deliver more irrigation water to the root zone. These numbers were chosen to examine the sensitivity of the model to this variable.

Hypothesis #14: The 0.5 plant architecture factor will decrease leaching and increase runoff but may potentially reduce evapotranspiration (and plant growth due to lack of water). The 0.9, 1.0 and 1.1 factors will have minimal impacts on water infiltration; a factor of 1.5 will increase leaching since more water is diverted into the container.

Hypothesis #14 examines the impact of plant architecture on N, P and water interception and leaching, with a smaller plant architecture factor decreasing nutrient and water flow into the container, and a higher factor increasing nutrient and water flow. It can be seen from the model analysis that plant architecture factor does have a substantial impact on nutrient and water allocation. Unintercepted (overhead) N was reduced from 2.92 g to 0 g from the 0.5 to 1.5 plant architecture values respectively (Table 5.10). This led to higher N rates applied into the container, which consequently increased denitrification and reduced N leaching through the container. Similar results were seen for unintercepted P, which was reduced from 632 mg to 0 mg from a plant architecture factor of 0.5 to 1.5 respectively (Table 5.11). Unintercepted water was also reduced from

112.2 L to 0 L under the same conditions (Table 5.11). From this information, I would conclude that the model is very sensitive to the plant architecture factor, and values should be limited to a suggested range of 0.8 to 1.2. If a grower is aware of the impact that plant architecture has on water and nutrient capture, they can use it to their advantage. Irrigation could be applied for a shorter period of time, knowing that water is being funneled into the pot, or they might switch from overhead irrigation to drip for certain plants that tend to shed water outside of the container surface area when water is applied overhead. Based on this information, hypothesis #14 would be accepted for N, P and water.

v. The crop factor (K_c) represents the amount of evapotranspiration that a plant has compared to a reference pan that is filled with water. A plant that has a K_c below 1 transpires less water than an open pan, while a K_c above 1 indicates that the plant transpires more water than an open pan filled with water. It is important for growers to match evapotranspiration to the amount of water applied to maximize the amount of water reaching the root zone and reduce water runoff. K_c values of 0.5, 1, 1.5, 2.0 and 4.0 were used in model simulations to test the sensitivity of the model to this variable. **Hypothesis #15: A lower K_c value will lead to more water runoff if the same amount of irrigation is applied, since the plant is evapotranspiring less, while plants with a higher K_c value should transpire more, which could lead to water deficits in the plant, under the same irrigation conditions.**

The crop coefficient (K_c) value was analyzed next, to test hypothesis #15 which states that as K_c values increase, ET should increase and water runoff should decrease.

This trend is seen in the model run results (Table 5.9), with almost a complete reversal of ET (35.2 L to 223.1 L) to leaching values (200.6 L to 14.2 L) from a K_c of 0.5 to 4 respectively. From this information, I would conclude that the models are sensitive to K_c values, but not nearly as sensitive as was seen for plant architecture. The values reported in Table 5.9 for K_c coincide with the values reported in Table 5.1, which report K_c values of 0.24 to 6.8 for 32 species of ornamental plants. Hypothesis #15 should be accepted, since increasing K_c values resulted in higher ET values and lower leaching rates. It can also be concluded that K_c values provide reasonable results for plant ET and leaching under the conditions tested.

vi. Cyclic irrigation represents a significant way of reducing overhead irrigation water volumes, without negatively impacting plant growth. There are several articles that have shown a 15-25% reduction in irrigation duration, with no negative impact on plant growth using both overhead and drip irrigation (Fare et al. 1994; Tyler et al. 1996a; Mathers et al. 2005). The container model, like the greenhouse model does not have a setting for cyclic irrigation, but cyclic irrigations can be simulated. To simulate cyclic irrigation, irrigation timing was reduced 25% from 120 to 90 minutes. The model was also run with an additional 25% reduction from 90 minutes to 70 minutes.

Hypothesis #16: A reduction of irrigation duration by 25% (representing a cyclic irrigation of 90 minutes, reduced from 120 minutes) will provide adequate water to meet plant requirements, while reducing the volume of runoff water, while a 70 minute irrigation will not provide enough water to meet daily plant water requirements.

Cyclic irrigation was tested for the container model in a similar way to that reported for the greenhouse model. Hypothesis #16 states that reducing irrigation by 25% (from 120 to 90 minutes) will reduce runoff volume while meeting plant irrigation needs, while a further 25% reduction (from 90 to 70 minutes) will be insufficient for plant water needs. Plant ET rates were the same for both the 90 and 70-minute runs, suggesting that the 70-minute irrigation was sufficient to meet irrigation needs under these conditions (Table 5.9). The 70-minute irrigation reduced container leaching from 137.7 L (for the 90-minute irrigation) to 95.7 L, with a similar reduction in the amount of water applied to the container. From this information, hypothesis #16 would be accepted for the 90-minute irrigation, but rejected for the 70-minute irrigation. It is likely that irrigation could be further reduced without negatively impacting plant ET, suggesting that irrigation water applications well exceeded plant requirements in this scenario.

vii. Changing irrigation frequency could have an impact on different model variables. The sensitivity of the model to irrigation frequency was tested by running the model with the same number of irrigations for each of two runs, but changing the frequency. For the weekly irrigation run, irrigations per week could be changed on a weekly basis, which would simulate a grower that irrigated according to different environmental conditions. The model was run a second time, and irrigation was changed only once every 4 weeks, simulating a grower that irrigated using a timer that was only changed periodically.

Hypothesis # 17: More frequent irrigation decisions (every week) should show reduced runoff rates compared to monthly irrigation decisions.

Hypothesis #17 states that increasing the frequency of irrigation decisions, adjusting frequencies on a weekly basis should reduce runoff rates compared to monthly irrigation decisions. The same number of irrigations were performed (179), although their frequencies changed over the weeks. The same values were reported for both runs, for the amount of water intercepted by the container and leaching values (Table 5.9). This is not surprising under these conditions, since irrigation is applied the same number of times, at approximately the same number of irrigations per month during each run (less frequently at the beginning and end of the run, more frequently in the middle, like a normal curve). It is likely that leaching would be reduced if fewer irrigations were performed over the course of the 40 week cycle, which would be the more likely scenario, where the grower controls irrigation directly (adjusting say for rainfall or cooler days) versus a situation where irrigation is controlled by a timer. This scenario was not tested, but the results are intuitive. Hypothesis #17 was rejected under these conditions, i.e., no difference in runoff volume was observed when irrigation decisions were made on a monthly versus a weekly schedule, although the assumptions in this hypothesis should be challenged.

F. Conclusions

In this chapter, the process behind the container model calibration, validation and scenario testing was discussed. The container model was calibrated with published research, and validated using two different datasets with 12 separate model runs representing both a high and low nutrient-using plant species. This model was shown to return accurate results under a number of different model scenarios. Seven additional hypotheses were generated and tested, based on information from 27 container operations representing 155 management units that were visited throughout Maryland, representing real-world scenarios. This model was designed to be used in different parts of the country, and potentially the world by changing a few key components, such as rainfall and temperature ranges to match local conditions.

The what-if scenarios tested above indicate the sensitivity of the model to a variety of inputs. Plant architecture was shown to have a significant impact on the amount of water entering a container, which is an important factor for growers to be aware of. The crop coefficient (K_c) was also shown to have a considerable impact on evapotranspiration rates. The benefit of cyclic irrigation was also demonstrated for reducing leaching losses. There are also additional areas for model improvement such as in the area of denitrification rates, crop coefficients, and phosphorus loss mechanisms in soilless substrates.

Chapter 6: Field model

A. Introduction

Field operations are different in many respects from container-nursery operations that were discussed in the previous chapter, although they do share a few similarities. Field operations typically grow plants at wide spacings in native soils (in the ground), compared with container and greenhouse operations which grow in soilless substrates above ground, with typically closer spacings. Native soils with high clay and loam contents have a high cation exchange capacity, compared to soilless substrates, so they retain plant nutrients much more effectively, especially P and K. Native soils also have a higher water holding capacity, compared to soilless substrates, and retain more water in the root zone between irrigations. In general, field operations tend to have low nutrient and irrigation inputs; the main concern in these operations is soil erosion that leads to nutrient and sediment loss, especially when rows are being harvested and re-established.

In Chapter 3, it was reported that the *highest* average fertilizer rates that were reported in field operations were 77 kg/ha/yr N, 24 kg/ha/yr P_2O_5 and 27 kg/ha/yr K_2O, compared to the *lowest* average rates for woody perennial in container-production reported as 372 kg/ha/yr N, 122 kg/ha/yr P_2O_5 and 176 kg/ha/yr K_2O. Field operations were reported to mainly apply a variety of solid fertilizers (standard chemical, tablets and biosolid forms), with 82 of 96 management units (85 %) reporting solid fertilizer, compared to 7 (7%) that applied soluble, and 7 (7%) that did not apply fertilizer (at least starting when nutrient management reporting was required by law). Although field operations are typically not large users of water and nutrients, they are usually extensive operations ranging in size from a few hectares to a hundred hectares or more.   It is the large field operations that have the potential to cause problems, mainly with sediment loading, if proper management practices are not followed.

Similar species can be grown in container-nursery operations and field operations, with the main overlap being woody perennial species. Field operations typically grow large shrub and shade tree varieties, with an emphasis on larger (2-4”) caliper trees. Production times are also typically longer in field operations, with production times between 3-8 years for most species. Field operations, like container operations, are open to rainfall. Rainfall provides a major water source for most field operations, with supplemental irrigation provided through drip or overhead irrigation, especially during the first few years for good establishment and reduction in losses. This is in contrast to container operations, which oftentimes must irrigate daily during the growing season. Frequent irrigation (daily to several times per week) is a necessity for plant survival in container operations, while field operations typically only apply irrigation during times when rainfall does not meet plant evapotranspiration requirements, especially in established plots where a grower is not trying to maximize plant growth.

B. Materials and Methods - Model development

This chapter discusses the development and testing of the field model, and reports the results of several hypothesis that were generated for testing as part of this project. General model development was discussed in Chapter 2, which discussed the general steps that were used to develop each model. In addition, Chapter 4 and Chapter 5 materials and methods sections covered specific information about the processes used to model irrigation, nitrogen (N) and phosphorus (P) flow into and out of the root zone that is also used in the field model. This information will be discussed briefly below, but more specific information can be found in the respective sections in Chapter 4 and 5.

i. Nitrogen

As previously described, N can be applied in several different ways. Soluble N can be applied through drip emitters, similar to that described for the container model, although soluble N is not able to be inputted through overhead irrigation, since this fertigation method is not common or recommended in field operations (Figure 6.1). The field model also does not have slow release fertilizer as an N input method, since this type of fertilizer is not often used, or recommended for field operations due to expense. The field model does have an input for biosolid (i.e. compost, manure, green manure) N application, which works similar to that described for the container model. Briefly, the total lbs of biosolid are added by the user on the interface layer, along with the percent N and percent P_2O_5 analysis (Figure 6.2). Since biosolid would usually be applied during field preparation or renovation, this factor is divided by the percent of the MU harvested each year, so for a 5-year rotation, this would be 20% (all model calculations are reported in Appendix F). The pounds of biosolid is divided by the percent harvested, since this value is only added once during the growing cycle. These values can be adjusted by the user on the interface layer of the model. Ideally, biosolid would be made available to the plant over several growing seasons, but the model is currently set up to simulate a single growing season. It would be possible to change the length of the run to match the growing period from planting to harvesting, but the setup required to do this would be very complex. Biosolid N is transferred to a stock at the beginning of the run, similar to that described for biosolid N in the container model. This N is then released over the course of the run, with an equivalent amount every week. Microbial breakdown of organic matter in biosolid fertilizer is certainly more complicated than described here, but modeling microbial breakdown was beyond the scope of this project.

Solid N is often applied several times during the growing season. In the model, the amount of solid fertilizer per application is a user input on the interface layer (Figure 6.2). This value remains constant during runs, but the number of solid fertilizations per month can be changed. In any given month that fertilizer is added, the model will spread the fertilizations out over that month. For example, if there is one fertilization in a given month, it will be added at the beginning of the month, two will be added on the first and third week etc. Solid N and P added to the soil is immediately available for plant uptake, although in reality, irrigation or rainfall would be necessary to make the fertilizer available to plant roots.

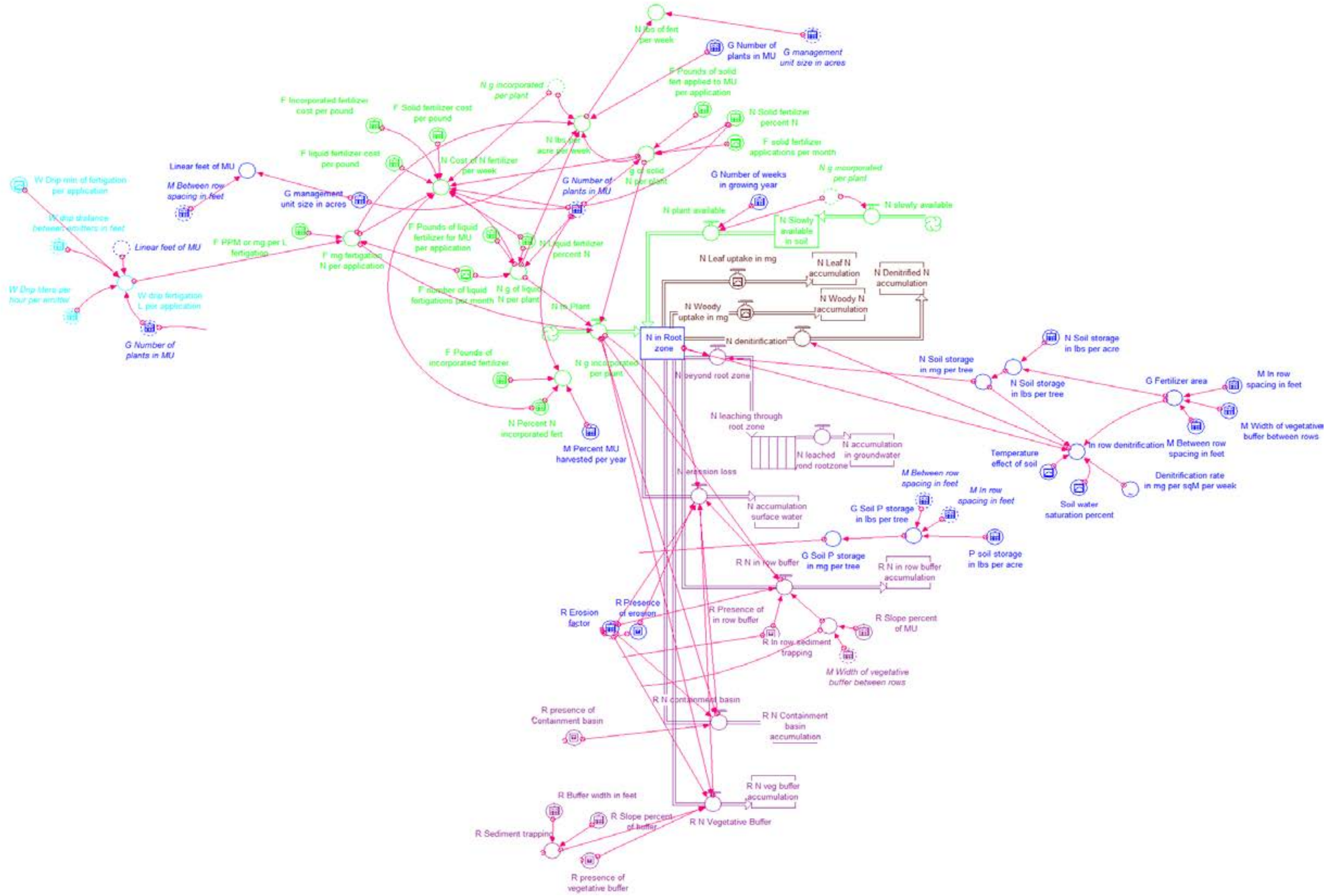

Figure 6.1. Field model illustrating all Nitrogen inputs and outputs from Stella. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Green variables indicate fertilizer variables, blue are general management variables, dark purple are plant uptake and denitrification loss mechanisms, light blue are irrigation variables and light purple are leaching and nutrient removal variables.

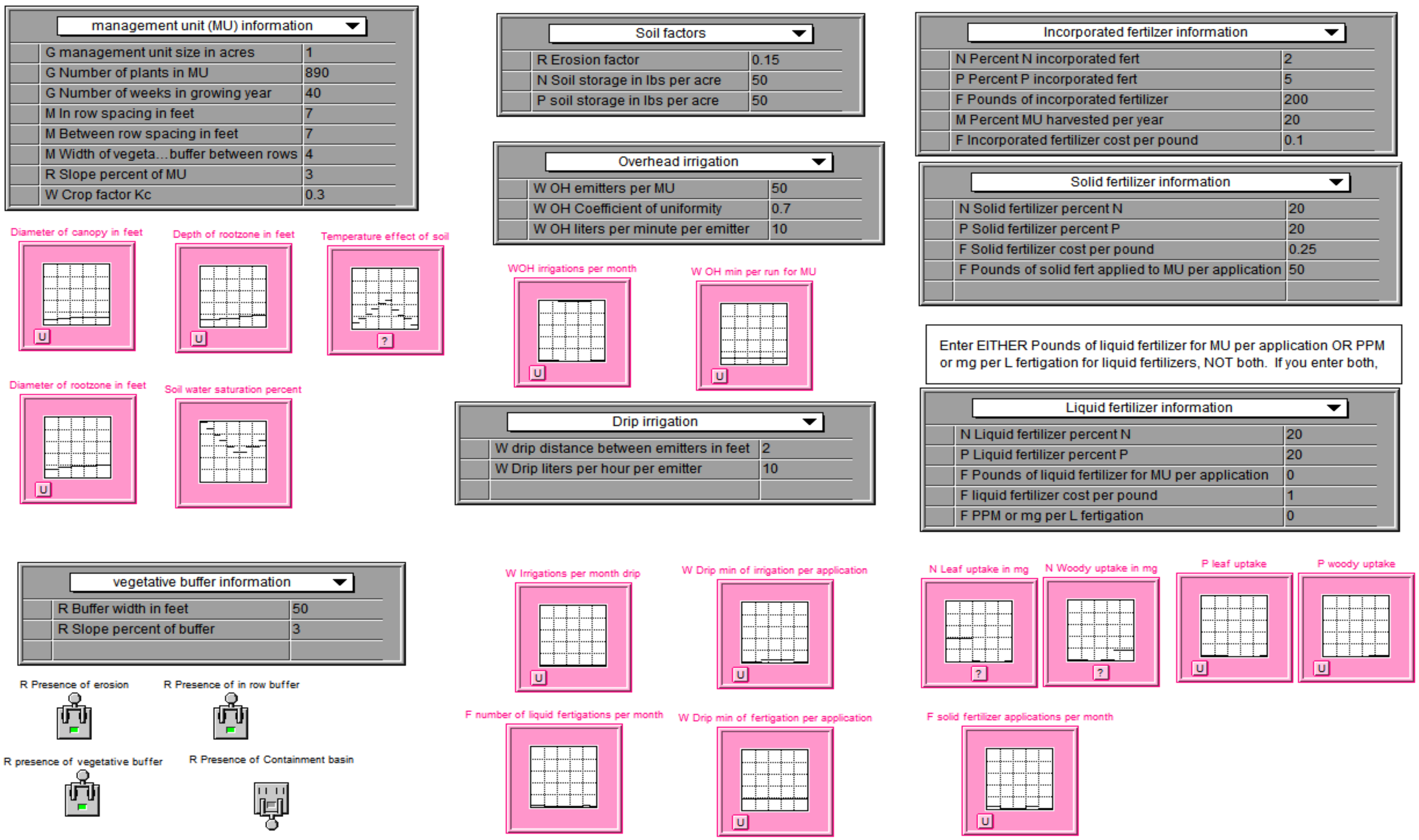

Figure 6.2. Field model interface layer from Stella, showing graphical inputs that can be changed weekly (i.e. diameter of canopy, average rainfall in cm/week), variables that can be controlled with switches (presence of containment basin, presence of vegetative buffer etc.), and table inputs that are constant for the model run (General management unit information table, irrigation tables etc.).

Soluble fertilizer through drip lines can also be used to provide N and P to plant roots. Fertigations per month can be entered in its respective graph on the interface layer, and can be changed on a monthly basis. The program automatically adds fertilizer at set intervals over the month, as described above for solid fertilizer. The amount of liquid fertilizer can be added as either mg/ L (ppm) or as pounds per application, since after speaking with growers, some add a specified amount (eg. 20 lbs) of fertilizer to the fertilizer concentrate container, fill the container with water, and irrigate until the container is empty. Others mix a concentrate, and irrigate at a certain rate (mg/L) for a certain amount of time. Both methods can be input into the model. Regardless of how fertilizer is applied, it is distributed evenly to the management unit. If mg/ L is used as fertilizer input, the minutes of drip fertigation need to be entered also, into the appropriate graph on the interface layer (Figure 6.2), along with the number of fertigations per month, which needs to be input if either mg/ L or lbs per application are used. Once N has been transferred into the plant root zone, it is made available for plant uptake and various loss mechanisms. Plant uptake is similar to the process described for the container model. Nitrogen can either go to leaf or woody tissue, with leaf tissue N accumulation typically occurring earlier in the season in the model runs, and woody N accumulation occurring later in the season, although this can be changed by the user on the interface layer. The process of denitrification is similar to that described in the container model (Chapter 5). Denitrification rate is based on the soil temperature, soil water saturation, denitrification rate (in mg/m^2/week), the amount of N in the soil, and the surface area attributed to each plant.

The soil temperature coefficients used in the model were based on a Q_{10} of 2, which was reported from 11 °C to 35 °C (Stanford et al. 1975). A temperature of 20 °C was used as the temperature value corresponding to a coefficient of 1 based on data from De Klein (1996). Soil temperature values were determined from data at the Natural Resources Conservation Services site (http://www.wcc.nrcs.usda.gov/scan/site.pl?sitenum=2049&state=md) for the Powder Mill, Maryland site (#2049) located at 39° 01' N Latitude, 76 degrees 51' W longitude, elevation 105'. Data for the 8 inch probe (C3TMP) were used for model inputs. Soil temperature coefficients were probably lower than actual values for model validation, since information from Maryland was used, and the experiments were run in Florida (Lea-Cox et al. 2001b) and Spain (Quinones et al. 2007). Soil temperature information for Florida and Spain could not be located, but should be higher than the values input for Maryland. The denitrification rates output by the model seemed to be in line with published results (see below), so the temperature values were not adjusted. The soil temperature coefficients are likely to be valid for most of Maryland, and much of the surrounding area, although these values can also be changed by the user, if data are available.

Denitrification rates were based on information from De Klein (1996), which were reported to vary from 3 mg/m^2/day to 360 mg/m^2/day. Rates used in the model ranged from 100 to 250 mg/m^2/day for all simulations (Appendix F Table F6.1). Since the field model uses a weekly time step, daily rates were multiplied by 7 to give final numbers. The amount of N in the soil is used by the model to determine the percent of N (actual amount/ holding capacity), which increases the denitrification rate at higher percentages, since more N in the root zone leads to less competition. The surface area available for denitrification is not necessarily the same as the total ground surface area available for each plant (distance in row x distance between rows), since fertilizer is not applied to the total ground area allotted to the plant, but is generally concentrated in a band down the center of the row. The area available for denitrification for each plant was determined by subtracting the width of the vegetative buffer from the width between rows, which was then multiplied by the distance between plants in the row. This is the area where fertilizer and irrigation (at least for drip irrigation) are concentrated, and will have the highest rate of denitrification. Operations that do not have a vegetative buffer strip would have denitrification occurring throughout the MU, even if fertilizer is not applied in these areas. Although this is likely a minor issue, it is something to consider for future model iterations.

Nitrogen runoff in the model is dependent on the presence of runoff, which is represented by a switch on the interface layer (Figure 6.2). If this switch is off, no surface N loss mechanisms will be activated. If this switch is activated, a percentage of the N applied will be removed from the root zone N each week (the current erosion factor is set to 15%). The 15% removal number could be updated in the future, if research information in this area becomes available, as no values could be found for this factor during an extensive literature search. Nitrogen that is removed can have a number of fates, depending on the management practices present at an operation. If an in-row or end-of-row vegetative strip is present (indicated by turning the respective switches on in Fig 6.2), the N that is removed through runoff is partially or totally removed by the buffer strips, depending on the conditions present, using Equation 5.1. Nitrogen runoff can also be removed by a containment basin, if one is present (indicated by turning the respective switch on). The containment basin is set to remove 50% of the incoming N, as a default, since it is known that N is removed through denitrification in the basin (White 2007). N removal from constructed wetlands, which should function similarly to containment basins, have been shown to reduce N levels by 40-55 % over the course of the growing season (Vymazal 2007; White 2007). These values are higher than the values used in the container model, since field operations apply less irrigation to a management unit per year, so presumably more time would be available between irrigation/rainfall events and water flowing out of the containment basin (i.e. increased hydraulic retention time), which would increase the time available for denitrification. No literature values could be found for N removal efficiencies for containment basins, even though they are considered a best management practice for P removal, but White (2007) does provide information on N removal in constructed wetlands. This would be an additional area for future research. It is worth repeating that all field operations that were visited employed the use of vegetative buffers in rows and at the end of rows, which is considered a best management practice (Chapter 3). Results are reported in the what-if section below for the effectiveness of in-row and end of row buffers for a number of model runs. We assume that any N that is remaining after vegetative buffer or containment basin removal is delivered to surface waters.

In addition to above-ground N removal, which can eventually be transferred to surface waters, if the proper management practices are not in place, N can also leach through the root zone, beyond the reach of plant roots. Once beyond the root zone, N could be used for microbial growth, or denitrified, or leached into groundwater supplies.

In the model, N leaches beyond the root zone when more N is applied than can be bound by the soil, which is determined by the N holding capacity of the soil in pounds per acre. Nitrogen holding capacity is dependent on a number of factors including soil type (clays and organic/loamy soils bind more N than sandy soils) and irrigation volume (more water flowing through the soil brings N through the soil faster). For simplicity, only soil nutrient holding capacity is included in the model, and can be controlled by the user on the interface layer (Figure 6.2). If more N is applied than can be bound by the soil, excess N is transferred to the conveyor (box with vertical lines, Fig. 6.2), which is similar to a stock, but inputs are moved along the conveyor like a conveyor belt instead of just being stored. N moves through the conveyor over a 2 week period, and is then transferred to the "N accumulation in groundwater" stock. Future model iterations could incorporate N movements, like those reported in Olson and Swallow (1984), who showed that over a 5 year period, 47% and 54% of the N that was applied was found beyond the root zone of winter wheat for application rates of 50 kg/ ha and 100 kg/ ha respectively. For example, a rate of 1% of N per month could be removed at a constant rate, with additional leaching possible if more N is applied than can be stored in the soil (already included in the model).

ii. Phosphorus

Phosphorus inputs into the model proceed similarly to those described above for Nitrogen. The amount of soluble P_2O_5 that is added to the soil is dependent on the percent P_2O_5 of the fertilizer used. If mg/ L N is used as an input, then percent P_2O_5/

percent N is used to calculate the amount of P_2O_5, as discussed previously (Figure 6.2). If a weight of fertilizer is used as the input, then the fertilizer amount is multiplied by the percent P_2O_5 and divided by the number of plants in the management unit to derive the amount of P_2O_5 that is applied per plant. Before entering the root zone, P_2O_5 is converted to P by multiplying by 0.434. Once P is in the root zone, it can be taken up by the plant (woody and leaf P). If P is over-applied, it can leach out of the root zone and enter groundwater, similar to that described for nitrogen above, depending on the nutrient holding capacity of the soil. If erosion is present, then the model removes 15% of the P from the root zone, which will go to surface water, if no management practices are used to reduce this runoff. Currently, nitrogen and phosphorus runoff are not linked to rainfall and irrigation, which is a limitation of the current models. Future model iterations should address the impact of water and sediment runoff on nutrient loss. In row and end of row buffers remove P using the same formula as described for N above (Equation 5.1). Containment basins were set to remove 90 % of the P that is contained in the surface runoff for validation, but rates of 60-75% are probably more realistic, based on research reported for constructed wetlands (White et al. 2006; Lu et al. 2009).

iii. Water

Water delivered to the plant is similar to that described for the container model discussed in Chapter 5, except for a few key differences. Water can be applied from drip or overhead irrigation, or rainfall, similar to the container model. Overhead irrigation volumes are determined similarly to the container model, except there is the potential for some of the irrigation water to not infiltrate into the soil. Application rates using large overhead irrigation guns can potentially apply more water than can infiltrate the soil, which would lead to runoff. Water runoff is determined by the rate of water applied (L/hr, which is converted by the model to cm/hr), and the infiltration capacity of the soil (Figure 6.3). The model assumes that irrigation is applied to the whole management unit simultaneously. Future model iterations could include a factor, which includes the distance of throw of the emitter, which would only apply irrigation to a smaller part of the MU at a time, which would give more realistic infiltration rates/ volumes. Currently, infiltration volume is likely overestimated, since the same volume of water is applied by the model to the whole management unit, if the grower uses a traveling gun. In reality, the volume of water is applied to a smaller section of the management unit at a time. If the grower uses fixed sprinklers, than this is not an issue, since water is being applied to the whole growing area, instead of being concentrated in one area. There were three operations that were visited that used overhead traveling guns for irrigation. Growers did not know the radius of throw, and it could not be determined through an online search, since the exact traveling gun model and pressure (PSI or bars) of the system was not known.

Drip irrigation is determined similarly to that described for the container model, except the model takes into account distance/ spacing between drip emitters, to determine the number of emitters per MU (based on the linear feet of row length, which is calculated based on spacing between rows and management unit size/area). It is assumed that the infiltration rate of the soil is greater than the output of the emitters, so 100% of the water that is applied goes into the soil. Drip irrigation is typically applied at a low rate, so this assumption is likely valid in most operations. Water can also spread out to a larger surface to infiltrate as required using drip emitters.

The rainfall contribution to irrigation is determined similarly to that described for the container model. For rainfall, the average rainfall for the month is divided by the number of storms (Figure 6.4). The program determines infiltration rate and runoff volume, as described for the container model. However, the field model determines the volume of rainfall delivered to the plant differently. Since field plants do not have a defined container size, the diameter of the root zone is used to determine the volume of rainfall applied, since plants can only take up water within their root zones. The acre-inches of infiltration, is multiplied by the surface area of the plant (in square inches, as defined by the diameter of the root zone in feet). This volume, in $inches^3$, is then converted into liters, and added to the stock “water in soil”. Soil volume is determined by the diameter of the root zone in feet, and the depth of the root zone in feet. The water holding capacity of the soil is based on the root zone volume multiplied by the soil water holding capacity. Both of these values are graphical inputs on the interface layer, and typically increase as the season progresses. This volume in $feet^3$ is then converted into liters, and multiplied by the water holding capacity of the soil in L/L. Although growers will most likely not know the exact root zone diameter of their plants over the course of the growing season, they should have a general idea of this value (or it can be based on the tree drip line). When irrigation or rainfall is applied in excess of the soil’s water

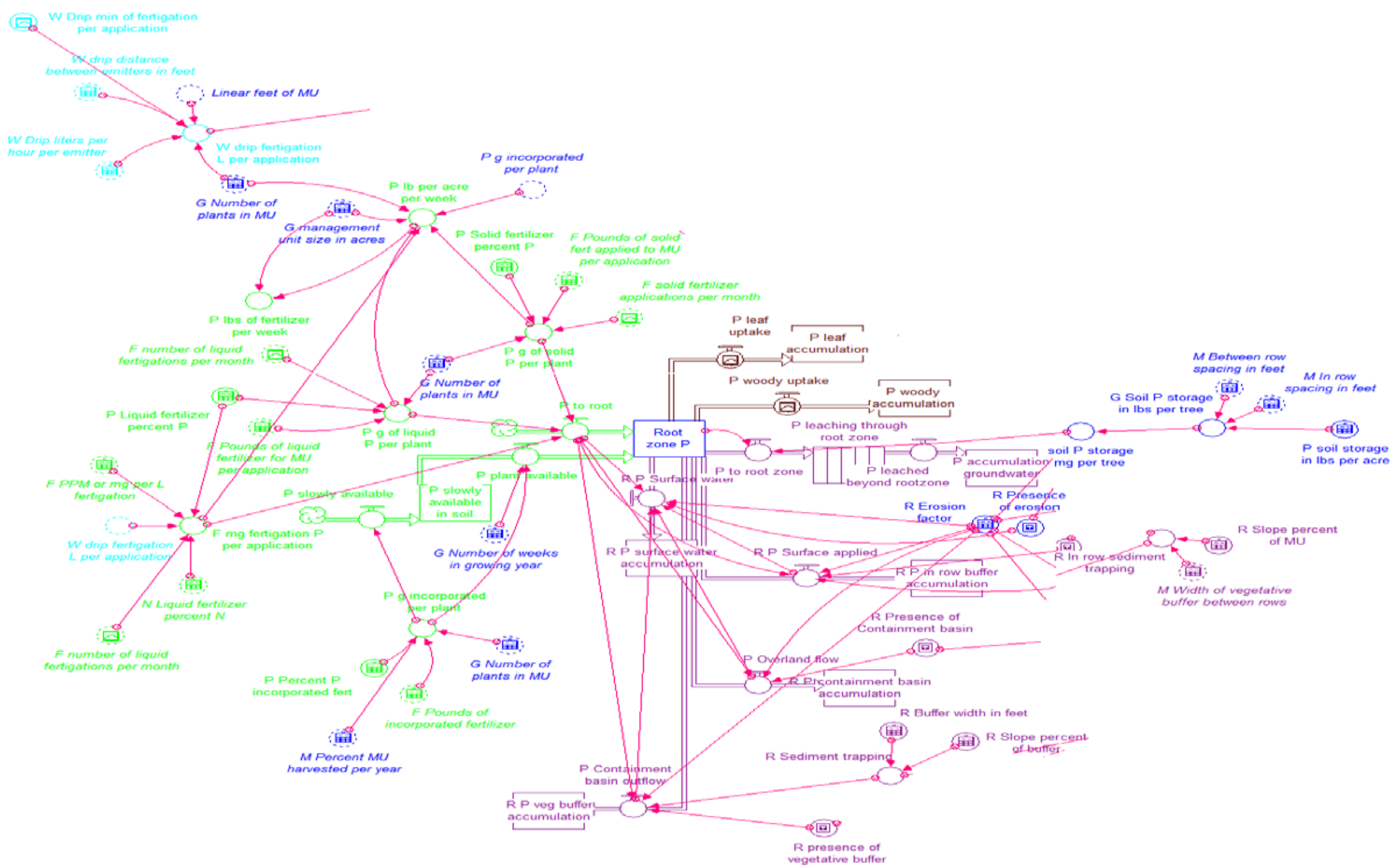

Figure 6.3. Field model showing all Phosphorus inputs and outputs from Stella. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Green variables indicate fertilizer variables, dark blue are general management variables, light blue variables represent irrigation, dark purple are plant uptake and light purple are leaching and nutrient removal variables.

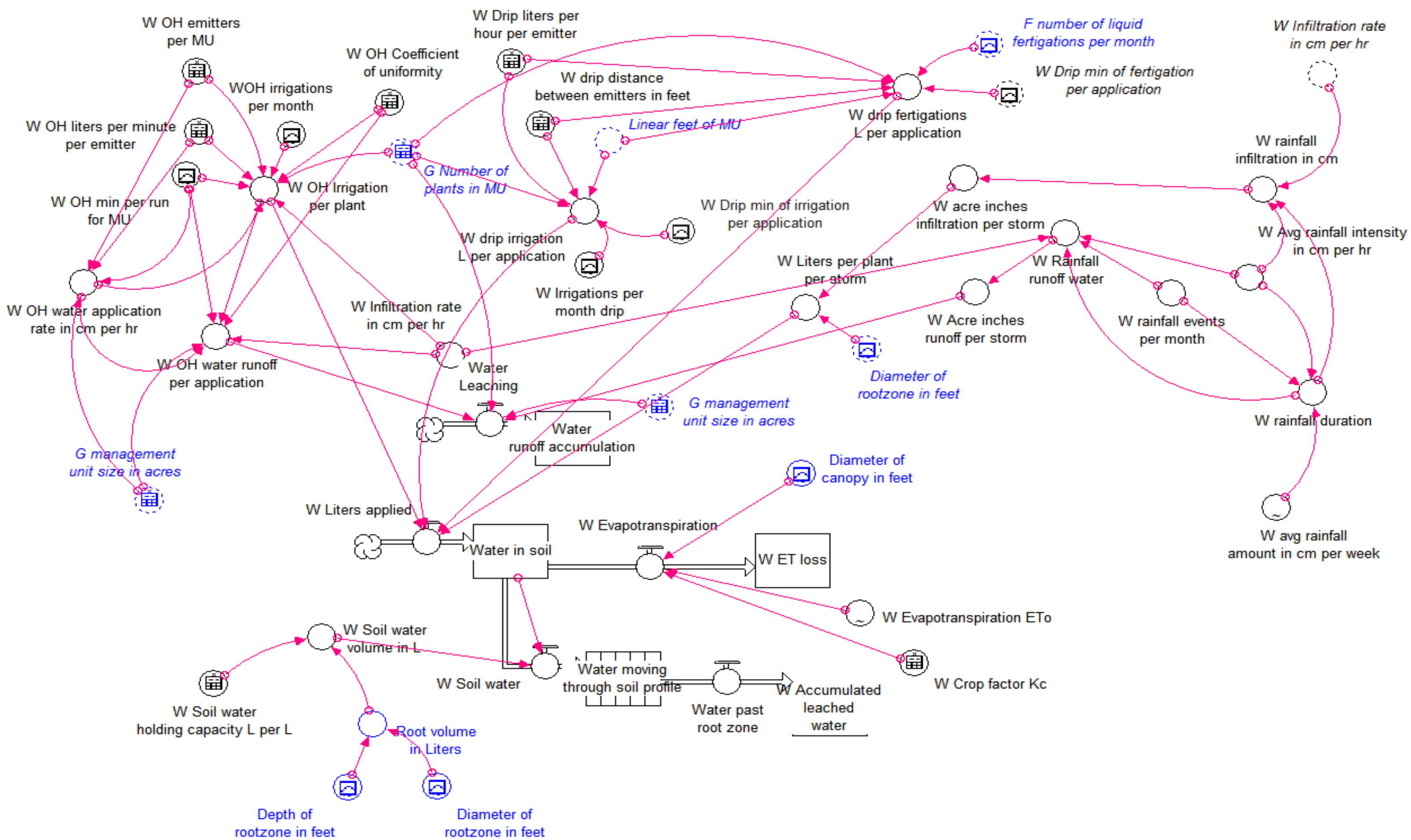

Figure 6.4. Field model showing all water inputs and outputs from Stella. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Dark blue variables are general management variables and black represent water variables.

holding capacity, it leads to leaching through the root zone. It is also possible that this water could be transferred to runoff, but this option was not explored in the current model. Future model iterations could also look into the possibility of water runoff (above infiltration capacity of the soil) impacting soil erosion, and any runoff would remove a certain amount of N and P from the soil.

iv. Additional calculations

Additional calculations such as those described for the greenhouse and container models were also included in the field model. The model calculates the total amount of N and P applied, the pounds per acre, and the cost of fertilizer over the course of the growing season (Fig. 6.5). These values will help growers understand the impact that changing certain values have on fertilizer cost and the amount of nutrients applied. Figure 6.5 provides the complete model layer nitrogen and phosphorus inputs and outputs, while the complete water portion of the model is provided in Figure 6.4.

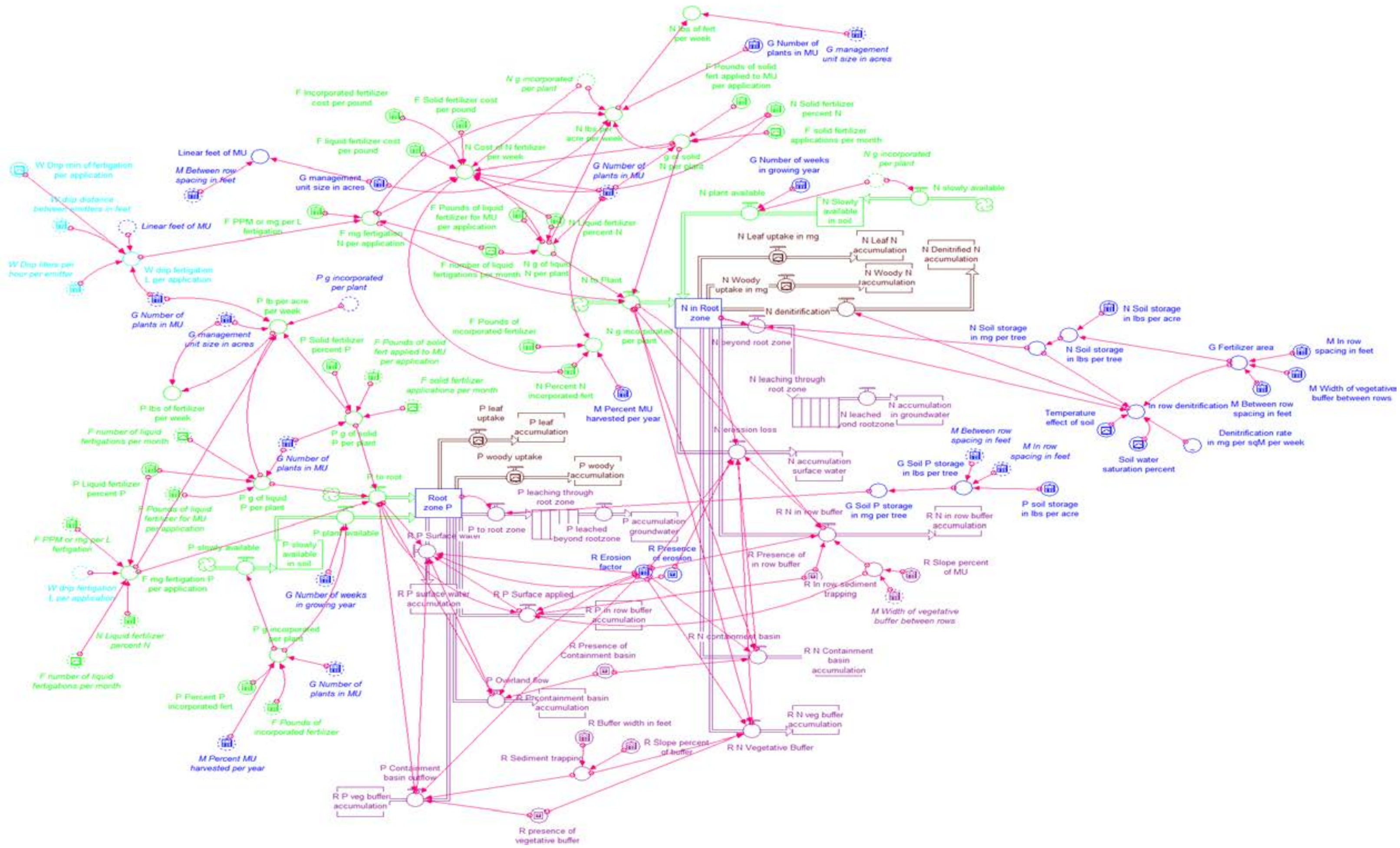

Figure 6.5. Field model showing phosphorus and nitrogen inputs and outputs from Stella. Circles are converters, squares are stocks, circles with bars on top (with arrows) are flows, and arrows are connectors. Green variables indicate fertilizer variables, blue are general management variables, brown are plant uptake and denitrification loss mechanisms, and purple are leaching and nutrient removal variables.

C. Model Calibration

The model calibration process was similar to that described for the greenhouse and container model. Data from Lea-Cox et al. (2001b) was used for model calibration, since no good nutrient dynamics study could be found in the ornamental field production literature. In this study, 'Redblush' grapefruit (*Citrus* x*paradisi* Macf.) was grown on two different rootstocks, a fast-growing 'Volkamer' lemon (VL) (*C. volkameriana* Ten & Pasq.) and the slower growing sour orange (SO) (*C. aurantium* L.), at three different N rates, 76, 140 and 336 g/tree/yr which represented 0.2, 0.4, and 0.9 the recommended rate, respectively, for four year old grapefruit trees at that time. Trees were either grown in lysimeter tanks, or in no-tank controls (fertilized at 140 g/ yr), representing eight separate model runs. For calibration, the VL 76 g/ yr data was used similarly to the procedures described for greenhouse and container-model calibrations. Briefly, any data that could be used to define model inputs were placed in the appropriate locations, in the tables, as graphical values, or used as switches. Constant values for calibration run can be found below (Table 6.1), with graphical values provided in Appendix Table F 6.1, F 6.2 and F 6.3. After model calibration was completed, the remainder of the data for this dataset was run through the model, changing only the variables necessary to simulate experimental conditions. It should be noted that in the published research, ^{15}N labeled fertilizer was added as a replacement for one springtime fertigation (with a total of 30 fertigations applied). Intensive sampling and soil, water and plant analysis of the ^{15}N allocation during the next 29 days was used as the basis for the results reported. The

Table 6.1. Constant values used for model calibration, based on information provided by Lea-Cox et al. (2001). Graphical values are included in Appendix F (Table F 6.1, F 6.2 and F 6.3).

Variable	Value
MU size (acres)	0.176
Plants in MU	24
Weeks in growing year	40
In row spacing (feet)	16
Between row spacing (feet)	20
Vegetative buffer width between rows (feet)	5
Slope of MU (%)	2
Crop factor (Kc)	0.3
Distance between drip emitters (feet)	16
Drip emitter volume (L/ hr)	60
Overhead (OH) emitters per MU	0
OH Coefficient of uniformity	0.9
OH emitter volume (L/ min)	0
Incorporated fertilizer N (%)	20
Incorporated fertilizer P2O5 (%)	10
Incorporated fertilizer (pounds)	0
MU harvested per year (%)	20
Incorporated fertilizer cost ($/ pound)	0.25
Solid fertilizer N (%)	20
Solid fertilizer P (%)	10
Solid fertilizer cost ($/ pound)	0.25
Solid fertilizer to MU (pounds/ application)	0
Liquid fertilizer N (%)	2
Liquid fertilizer P (%)	2.1
Liquid fertilizer to MU (pounds/ application)	6.7
Liquid fertilizer cost ($/ pound)	0.95
mg/ L (PPM) fertigation	0
Buffer width (feet)	0
Buffer slope (%)	3
Soil erosion factor	0.1
Soil N storage lbs/ acre)	55
Soil P storage (lbs/ acre)	55

results from the model represent 40 weeks of growth. The impact of this difference will be discussed where appropriate below.

D. Results and Discussion

i. Model Calibration/ Validation - Lea-Cox et al. (2001)

Eight separate model runs were completed for the Lea-Cox et al. (2001) data. Sour orange rootstock at 76 g/ yr data was used to calibrate the model, and the remaining data was run after calibration was complete. Results for comparison of N data reported by the model are compared to published results in Table 6.2. The amount of N applied from model runs correspond well to the published rates, except the model showed a slightly higher rate applied at the highest level (336 g/ yr). There was also good agreement between plant uptake rates for model runs and published results, with all values reported by the model similar to the published uptake rates. The comparisons of N leaching were similar for all model runs except the highest rate (336 g/ yr) (Table 6.2). The model reported higher leaching values than the published results. It is likely that the model rates are higher because the reported results only include data from the 29 day sampling window discussed above. Plant N uptake rates were likely higher during this time period, which would have lead to less leaching during this time. After the spring flush, plants would most likely had reduced N uptake rates (J. Lea-Cox, *pers. comm.*), leading to higher leaching values. The results reported by the authors represent the values obtained over the 29-day sampling period, while the model results are for the 40-week growing season. This is also likely the difference seen in soil N reported in Table 6.2. The model reported higher rates of soil N for all runs, except the sour orange at 336 g/ yr rate, which had similar soil N values. The 336 g N/yr rate of sour orange are likely similar since this was the slower growing rootstock, with the highest rate of N added, so there was an excess amount of N added over plant requirements, leading to higher leaching, and higher residual N levels in the soil. Unaccounted for nitrogen values were similar to denitrification values reported by the model (Table 6.2). This indicates that the values used for denitrification in the model were appropriate, at least under the conditions tested.

Phosphorus rates were not included in the published paper, but were calculated at 10% of N uptake. Initial P (Table 6.2) is calculated as the maximum P storage capacity of the soil/10, which equates to 10% of the P from the previous year remaining in this Floridian sandy soil. It is likely that this value is higher for most soils, since P is often applied in excess in field soils, and most clay and loamy soils adsorb P tightly. Most growers would have an idea of soil P fertility levels, especially in Maryland where yearly soil fertility tests are required. Applied P was determined from reported percentages of N - P - K provided by the authors. By comparing the applied P to the amount of P taken up by the plants (based on N values, an excessive amount of P was applied, compared to plant growth requirements. This lead to an increased amount of soil P at the end of the run, but did not result in groundwater leaching under these conditions. Soil P storage was inputted as 55 lb/acre of P.

Water application results are shown in Table 6.4, although no comparison could be made to published results, since irrigation volumes were not provided in the publication. Overall rainfall depth was included in Lea-Cox et al. (2001), which was incorporated into model inputs. Results are provided for the Sour orange 76 g N/yr run;

Table 6.2. Data comparison of Nitrogen values for Lea-Cox et al. (2001) compared to model outputs. Shaded values represent published results, while unshaded values represent model outputs. The published research reported unaccounted N, while the model reported denitrified N. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Rootstock	Applied N (g)		Deviation	Plant N (g)		Deviation	Leached N (g)		Deviation
Sour orange	76	76	0	24	25.7	0.071	0.8	0	1.0
	140	140	0	42.15	44.4	0.053	0.1	0	1.0
	336	360	0.071	40.18	44.2	0.10	9.7	71.0	6.3
	140 (NT)	140	0	48.15	49.2	0.022	0	0	0
Volkamer Lemon	76	76	0	32.35	34.6	0.070	0	0	0
	140	140	0	38.55	40.5	0.051	0.7	0	1.0
	336	360	0.071	94.96	98.1	0.033	3	33.6	10
	140 (NT)	140	0	58.65	60	0.023	0	0	0
Avg. Deviation			**0.018**			**0.053**			**2.4**

Table 6.2. Continued

Rootstock	Unaccounted/ Denitrified N (g)		Deviation	Soil N (g)		Deviation
Sour orange	23.8	24.6	0.034	3.42	39.4	11
	62	39.7	0.36	1.12	69.5	61
	117.3	106.6	0.091	130	135.9	0.045
	48.2	37.4	0.22	4.06	67.0	16
Volkamer Lemon	12.1	20.4	0.69	0.1	34.7	346
	63.1	41.5	0.34	5.9	71.5	11
	107.9	92.4	0.14	41	135.4	2.3
	27.4	32.4	0.18	5.7	61.3	9.8
Avg. Deviation			**0.26**			**57**

Table 6.3. Model output values of Phosphorus, based on inputs from Lea-Cox et al. (2001). Phosphorus values were not reported in the publication, so no comparison could be made between model outputs and published results.

Rootstock	Rate (mg/ yr N)	Initial P (g)	Applied P (g)	Plant P (g)	Soil P (g)	Groundwater P (g)
Sour orange	76	18.3	34.5	2.6	50.3	0
	140	18.3	21.2	4.4	35.1	0
	336	18.3	27.2	4.4	41.2	0
	140 (NT)	18.3	21.2	4.9	34.6	0
Volkamer Lemon	76	18.3	34.5	3.5	49.4	0
	140	18.3	21.2	4.1	35.4	0
	336	18.3	27.2	9.8	35.8	0
	140 (NT)	18.3	21.2	6.0	33.5	0

the same results were reported for the remaining 7 runs (data not shown). The same irrigation volume was used across all treatments, so irrigation volumes would be the same. Tree canopy diameter was not changed for any of the runs, so ET and leaching levels reported by the model are the same as well.

Table 6.4. Model output values for water, based on inputs from Lea-Cox et al. (2001). Water values were not reported in the publication, so no comparison could be made between model outputs and published results.

Rootstock	**Rate (g N/yr)**	**Water Applied (L)**	**Evapotranspiration (L)**	**Water leached (L)**
Sour orange	76	5582	3653	1351

ii. Validation Quinones et al. (2007)

The second dataset that was analyzed was based on the published results of Quinones et al. (2007). In this article, the authors were looking at the effect of low frequency N applications and flood irrigation compared with high frequency N application and drip irrigation. This study used ^{15}N to analyze seasonal N dynamics in citrus. For the study, *Citrus sinensis* c.v. Navelina were grafted onto Carrizo citrange (*Citrus sinensis x Poncirus trifoliate*) rootstock. Trees were grown in lysimeters over the course of the study.

In reviewing this article, there were a few areas of concern that should be addressed, which could help explain some of the differences observed between published values and model outputs. The authors reported N recovery rates of 92.3% for the drip system, and 85.4% for the flood system, even though typical recovery rates are less than

80%, which is usually attributed to denitrification (Cabrera 2003; Ristvey 2004). In addition, the authors report applying 175 g of N per tree, with 125 g from ^{15}N labeled fertilizer, and 50 g from irrigation water, which contained 36.5 mg/ L N. For the drip system, 5722 L were applied, while it was reported that flood irrigation applied 6498 L, with 1235 L rainfall for both treatments. Based on this information, I calculated the total N applied through irrigation water was calculated to be 209 g N for drip, and 237 g for flood, plus the 125 g applied through solid fertilizer, which provides a total of 334 g for drip and 362 g for flood irrigation over the course of the experiment. For the model, solid N was applied as described in the article for the fertilizer applications, while irrigations were treated as fertigations, with an N rate of 36.5 mg/ L.

Applied N values were higher for model outputs compared to published results (Table 6.5), for the reason described above. Leaf and woody uptake values were similar to published values, as well as residual N in the soil. The model predicted higher rates of denitrification than the reported values, especially for the flood treatment, which had more than double the denitrification rate reported by Quinones et al. (2007), but the published article only takes the ^{15}N numbers into account, and does not factor in the N applied in the irrigation water. As discussed above, the N recovery rates were higher than typically reported, and it was unclear why unaccounted for N percentages were so low in the published results. The amount of N leached was reported by the authors to be zero g for the drip system, and 0.2 g for the flood system, compared to 215.1 and 221.4 g for drip and flood from model outputs respectively (Table 6.5). It is likely that these values for leaching reported by the model are higher because of the higher N rates that were accounted for in the inputs.

Table 6.5. Data comparison of nitrogen values for Quinones et al. (2007) compared to model outputs. Shaded values represent published results, while unshaded values represent model outputs. Published results reported unaccounted N, while the model reported denitrified N. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Irrigation type	**Applied N (g)**		**Deviation**	**Leaf N uptake (g)**		**Deviation**	**Woody N uptake (g)**		**Deviation**
Drip	175	388	1.2	51.6	52	0.008	58.1	58	0.002
Flood	175	405	1.3	50.6	50.8	0.004	80.9	76	0.061
Avg. Deviation			**1.3**			**0.006**			**0.031**

Table 6.5. Continued

Irrigation type	**Soil N (g)**		**Deviation**	**Unaccounted/ Denitrified N (g)**		**Deviation**	**N leached (g)**	
Drip	34.5	38.6	0.12	25.6	31.9	0.25	0.0	215.1
Flood	27.3	32.1	0.18	13.5	32.7	1.42	0.2	221.4
Avg. Deviation			**0.15**			**0.83**		

Quinones et al. (2007) did not report P values as part of their results, so no comparison could be made between published results and model outputs. It was assumed that P uptake was 10% of the values reported for N, which are shown in Table 6.6. The amount of P applied (27.0 g) was reasonable given the amount of P taken up by the plants (11.0 g drip, 12.7 g flood), but could likely still be reduced. No P leaching was reported by the model under these conditions.

Table 6.6. Model output values of Phosphorus, based on inputs from Quinones et al. (2007). Phosphorus values were not reported in the publication, so no comparison could be made between model outputs and published results.

Irrigation type	Applied P (g)	Leaf P (g)	Woody P (g)	Root zone P (g)	Leached P (g)
Drip	27.0	5.2	5.8	19.7	0
Flood	27.0	5.1	7.6	18.0	0

A comparison of model outputs compared to published results for water are reported in Table 6.7. Similar rates of water were applied (values for rainfall were included) by the model, compared to published results. Similar ET rates were reported as well, using a K_c value of 0.3 (published monthly values ranged from 0.22 to 0.32), which suggests that the ET values used in the model were functioning appropriately under these conditions.

Table 6.7. Data comparison of water values for Quinones et al. (2007) compared to model outputs. Shaded values represent published results, while unshaded values represent model outputs. The deviation between model outputs and published results (Deviation) was calculated as follows: (absolute value of (published value - model value)) / published value. The closer the deviation is to 0, the closer the model value was to the published value.

Irrigation type	**Applied water (L)**		**Devia-tion**	**Evapotranspiration (L)**		**Devia-tion**	**Water Leached (L)**
Drip	6957	6653	0.044	5634	5255	0.067	1398
Flood	7733	7094	0.083	5634	5059	0.10	2035
Avg. Deviation			**0.063**			**0.085**	

The model also reported 1398 L of leaching for the drip irrigation run, and 2035 L for the flood run, although authors did not report leaching volumes. It should be noted that a number of field studies published for ornamental plants and orchard trees did not have adequate data that could be used for model validation, and were much fewer than the number of studies published for either container or greenhouse operations. Additional research in this area would be beneficial not only for these models, but also for this production method in general.

E. Field Production Hypotheses

A total of fourteen different model runs were completed to test the six hypotheses listed below. The constant and graphical values for model inputs are listed in Appendix F (Table F. 6.4 and Table F.6.5 - F 6.8 respectively). The following model conditions were used for testing the hypotheses stated below, except where indicated for that particular scenario. Plants were grown at a 2.1 m x 2.1 m (7 ft x 7 ft) spacing with a 1.2 m (4 ft) vegetative buffer. Biosolid fertilizer was added at the rate of 1120 kg/ha (1000 lb/acre), with a 2% N and 5% P content. In addition, 23 kg (50 lbs) of solid fertilizer with a 20% N and 20% P content was added four times a year. Soil N and P storage rates were 56 kg/ha (50 lb/ac). Plant N and P uptake rates were ½ of the rates used for Lea-Cox et al. (2001) 76 g/ yr sour orange rootstock, to represent immature trees. Drip emitters were used for irrigation at a spacing of 0.6 m (2 ft) between emitters, with each emitter applying 10 L/hr (2.6 gal/hr) of water. Two irrigations were applied per week during weeks 16 to 36 (40 irrigations total).

i. Vegetative buffer percent slope and width has been shown to have a significant impact on sediment removal efficiency (Mankin et al. 2007; Liu et al. 2008). There are many factors which influence buffer sediment and nutrient removal efficiency such as the type of vegetation used, buffer maintenance, buffer age, and soil type (Wenger 1999; Mankin et al. 2007). The model assumes that appropriate vegetation and maintenance are provided, so only buffer slope and width are used as inputs into the model. The buffer removal efficiency is based on the results from Liu et al. (2008) who used width and slope to measure vegetative buffer sediment removal effectiveness. For the model runs, three different vegetative buffer strips were run, as well as a run with just a containment basin. The model was run with only a 15 meter (50 foot) buffer strip at the end of the row, with only a 1.2 m (4 ft) vegetative strip between rows, and with both in row and end of row vegetative strips.

Hypothesis #18: In-row, and end-of-row buffers will effectively remove a proportion of N and P runoff, while a combination of both in-row and end-of-row buffers will

be most effective. The containment basin will be more effective than the end-of-row and in-row buffers individually, but less effective that the two buffers used together.

Hypothesis #18 states that the combination of in-row and end-of-row buffers will be most effective for removing N and P, followed by the containment basin, end-of-row buffers, with in-row buffers being least effective. Without any buffers, the results of model runs predicted that 3.06 g of N will run off into surface water, using the stated conditions (Table 6.8). Using an in-row buffer, runoff is reduced to 2.00 g, while an end–of-row buffer reduces surface runoff to 1.65 g of N. Using the combination of in-row, and end-of-row buffers reduced surface runoff N to 0.59 g, which is over a 5x reduction over the course of the growing season. The presence of a containment basin reduced N runoff from 3.06 g to 1.53 g. Similar results were seen for P removal. The model predicted 1.32 g of P runoff without any form of nutrient removal practice (Table 6.9). This value dropped to 0.4 g with an in-row buffer and to 0.11 g with and end-of-row buffer. The containment basin was predicted to remove all but 0.13 g of P, while both an in-row, and end-of-row buffer removed all P, so zero g was transferred to surface waters. This information supports the hypothesis, that a combination of in-row and end-of-row buffers are the most efficient way of reducing N runoff, while containment basins and end-of-row buffers are similar, and in-row buffers alone remove the least amount of N. The model assumes that the slope is between rows (i.e. on the contour), so in-row buffers would be less effective if slopes ran down the rows. Vegetative buffers have been repeatedly shown to be an effective method for increasing infiltration, and reducing sediment loading to surface waters.

ii. As mentioned above, buffer width and slope are critical determinants of sediment removal efficiency, as well as water infiltration. Three different buffer widths and slopes 6 m (20 ft.) width, 5% slope; 15 m (50 ft) width, 3% slope and 30.5 m (100 ft.) width and 7% slope were run through the model, to the determine the impact of width and slope on nutrient removal.

Hypothesis #19: As buffer width increases, N and P trapping efficiency will increase to a certain limit.

Hypothesis #19, i.e., increased buffer width increases N and P trapping efficiency was tested. Under the stated conditions, a 6.1 m buffer reduced surface water N runoff by 1.28 g, while a 15 m buffer reduced surface N runoff by 1.41g, and a 30.5 m buffer reduced N runoff by 1.93g (Table 6.8). Both the 6.1 m and 30.5 m buffer resulted in zero g of P reaching surface waters, while the 15 m buffer run resulted in 0.11 g of P reaching surface waters (Table 6.9). The decreased P removal at 15 m is most likely due to the slope, which was set at 3% for the 15 m buffer and 5% for the 6.1 m buffer, where the optimal slope for a buffer is reported to be 9.2% (Liu et al. 2008). Under the conditions tested, this hypothesis would be rejected, since both the 6.1 m and 30.5 m buffers resulted in 0 g P runoff, but the 15 m buffer resulted in 0.11 g of P runoff (data in "End-of-field buffer only" row). If the model was run again, with the same slopes, I am confident that this hypothesis would be accepted, since the slope of the 15 m run was 3%, while the 6.1 m slope was 5%, which was closer to the optimal slope of 9.2%. Different slopes were used to show the difference that both buffer slope and width have on nutrient removal efficiency, since the effect of buffer width is well documented in the literature. It should

Table 6.8. Nitrogen results for six different what if scenarios representing fourteen separate model runs**.**

	Applied N (g)	Leaf N (g)	Woody N (g)	Leached N (g)	Denitrified N (g)	Containment basin N (g)	In-row buffer N removal (g)	Vegetative buffer N removal (g)	Surface water N (g)
No buffer	20.8	9.2	2.5	0	1.4	0	0	0	3.06
In-row buffer only	20.8	9.2	2.5	0	1.4	0	1.06	0	2.00
End-of-field buffer only	20.8	9.2	2.5	0	1.4	0	0	1.41	1.65
Containment basin only	20.8	9.2	2.5	0	1.4	1.5	0	0	1.53
In-row and end-of-field buffer	20.8	9.2	2.5	0	1.4	0	1.06	1.41	0.59
6.1 m buffer width 5% slope	20.8	9.2	2.5	0	1.4	0	1.07	1.28	0.71
30.5 m buffer width 7% slope	20.8	9.2	2.5	0	1.4	0	1.07	1.93	0.06
22.4 kg/ha N and P soil storage	20.8	6.6	2.4	4.9	2.0	0	1.07	1.41	0.58
168 kg/ha N and P soil storage	20.8	10.2	2.7	0	0.8	0	1.07	1.41	0.58
Crop factor (Kc)= 0.5	20.8	9.2	2.5	0	1.4	0	1.07	1.41	0.58
Crop factor (Kc)= 1.5	20.8	9.2	2.5	0	1.4	0	1.07	1.41	0.58
45.4 kg x 4 applications solid	41.2	10.2	2.7	11.1	3.4	0	2.14	2.81	1.16
1120 kg/ha biosolid, 4.5 kg x 20 applications liquid	22.4	10.2	2.7	0	2.0	0	1.07	1.41	0.58
0 kg biosolid, 4.5 kg x 20 applications liquid	20.4	10.2	2.7	0	1.4	0	1.07	1.41	0.58

Table 6.9. Phosphorus results for six different what if scenarios representing fourteen separate model runs**.**

	Applied P (g)	Leaf P (g)	Woody P (g)	In row buffer P (g)	End of row buffer P (g)	Containment basin P (g)	Surface water P (g)	Leached P (g)
No buffer	9.3	0.52	0.15	0.00	0.00	0	1.32	0
In-row buffer only	9.3	0.52	0.15	0.92	0.00	0	0.40	0
End-of-field buffer only	9.3	0.52	0.15	0.00	1.22	0	0.11	0
Containment basin only	9.3	0.52	0.15	0.00	0.00	1.2	0.13	0
In-row and end-of-field buffer	9.3	0.52	0.15	0.92	1.22	0	0	0
6.1 m buffer width 5% slope	9.3	0.52	0.15	0.92	1.11	0	0	0
30.5 m buffer width 7% slope	9.3	0.52	0.15	0.92	1.67	0	0	0
22.4 kg/ha N and P soil storage	9.3	0.52	0.15	0.92	1.22	0	0	0
168 kg/ha N and P soil storage	9.3	0.52	0.15	0.92	1.22	0	0	0
Crop factor (Kc)= 0.5	9.3	0.52	0.15	0.92	1.22	0	0	0
Crop factor (Kc)= 1.5	9.3	0.52	0.15	0.92	1.22	0	0	0
45.4 kg x 4 applications solid	18.1	0.52	0.15	1.85	2.43	0	0	0
1120 kg/ha biosolid, 4.5 kg x 20 applications liquid	11.0	0.52	0.15	0.92	1.22	0	0	0
0 kg biosolid, 4.5 kg x 20 applications liquid	8.8	0.52	0.15	0.92	1.22	0	0	0

be noted that the rate of 3.06 g of N runoff per tree only equates to 11 kg/ha (10 lb/ac) at the highest tree density used, 3580 trees/ ha. As mentioned previously, it is unlikely that nutrient runoff from field operations poses a substantial risk to surface water under the conditions tested above, but sediment runoff is a concern for field operations (along with any phosphorus bound to sediment). The field model does not currently take sediment loss into account, which is likely the larger contribution field operations make to surface waters.

iii. Soil anion and cation exchange capacities are typically much higher in native soils compared to soilless substrates, especially native soils with high levels of organic matter or clay. This benefits field growers, since nutrients are retained longer in the root zone in native soils compared to soilless substrates, which decreases leaching losses. Models were run with three different N and P storage capacities, i.e. 22.4 kg/ha (20 lbs/ac), 56 kg/ha (50 lb/ac) and 168 kg/ha (150 lbs/ac).

Hypothesis #20:   Increasing soil N and P storage capacities should increase both plant N and P uptake and denitrification, and decrease soil N and P loss.

Increasing soil storage capacity of N and P should decrease soil N and P loss, while increasing denitrification, and N and P uptake, if uptake rates are not maximized at lower storage capacities (Hypothesis #20). At 22.4 kg/ha (20 lb/ac) N and P storage capacity, the soil could not store sufficient N for maximum plant uptake, with N uptakes of 6.6 g and 2.4 g for leaf and woody tissue respectively (Table 6.8). At 56 kg/ ha (50 lb/ac) N and P storage capacity, uptake rates were higher at 9.2 g and 2.5 g for leaf and woody tissues respectively, but were slightly less than uptake rates at 168 kg/ha (150 lb/ac) storage capacity, i.e. 10.2 g and 2.7 g for leaf and woody N respectively. The lowest rate (22.4 kg/ ha) did show N leaching, at 4.9 g, while the other two rates did not, as expected. The lowest rate (22.4 kg/ ha) also had a slightly higher denitrification rate (2.0 g) compared to 56 kg/ ha rate (1.4 g) and 168 kg/ ha (0.8 g) (Table 6.8). The model did report sufficient P storage for maximum P uptake at all P storage capacities tested, with maximum P uptake rates, and no leaching, even at the 22.4 kg/ ha capacity (Table 6.9). Hypothesis #20 should be accepted for N uptake and soil N loss, but rejected for denitrification, P uptake and P loss. Denitrification was slightly higher at the lowest rate, probably because in the model, the closer the N storage is to its maximum amount, the higher the denitrification rate is, since there is less competition between the plants and microorganisms. At the lower storage capacity, N is likely to be nearer to maximum amount for a longer period of time than at higher storage capacities. This is a minor issue that may be addressed in future model iterations, especially if better information regarding denitrification rates in field operations becomes available. P uptake rates were maximum at all rates applied, and P loss was 0, indicating that the soil had sufficient P capacity to meet plant growth needs under all tested conditions.

iv. As discussed previously, plant evapotranspiration rate (K_c) has an impact on how much water a plant uses over a given amount of time, or in other words how efficiently the plant uses water. Plant water use has an impact on the frequency of irrigation in field operations, since plants with a higher K_c are going to require more frequent irrigation, while a plant with a lower K_c would require less irrigation given the same conditions. For the model, a K_c of 0.3, 0.5, and 1.5 were run to determine the impact of this variable on the model.

Hypothesis #21: Since plants with a lower K_c use less water in a given time, these plants should have lower evapotranspiration, and more water should be available for leaching and runoff, since it is not being used by the plant.

Hypothesis #21 stated that plants with a lower K_c would leach more water, since less was being used for evapotranspiration. Of the 746 L of water applied at the highest K_c (1.5), all of the water applied was used for ET, suggesting that plants were in drought stress at some time during the run, while the 0.5 K_c plants used 735 L, and the 0.3 K_c plants used 495 L over the course of the run (Table 6.10). The 0.3 K_c plants reported 173 L of leachate, while the 0.5 K_c run produced 11 L of leachate and the 1.5 K_c run produced zero leachate, since all applied water was used in ET. Although "leaching" in the field model means water applied in excess of the holding capacity of the soil, what this number illustrates is the potential for nutrient movement (mainly N) in the soil, if irrigation or rainfall exceeds the holding capacity of the soil. These data support the hypothesis that lower K_c values increase water loss mechanisms.

v. A variety of different chemical fertilizers application rates and timings were applied to determine their effect on plant growth, denitrification, and leaching. Solid fertilizer was added at 56 kg/ha (50 lb/ac) four times during the growing season at 20% N and 20% P. Liquid fertilizer was added at the rate of 11 kg/ha (10 lb/ac) with 20 applications over the growing season of a 20% N and 20% P soluble fertilizer, with either 0 kg/ha or 1120 kg/ha (1000 lb/ac) biosolid at 2% N and 5% P, added at the start of the growing season. Organic (biosolid) material can be added to an operation in various forms such as manure, nitrogen fixing cover crops (i.e. legumes, or clover) or compost. Organic matter benefits the soil by increasing the water and nutrient holding capacity of the soil, and breaking down slowly over the course of one or several growing seasons, which gradually releases stored nutrients for plant uptake (LeBude 2006). In the model, biosolid application is designed to release nutrients over the course of one growing season.

Hypothesis #22: As application rate increases for both solid and liquid fertilizer, plant uptake and denitrification should increase. Liquid fertilizer should be more efficiently taken up by plants, and have less runoff loss than solid fertilizer. Since there are more applications of liquid fertilizer, plant uptake should be more efficient, compared to solid fertilizer, because plants are getting a smaller amount of fertilizer more frequently compared to solid fertilizer application.

Hypothesis #22 states that increased fertilizer rate should increase plant uptake and denitrification, while liquid fertilizer should be taken up at a higher rate than solid fertilizer, since there are more applications. Plant N and P uptake were maximized at the lowest rates of N (Table 6.8) and P applied (Table 6.9). The solid fertilizer did have leaching, and the highest denitrification rates, but twice the amount of fertilizer was applied, so it is unclear if the higher denitrification and leaching rates were due the frequency of fertilizer application or the rate. Under these conditions, this hypothesis cannot be accepted nor rejected.

vi. Hypothesis #23: Biosolid applications, having relatively low nutrient contents, should not strongly impact potential nutrient leaching even at 1120 kg/ha, especially in soils that have higher N and P holding capacities (e.g. clay or loamy soils), and since they are incorporated in the soil, reducing potential erosion losses, assuming excess water is applied to produce overland flow.

Potential nutrient leaching should not be negatively impacted by the addition of biosolid (Hypothesis #23). At the rate of 1120 kg/ha of biosolid addition, the amount of N only increased from 20.4 g to 22.4 g per tree (Table 6.8), while P only increased from 8.8 to 11.0 g, at the same tree density (Table 6.9). Denitrification was slightly higher at 2.0 g for biosolids application vs. 1.4 g for non-biosolid application, with all other outputs being the same between the two runs (Table 6.8). From this information, hypothesis #23 can be accepted, i.e., that biosolid applications do not increase N and P leaching, at least at the rates tested.

Table 6.10. Results for six different what-if scenarios, representing fourteen separate model runs for water.

	Applied water (L)	Evapotrans-piration (L)	Water leached (L)	Surface water runoff (L)
No buffer	863	495	287	29
In-row buffer only	863	495	287	29
End-of-field buffer only	863	495	287	29
Containment basin only	863	495	287	29
In-row and end-of-field buffer	863	495	287	29
6.1 m buffer width 5% slope	746	572	109	29
30.5 m buffer width 7% slope	746	572	109	29
22.4 kg/ha N and P soil storage	746	495	173	29
168 kg/ha N and P soil storage	746	495	173	29
Crop factor (Kc)= 0.5	746	735	11	29
Crop factor (Kc)= 1.5	746	746	0	29
45.4 kg x 4 applications solid	746	572	109	29
1120 kg/ha biosolid, 4.5 kg x 20 applications liquid	1096	572	420	29
0 kg biosolid, 4.5 kg x 20 applications liquid	1096	572	420	29

F. Conclusions

Rates of nutrient application are typically low in field operations compared to the rates reported for greenhouse and container-nursery operations. In Chapter 3 it was reported that the *highest* average rate reported for the field operations that were visited was 77 kg N, 24 kg P_2O_5, and 27 kg K_2O per ha/yr, respectively, compared to the *lowest* average rates for woody perennials reported in Chapter 3 as 372 kg N, 122 kg P_2O_5, and 176 kg

K_2O per ha/yr respectively. With increased rooting volumes in field production compared to container-nursery or greenhouse operations, and slower movement of nutrients through the root zone in soils compared to soilless substrates, nutrient availability should be increased along with nutrient uptake efficiency, decreasing the risk of nutrient loss compared to plants grown in soilless substrates. The main risk for nutrient runoff with field operations is from overland flow, which can carry dissolved or undissolved fertilizers and sediment-bound P, if proper irrigation and sediment reduction best management practices are not followed. While nutrient and sediment runoff in field operations is important, and growers should implement best management practices wherever possible, it has been demonstrated that the low rates of N and P applied in field operations have a much smaller impact on nutrient runoff, compared to greenhouse and container operations.

The field model was developed based on site interviews with seventeen field operations in Maryland, along with an extensive review of the literature in this area. Model validation showed N and irrigation values similar to published results under a variety of conditions. There were no rigorous studies that could be found that appropriately addressed P uptake in the field soils for ornamentals, which could be used for validation of the field model. Although similar processes were used in the field model, compared to the greenhouse and container-nursery models, which were validated with P results, further testing is recommended to increase confidence in the P portion of the field production model.

The hypotheses tested in this chapter represent only a small number of the possible hypotheses that could be tested with these models. The hypotheses presented here represent some of the more critical questions that are being asked by both growers and researchers today. It is also worth repeating that all three of the models that were developed can be used to generate information that was not reported in the original research, increasing the usefulness of these models.

Chapter 7: Overall Discussion and Conclusions

A. Database

The database that was developed for this project is the most comprehensive and detailed list of nutrient and irrigation practices for the nursery and greenhouse industry available either in Maryland or anywhere in the United States, to our knowledge. This information is particularly useful for researchers in this area, to gain a better understanding of nutrient and irrigation practices in these highly intensive specialty crop production systems. Additional data collected from around the country would enhance the usefulness of this database by being able to compare the data gathered from Maryland to different parts of the country. Data presented in this dissertation represents a broad analysis of some of the most important information that was gathered from forty-eight individual operations across Maryland. For all three types of operations (greenhouse, container and field), a list of recommended rates for a variety of different species and container sizes was developed. These recommendations could be further refined with information from additional growers, especially if certain species or container sizes are targeted. In addition, the grower database that is presented here still has a large amount of data that was not analyzed as part of this project. Additional analysis of this database could lead to further insights into this industry that would be helpful for both growers and researchers.

Fertilizer ratios that were reported by growers were typically high in phosphorus (P_2O_5) and potassium (K_2O) compared to the percent of nitrogen (N) in the fertilizer for greenhouse, container and field operations. Higher P_2O_5 and K_2O ratios, compared to specific plant uptake requirements could lead to higher P and K runoff, since these nutrients can be applied in excess of plant requirements, without custom blend fertilizers being available for growers. In general, container operations had N: P_2O_5 application ratios more in-tune to plant requirements compared to greenhouse and field operations, but the results of this study suggest that P application ratios could likely be reduced further without negatively impacting plant growth. Based on species-specific data published for N and P uptake rates in ornamental plants, a ratio of 4 : 1 : 3 to perhaps 8 : 1 : 6 (N : P_2O_5 : K_2O) would optimize plant growth, while reducing unused nutrient amounts in the substrate (Ku and Hershey 1997b; Ku and Hershey 1997a; Ristvey 2004; Sammons 2008). If fertilizer manufacturers provided formulations that more closely matched plant uptake requirements, nutrient leaching could be reduced (assuming appropriate application rates by growers), since plants would be taking up nutrients in approximately the same ratios they are applied.

Irrigation management is an integral part of the ornamental nursery and greenhouse industry. Supplemental irrigation is required for plant survival both in greenhouse and container nursery operations. In field nursery operations irrigation is used to increase plant growth and survival during early stages of production, and during extended periods of dry conditions during the later stages of production. Rainfall and irrigation can lead to water runoff from an operation, under the right conditions. Water runoff can carry sediment and nutrients, which can reach surface water, if proper mitigation practices are not used at an operation. Water management is a key component of nutrient and sediment reduction and loss at an operation.

Nutrient management plans and annual reporting forms acquired from the Maryland Department of Agriculture as part of this research were found to contain an insufficient level of detail for this project about nutrient application rates and timings, and minimal or no information on irrigation practices at an operation. Since water management plays an integral role in operational efficiency and nutrient and sediment runoff, it is an important area for future research and grower education. As fresh water resources continue to be an area of concern in Maryland and across the country, water management will continue to be a focus for both growers and researchers now and in the future.

i. Greenhouse

In addition to adjusting fertilizer ratios, the greenhouse model outputs, and the values reported by growers predict that rates and frequencies of fertilizer applications can be reduced in most production situations, without negatively impacting plant growth. Eighty percent of the greenhouse management units surveyed as part of this project used soluble fertilizer as either the main or only fertilizer source. Based on grower interviews, growers in Maryland typically fertigated continuously, although some fertigated up to once every four irrigation cycle, with fertilizer rates between 100 - 380 mg/L (ppm). Cabrera (2003) recommended continuous fertigation at 60 mg/L N for *Ilex opaca* ‘Hedgeholly’ and *Lagerstroemia* x ‘Tonto’, similar to other studies recommending 50-100 mg/L for maximum growth for a variety of woody ornamental species. We conclude that most current greenhouse fertigation practices are applying N, P_2O_5 and K_2O in excess of plant requirements for maximum growth. Reducing fertilization rates applied by this industry would likely have a substantial impact on both cost savings from reduced fertilizer use, and an environmental benefit from reduced nutrient leaching from the container. Recommended application rates are provided for sixteen common greenhouse grown plants and container sizes in Chapter 3 (Table 3.6). It is likely that most growers could reduce nutrient application rates between 20% and 75%, while still maintaining maximum plant growth, since those growers in the lowest quartile are producing similar quality plants on the same production schedule as growers applying higher rates of fertilizer. Controlled greenhouse studies would be recommended before implementing rates at or below these rates, since there is a possibility of scaling errors in the model, given the small size of some of the management units reported.

ii. Container

For the container operations that were analyzed in this study, over 80% of the management units used slow-release fertilizer, while 4% used soluble fertilizer. Container operations typically applied fertilizers that had ratios similar to the 4 : 1 : 3 rate recommended by Sammons (2008), with 84% of the management units reporting use of fertilizers with an N : P_2O_5 ratio within the previously discussed ranges. Ratios of N : K_2O were often lower than recommended, suggesting that K_2O percentages could be reduced without negatively impacting plant growth. It is likely that SRF ratios could be modified to better match plant uptake ratios of N : P : K, although in general SRF ratios are more in line with plant requirements than soluble and solid fertilizer, for the operations studied in Maryland.

Actual fertilizer application rate ranges are reported for eleven different plant type/ container size combinations in Chapter 3 (Table 3.10). Fertilization rates for container operations were several times higher than the rates reported for greenhouse operations on a crop cycle basis, but not on an annual basis. Greenhouse application rates were reported on a per cycle basis. If you take into account that greenhouse operations typically grow three or more rotations of plants on the same physical space over the course of the year, container and greenhouse application apply very similar nutrient application rates on a per acre / year basis. It should also be noted that these rates are much higher than recommended rates for most agronomic crops. Plant densities in greenhouse (Table 3.2) and container-nursery (Table 3.7) operations can range from $1/10^{th}$ to 100 times or more of current corn planting densities of 33,000 plants per acre. Plant density has a strong influence on nutrient application rate (kg / ha) particularly in container operations, where SRF is added directly to the container, so the higher the plant density, the higher the rate of fertilizer per area (kg / ha).

It was also found that container operations used more than twice the volume of water per irrigation on a per hectare basis, compared to greenhouse operations. It is possible that the difference in irrigation volume is due to greenhouse operations irrigating more frequently than container operations. The difference may also be due to container operations typically using larger container sizes, which require longer irrigation times to rehydrate, and wider spacing which leads to lower irrigation interception efficiencies. Longer irrigation durations are required to fill the larger containers, and account for the larger volume of water that falls between containers, compared to greenhouses operations. Factors such as wind and evaporation would also be factors in an open field (container) compared to the greenhouse. Based on grower interviews, it was determined that container operations using overhead sprinklers could be applying 18 cm (= 7 acre inches = 193,000 gallons/acre = 1,800,000 liters/ha) or more of irrigation per week to their growing areas, especially during the hottest times of the year. Higher irrigation volumes would also increase the potential for nutrient and sediment runoff under the right conditions at these operations.

iii. Field operations

Field operations were typically extensive, with low nutrient and irrigation inputs. All operations that were visited as part of this study had vegetative buffers both between rows and at the end of rows, which are considered best management practices for reducing sediment and nutrient runoff. Irrigation was typically applied with drip emitters, although a small number of operations did use impact sprinklers or traveling guns at their operation. Irrigation was typically applied frequently (several times a week) when newly transplanted blocks were being established (during year one and two), and as needed during extended periods without rain during the remaining time plants were being grown. Average drip irrigation depth was found to be 2 cm (= 0.8 acre inches = 21,750 gallons/acre = 230,000 liters/ha) per irrigation, with one to several irrigations per week depending on species, plant age, environmental conditions etc., which is similar to typical recommendations of 1 inch of water per week for in-ground ornamental plants.

Solid chemical fertilizers were used at 79% of the operations that were interviewed, with the remaining operations applying either biosolid, slow release, foliar urea, or no fertilizer at their operation. Even the highest reported rate of 77 kg/ha N, 24 kg/ha P_2O_5, and 27 kg/ ha K_20 was much lower than the rates reported for both greenhouse and container operations, and equivalent to recommended rates for corn (168 kg N/ ha / yr or 150 lb N acre/year). The N: P_2O_5 : K_20 ratios reported by growers were found to have lower ratios of N: P_2O_5 and N: K_20 compared to plant uptake rates, suggesting that these ratios could be increased to more closely match actual uptake rates, and decrease the potential for nutrient runoff of one or more nutrient that is applied above plant requirements. Based on the ranges reported by growers (Table 3.12), the following general application rates are recommended for field-grown plants: 25-50 kg N / ha / yr, 6-15 kg P_2O_5 / ha / yr and 20- 40 kg K_2O / ha / yr.

B. Stella Modeling Software

The Stella software package has been used for modeling systems in a variety of fields including economics, natural sciences, and business. The Stella program uses a systems thinking approach to model systems with varying degrees of complexity. The Stella program proved to be an appropriate tool for this project. The models that were developed as part of this project were able to incorporate the necessary complexity of these systems, and created models that functioned as required. Modeling these complex systems was accomplished using a small number of "building blocks" included with the program, which can be constructed and manipulated as needed. The necessary relationships in the model were developed and defined without having to understand the underlying programming that was involved. Model equations were defined by the program based on the relationships that were developed in the model layer.

In addition to simplifying model construction, the program is also able to create graphs and tables that are useful for understanding the impact of certain changes on the model, once the models are complete. Stella was also able to interface with Excel for importing and exporting data quickly and accurately, which proved to be very beneficial. In addition, the ability to publish models online will be valuable for disseminating the models to growers and researchers in this field in Maryland and across the country. We intend to include three learning modules on the use and application of these models in the Green Industry Knowledge Center at http://www.water.org/moodle (Lea-Cox et al., 2008) in the near future.

The current models do have some restrictions that the user does need to be aware of. There are some restrictions that have to do with the program itself, while others are due to a lack of information about certain processes that are included in these particular models. The most important areas for model improvement for these models in particular are included in the sections below, and in Chapters 4-6. There are a number of peculiarities in the program itself that need to be understood in order for the model to function as intended. The program uses the concept of Delta Time (DT) to determine the frequency between model steps, which can be confusing. For example, the container and field models run on a weekly time-step, but the DT of the models are 1/7, so the model reports a value each day. A weekly time-step decreases the number of values that need to be entered for the graphical inputs, which makes model inputs less cumbersome. Model outputs are retuned daily, but are based on the weekly time-step information (e.g. N and P uptake). If model outputs were totaled for graphical information, they would equal seven times the value that they should, although the program is functioning correctly.

Currently, it is cumbersome for someone who is not familiar with the model to increase the length of the model runs above the current set points (20 weeks for greenhouse, 40 weeks for container and field). If a user wanted to increase the run length, all pertinent graphical values would have to be adjusted. Lastly, it would also be beneficial if a maximum value for the stock building blocks could be included. Currently, stocks can hold an unlimited amount of “stuff” that flows into them. The models had to be designed so the stocks could only hold a certain amount of N, P and water to mimic actual conditions.

In general, the basics of the Stella program are relatively easy to understand, with quality introductory information included with the program. The help information is able to answer a majority of questions about the program, and technical support was also very helpful and responsive. There can be some difficulty understanding how the program processes input and output information especially as models become more complex.

C. Greenhouse Model

i. Areas of model proficiency

The greenhouse model incorporates the most important variables for water and nutrient runoff in this intensive plant production system. After the important variables were identified in the greenhouse production system, the model was calibrated. Calibration involved inputting data from a published dataset, and systematically adjusting pertinent model variables until model outputs approximated published values. After calibration, models were validated with additional datasets, from two published research articles. The only input values that were changed during verification were the values that were being studied in the published research. Model calibration and independent verification results show that this model accurately simulates plant N, P and water cycling under the conditions reported in the peer-reviewed publications used for model calibration and validation.

The models were able to accurately replicate the N and P inputs reported in the original research studies, under a variety of conditions. In addition, N and P uptake rates were similar for each model run, compared to the original research results, suggesting that these variables are running correctly in the models. Leaching values and N and P amounts in the container at the end of a run also corresponded well with the research results in the validation runs (independent of the model calibration), which increases our confidence in these subroutines of the models.

Another benefit of these models is that the sum of the input values matches the sum of the output values. For example, if a grower applies 10 grams of N to a plant over the course of the growing season the model accounts for 10 grams in the output, whether it is in the plant, runoff, denitrification, or in the container. This is not always the case in published research, especially if factors such as loss mechanisms (e.g. denitrification, conversion to organic N or P) or all sources of nutrient inputs or outputs are not taken into account (e.g. starter charge in substrate). The greenhouse model also includes microbial accumulation, since microbial use can impact N and P cycling.

Another benefit of a modeling approach is being able to predict values for variables not measured in the original research. This benefit was shown in the greenhouse model validation, since not all variables were reported in the published results, the model was able to predict plant evapotranspiration rate and leaching volumes, even though those values were not reported. This benefit was seen for all three models that were developed. It should be noted that the accuracy of model predictions is dependent on the quality of model inputs. The better the information that is input into the model, the more accurate the results will be. For example, there are a number of K_c values that are reported in Table 5.1. If two species have similar water use requirement and one has a published K_c value, the ET calculation for the species with the unknown K_c value is likely to be accurate. A species that does not have a similar water use requirement to a reported plant will not be modeled as effectively.

The real impact of all the models is their ability to quantify the effects of changing grower practices. Using information from the research grower database, poinsettias averaged 618 kg / ha for N and 243 kg / ha for P_2O_5 for 8-18 cm poinsettias. For the "ideal" what-if scenario, it was shown that 78 kg / ha was sufficient to maintain optimal N uptake rates, and 31 kg/ ha was sufficient for maximum plant P uptake, under greenhouse growing conditions. This equates to an eight-fold reduction in N and P_2O_5 rate, compared to the average rate applied by the growers in this study. This would translate into a significant cost saving in fertilizer and environmental benefit for growers, by reducing any mitigation requirements. Similar reductions are likely for a variety of different species grown in greenhouse operations.

The three models presented here are designed to be adapted to different climatic conditions so they can be adapted for use across the United States, and potentially in other parts of the world, by changing a small number of variables. Temperature and rainfall variables can be easily changed to match average local conditions, incorporate specific data from a weather monitoring station, or model a hypothetical situation for a particular location. The models were also designed to be as simple and user-friendly as possible, so growers can quickly get a relatively thorough understanding of the impact of their current water and nutrient management practices, and understand potential ways to increase their operational efficiency. The models were also designed so that someone who understands the complexities of these production systems can change additional (pre-set) variables to get more accurate results, or ask a variety of different questions that many growers might not be interested in.

ii. Areas for model improvement

Although the greenhouse model has a number of areas that have never been represented by any other model, there are a number of areas in the model in which improvements could be made, to increase model accuracy under a variety of conditions. Currently, the N, P and water subroutines of all three of the models are not linked together, since no way could be found to do so without negatively impacting other aspects of the model. In the current models, N and P leaching occurs if more of the nutrient is applied than can be held by the substrate or soil (i.e., container or rooting volume) without interaction with the amount of water present, which is necessary to cause nutrient leaching. Nutrient dynamics in the root zone are known to be more complex than they are currently represented by the models. For example, nitrate nitrogen is not efficiently bound by soils or soilless substrates, and will leach if excess water is applied to the container or soil over container capacity. It is clear that water is the transport mechanism of N and P in the system, although this is not accurately reflected in the current models. Ideally, the models would be able to use water runoff information to, in part, determine the amount of N and P that is leached from the container. Nutrient movement should be at least partially linked to water movement in the container, instead of container capacity, especially for N.

Similarly, the current model predicts leaching if excess nutrients or water are applied over container capacity. In reality, this is true for water, but not necessarily for N and P since if there is no water leaching from a container, there will be no nutrient leaching. However, at present, nutrient leaching does occur if nutrients are applied above container capacity, regardless of the water status of the container. Model results showed that this was not a significant problem except for the Ku and Hershey (1997 a; b) zero leaching fraction dataset, where the model predicted nutrient leaching based on container capacity, but there was no nutrient leaching since there was no water leaching (deficit irrigation). In effect, the models predict “potential leaching”, which is the leaching that will occur if excess water is applied to the container or soil.

An additional benefit to linking the N, P and water subroutines would be the ability of the models to limit nutrient or water uptake if N, P or water was limited during the growing period. For example, if N was limiting during some part of the growing period, this would be reflected in the N uptake rates, but not in the P uptake or ET values in the model. In reality, limiting one of these uptakes would limit the others as well, but the current models do not account for this type of biological system complexity.

Currently, it is possible for both irrigation water and fertigation water to be added to the container on the same day, which would lead to increased water leaching losses over actual conditions. After discussions with Stella model technical support, a viable solution could not be determined, at least the way the model is currently constructed (Sarah Davie, *pers. comm.*). Ideally, the model would be able to take irrigation and fertigation application information and only apply one or the other during a time-step (one day). Model evapotranspiration prediction would likely be improved with the inclusion of daily light integral, based on data from van Iersel (2010), since light interception impacts transpiration. Adding this variable would help the model be more predictive on a short-term basis, since real-time data could be integrated into the model, to help a grower make irrigation decisions. Similarly, a better understanding of ET values for a variety of greenhouse plants and conditions would also make the models more accurate.

Current models are based on user inputs, and cannot adjust nutrient uptake rate to account for luxury consumption or compensate for N or P limitation during some part of the growing period. The inputs can be adjusted manually to account for these factors, but there would be some benefit, especially to researchers, if the models could automatically mimic plant uptake during luxury consumption, or increased nutrient uptake after limiting conditions (i.e. incorporate more 'plasticity', a well-documented biological response).

Each of the three models presented here could use improvement in the microbial loss mechanisms of the model. Microbial populations in a container substrate or field soil compete with plant roots for available N and P. Part of this N and P is then incorporated into microbial biomass, and cycled for eventual re-use by plant systems. Values for the amounts of N and P that are bound by the microorganisms in a container or soil would be beneficial for a more accurate model, but none could be found after an extensive literature search. In addition, the denitrification portion of the model could also be improved with better research. As discussed previously, under anoxic conditions microorganisms use nitrogen to produce energy, creating N_2 as a final product. Denitrification losses are thought to account for 20-40% of the N that is applied to a container or soil, depending on the conditions in the root zone. There are a number of factors that can impact denitrification including plant age, nitrogen concentration, carbon availability, substrate compaction and temperature. The models currently incorporate nitrogen level and temperature into the denitrification equation. Additional research into denitrification rates under varying conditions would be valuable for the models.

Over 80% of the management units that were characterized in Maryland used soluble fertilizer either exclusively or as the main nutrient source. In order to simplify the model, slow-release fertilizer is currently not able to be utilized in the greenhouse model, but the container model can be used to model SRF application in the greenhouse by setting rainfall to zero for the course of the growing period. Since a number of growers used SRF on some plants (e.g. hanging baskets, mums and some additional longer-term plants) this would be a useful addition to this model.

D. Container-Nursery Model

i. Areas of model proficiency

There are many aspects of the container model that show the benefit of this model to the industry. Nitrogen and P inputs can be in three different fertilizer forms; slow release, soluble and biosolid applications, representing a variety of options available to growers. The SRF subroutine includes substrate temperature (Q_{10}) information which should closely match actual release patterns in SRF and lead to accurate analysis of this portion of the model.

The container model accurately predicts N, P and water application rates, timing and nutrient uptake using the variables included in the model. If a user accurately inputs the proper variables into the model, application results will closely match actual practice. Using container diameter and container spacing, the model also automatically calculates theoretical overhead irrigation and rainfall interception efficiency for the management unit. The model determines intercepted and non- intercepted portions of the rainfall and overhead irrigation, and keeps them separate.

The model also incorporates a “plant architecture factor” which can increase or decrease the amount of water that is captured by the plant canopy. The branching pattern and general growing habit of a plant either sheds water (i.e. a weeping habit) or funnels water (i.e. upright branching) into the container / root zone. The model is highly sensitive to this variable, so it is recommended that only experienced users adjust this factor. Additional research would be beneficial to provide additional plant architecture values for a number of commonly grown ornamental species.

As mentioned previously for the greenhouse model, the container model predicts additional values that were not measured in the original research, using the values and equations that are incorporated into the model. For example, the data reported by Cabrera (2003) used to validate the model did not include plant P uptake information. The model was used to predict P uptake information using the application rates and growing conditions reported in the original article.

ii. Areas for model improvements

A number of potential model improvements are similar to those described for the greenhouse model above, which will not be discussed again in this section. The container model does not take microbial nutrient accumulation into account, although the greenhouse model does. No values could be determined from the literature for microbial N and P uptake, so research in this area is necessary for defining these values. However, in the overall system nutrient balance, this microbial component is likely to be very small. Container-substrate amendments, such as crushed brick, grape marc and coir will likely have an impact on water and nutrient holding and release patterns in soilless substrates. Research is necessary to determine the impact on the physical and nutrient holding properties of these amendments.

The denitrification subroutine could also benefit from more research. As mentioned previously, no articles could be found that measured denitrification in an external production environment. Currently, the container model uses a surface area approach where the denitrification rate is dependent on the surface area of the container.

Research in this area should perhaps determine a volumetric denitrification rate, which might be more appropriate for containerized plants. This research should also include the impact of soil moisture on denitrification rate, since this is an important factor in native soils. It is possible that denitrification is an exponential function instead of a linear function, which is the current model setting. With a better understanding of denitrification values under a variety of conditions, the model will be able to be able to more accurately predict N loss. Lastly, future container model interactions could incorporate a "pruning" function that removes a certain amount or percentage of N and P from the leaf and stem tissue portion of the model. This would better represent the nutrient loss from pruning for a particular species. This will allow us to better model the impact of water and nutrient application rates and timings to match plant growth requirements.

Runoff and runoff abatement is important for decreasing an operation's environmental impact. The containment basin and vegetative buffer model components provide an appropriate starting point, but would benefit from additional research and refinement of the models. Additional research should determine the impact of soil type, vegetation type, buffer maintenance, denitrification and rainfall intensity into account, in order to gain a better understanding of the interaction of these factors on nutrient and sediment reduction. A variety of research questions are important such as: How does sediment removal translate into N and P removal? What impact does water infiltration rate into the soil have on N and P runoff? How much denitrification is occurring in containment basins and vegetative buffers when N is present in these systems? Answers to these and other questions would be beneficial to future modifications of both the container-nursery and field models.

The container-nursery model might also benefit from added BMP's to account for more practices that are in use for nutrient and water remediation in Maryland or around the country, such as constructed wetlands, or nutrient removal by plants using floating mats in containment basins. The container model would also benefit from additional research on plant architecture values, better rainfall modeling and additional plant crop coefficient (K_c) values. The rainfall portion of the model might be modified to include actual historic rainfall data (perhaps linked to an online database input) to be more realistic. Although Table 5.1 provides a number of ornamental K_c values, additional species would be valuable for higher model accuracy. It is also unclear why the same species have different K_c values, as reported in Table 5.1. We need to know whether K_c values are partially dependent on seasonal or microclimatic conditions. Also, is the surface area of the canopy a sufficient metric for determining ET? Answers to these questions would be invaluable in further refining the container model.

E. Field Nursery Model

i. Areas of model proficiency

The field model that was developed for this project allows for N and P inputs from soluble fertilizers through drip lines, solid fertilizer surface applications, and/ or biosolid fertilizer incorporation into soils. These nutrient inputs cover the standard nutrient application practices in Maryland, and likely many parts of the country. The models showed good agreement with published results for N application and uptake for both research papers that were used to calibrate and to validate the model. Containment basins and vegetative buffers provided reasonable rates for N and P removal, although additional testing and research would be beneficial. The evapotranspiration portion of the model was validated using data from Quinones et al (2007), and was found to be function correctly under the conditions tested. As mentioned for the other models, it was shown that the field model could also predict values that were not reported in the original research, enhancing the usefulness of these models for answering a variety of questions (e.g. P uptake rates).

The what-if scenarios that were run through the model showed that the low N and P rates used in field operations in this research study had little or no N or P runoff, with standard irrigation and buffer best management practices that are routinely used by growers. These operations may be contributing some sediment loading to surface water near production operations, but we could not predict this since a sediment runoff subroutine is not included in the current field model.

ii. Areas of model improvements

Currently, the model applies biosolid fertilizer to only the portion of the management unit that is turned over each year, and this biosolid application is broken down over a one-year period. Future model iterations could include a more precise biosolid application subroutine that allows for long-term microbial breakdown and nutrient release over longer periods. It would also be better to make solid fertilizer amounts per application a graphical input instead of a constant in the model, so it can be varied over the growing season. This way, if a grower applies different rates of fertilizer over the growing season, this can be taken into account. It would also be recommended to add a factor that would take into account operations that do not have a vegetative buffer strip between rows. The main concern with this is that denitrification would be overestimated if there is no vegetative buffer strip, and fertilizer is applied as a side band to part of the row (i.e. a 1 m wide fertilizer application to a 2 m row spacing). By adding this factor, denitrification would be limited to the area where the fertilizer is banded, instead of over the whole management unit area as would currently occur in the model if no vegetative buffer is used in the row.

The current field model does not estimate sediment loss, but this would be a major improvement for future models. Sediment loss was not included because a user-friendly soil loss procedure could not be easily incorporated into the model. The Maryland phosphorus site index procedure, which uses the revised universal soil loss equation (RUSLE) was considered, but was not practical due to the amount of site-specific information that is required for accurate results using this tool (Coale et al. 2002). Including a sediment loss equation would be beneficial for a number of reasons including determining how much sediment is lost due to water runoff, and where the sediment goes under different scenarios (i.e. rainfall event soon after transplant or fertilizer application). It would also be beneficial to link sediment and nutrient loss from water runoff due to rainfall events and / or overhead irrigation (traveling guns). Additionally, no information could be found for N removal efficiency in containment basins. The information in the models is based on information for constructed wetlands, but the dynamics in a containment basin are likely to be different. Wetlands are designed to remove sediment and nutrients, while containment basins and sediment basins are designed to capture sediment and water, and are likely to be carbon-limited, which would greatly reduce denitrification rates.

Nitrogen movement through the soil profile in the field model is dependent on the soil nutrient retention capacity, similar to the process reported for greenhouse and container-nursery models. It is likely that linking N to water movement in the soil would be more accurate than using soil holding capacity. As discussed in Chapter 6, Olson and Swallow (1984) showed that 47% and 54% of the applied N moved past the root zone over a 5-year period with application of 50 kg/ ha and 100 kg/ ha respectively in winter wheat. Ideally, both N and P movement through the soil profile and surface runoff should be linked to rainfall and irrigation application rates and timings.

Currently, irrigation from traveling guns is applied evenly to the management unit, but this overestimates water infiltration. For the overhead irrigation portion of the model, the nozzle discharge rate and the radius of throw of the overhead sprinkler should be used to determine the water application rate for the area being irrigated. The infiltration rate of the soil is dependent on the soil properties, with the amount of water runoff determined by the amount of water applied to a given area over a given time minus the amount of water that infiltrated into the soil over that same time.

The field model would also benefit from additional ornamental field studies that could be used for further validation of the model, especially the P portion of the model. No suitable datasets were located that could be used for phosphorus validation in the field model. The phosphorus subroutine of the model works similarly to that developed for the greenhouse and container models, so we are confident that this portion of the model is running correctly, but additional validation would be beneficial.

F. Conclusions

This project developed a detailed nutrient and irrigation database and three specific operational models as tools to target water and nutrient reduction efforts for container-nursery, field-nursery and greenhouse operations in the State of Maryland. This effort is a unique approach which has not been done before to our knowledge, and provides a valuable tool for researchers and growers in the ornamental industry. The use of these models has the potential to improve the understanding of both researchers and growers, and help growers implement more efficient and sustainable practices by illustrating the impacts of a combination of site-specific practices. By demonstrating targeted reductions in irrigation and fertilization practices, we can predict the best combination of management practices to enhance profitability for growers, which are strong incentives for changing practice. This study adds significantly to the body of knowledge in the areas of nutrient runoff and modeling, and has the potential of being used in other states, and in other countries to reduce nutrient runoff from nursery and greenhouse operations.

Appendices

Appendix A

Table A 1-1. Proposed TMDL and 2009 loading rates in 1000's of pounds per year. Data modified from (U.S. Environmental Protection Agency 2010).

Juris-diction	**Cheaapeake Bay 303(d) Segment**	**TMDL** 1000 lb N /yr	**2009 Load** 1000 lb N/yr	**TMDL** 1000 lb P /yr	**2009 Load** 1000 lb P/yr	**TMDL** 1000 lb sediment /yr	**2009 Load** 1000 lb sediment/ yr
DC	Anacostia River, DC	115	131	15	27	1.889	4.741
DC	Anacostia River, MD	8	13	3	3	0.374	0.609
DC	Upper Potomac River, DC	2,171	2,507	102	35	8.414	8.418
DC	Upper Potomac River, MD	26	202	1	21	0.481	18.042
DE	Bohemia River	39	56	5	6	0.612	0.624
DE	C&D Canal, DE	20	29	3	3	0.502	0.627
DE	C&D Canal, MD	54	72	6	7	1.074	1.291
DE	Elk River	9	13	0.5	0.91	0.06	0.107
DE	Middle Nanticoke River	319	478	36	43	7.35	7.696
DE	Sassafras River	29	42	4	4	0.641	0.685
DE	Upper Chester River	112	162	14	16	3.078	3.351
DE	Upper Choptank River	242	376	35	42	7.265	7.429
DE	Upper Nanticoke, DE	2,029	2,805	151	181	36.337	42.031
DE	Upper Nanticoke, MD	0.1	0.4	0	0.02	0	0.001
DE	Upper Pocomoke River	93	134	9	10	10.841	11.191
DE	Wicomico River	6	12	0.48	0.97	0.103	0.174
MD	Anacostia River, DC	46	54	7	11	0.89	1.616
MD	Anacostia River, MD	422	500	41	62	70.171	111.376
MD	Back River	1,758	2,258	92	76	16.386	9.428
MD	Big Annemessex River	145	154	8	8	0.801	0.522
MD	Bohemia River	135	180	15	20	3.251	3.759
MD	Bush River	871	1,001	38	64	24.088	35.409
MD	C&D Canal, DE	0.1	0.2	0.01	0.04	0.004	0.005
MD	C&D Canal, MD	49	59	5	6	1.083	1.259
MD	Eastern Bay	907	1,125	70	72	10.443	11.317
MD	Elk River	362	468	26	30	8.736	9.989
MD	Fishing Bay	733	874	73	78	4.679	5.114
MD	Gunpowder River	1,142	1,290	31	59	33.801	57.277
MD	Honga River	144	164	5	7	0.544	0.647
MD	Little Choptank River	282	336	22	23	3.212	3.49
MD	Lower Central	1,142	1,265	12	29	3.882	5.354

	Chesapeake Bay, MD						
MD	Lower Chester River	690	865	52	52	12.918	14.317
MD	Lower Choptank River	543	656	38	41	4.966	5.816
MD	Lower Nanticoke River	182	198	10	11	0.785	0.829
MD	Lower Patuxent River	650	789	40	64	6.989	12.133
MD	Lower Pocomoke River, MD	216	227	11	11	1.194	1.611
MD	Lower Potomac River, MD	1,126	1,358	112	126	60.801	72.285
MD	Magothy River	236	288	6	21	1.397	2.109
MD	Manokin River	341	343	30	26	1.551	1.494
MD	Mattawoman Creek	171	206	16	21	5.972	6.869
MD	Middle Central Chesapeake Bay	1,545	1,717	20	36	1.786	2.035
MD	Middle Chester River	592	839	63	68	9.687	10.775
MD	Middle Choptank River	587	711	66	64	4.588	4.51
MD	Middle Nanticoke River	677	839	79	84	7.622	8.164
MD	Middle Patuxent River	315	388	18	31	5.909	10.781
MD	Middle Pocomoke River, MD	110	118	9	8	0.686	0.714
MD	Middle Pocomoke River, VA	63	69	8	8	0.691	0.978
MD	Middle Potomac River, MD Mainstem	49	54	4	4	1.65	1.926
MD	Middle Potomac River, MD Nangemoy Creek	137	152	10	11	2.306	2.653
MD	Middle Potomac River, MD Port Tobacco River	128	143	9	10	3.035	3.514
MD	Middle River	106	184	3	12	0.728	1.577
MD	Mouth of Choptank River	478	522	41	42	3.956	3.79
MD	Northeast River	221	251	12	13	14.587	16.453
MD	Northern Chesapeake Bay	1,481	1,919	70	82	70.138	80.793
MD	Patapsco River	4,502	7,821	210	397	79.455	113.382
MD	Piscataway Creek	519	469	32	25	7.609	6.183
MD	Rhode River	55	69	3	4	0.5	0.74
MD	Sassafras River	270	395	33	37	8.628	9.99
MD	Severn River	482	518	24	51	3.809	3.724
MD	South River	225	262	10	20	1.931	3.03
MD	Tangier Sound, MD	712	782	8	8	0.016	0.02
MD	Upper Central Chesapeake Bay	746	771	17	24	3.637	5.412
MD	Upper Chesapeake Bay	723	868	30	35	3.055	2.647
MD	Upper Chester River	422	572	52	52	12.327	13.398
MD	Upper Choptank River	1,102	1,474	134	147	19.338	20.301
MD	Upper Nanticoke, DE	24	26	3	3	0.124	0.128

MD	Upper Nanticoke, MD	53	68	7	7	0.513	0.557
MD	Upper Patuxent River	1,770	1,767	127	151	59.403	67.342
MD	Upper Pocomoke River	799	897	96	95	11.643	11.713
MD	Upper Potomac River, DC	2,210	2,338	105	46	32.32	25.206
MD	Upper Potomac River, MD	10,945	13,298	569	696	497.574	544.927
MD	West River	54	61	3	4	0.518	1.001
MD	Western Branch Patuxent River	215	237	20	26	16.939	23.234
MD	Wicomico River	648	910	62	85	6.483	7.184
NY	Northern Chesapeake Bay	8,232	10,542	524	801	292.96	327.154
PA	Elk River	248	383	12	17	18.956	28.363
PA	Gunpowder River	20	30	1	1	0.372	0.727
PA	Northeast River	35	55	2	2	2.168	3.254
PA	Northern Chesapeake Bay	71,745	99,833	2,305	3,408	1,758.20	2,225.88
PA	Upper Potomac River, MD	4,721	6,112	422	537	233.932	307.04
VA	Appomattox River	2,242	2,159	177	242	64.751	104.214
VA	Chickahominy River	403	446	59	80	2.539	4.339
VA	Corrotoman River	191	218	14	16	1.061	1.276
VA	Eastern Branch Elizabeth River	129	279	20	45	1.875	4.406
VA	Eastern Lower Chesapeake Bay	2,585	3,227	116	140	1.759	3.58
VA	Lafayette River	56	79	7	13	1.096	2.336
VA	Lower Central Chesapeake Bay, VA	971	1,143	36	45	0.343	0.388
VA	Lower James River	1,827	2,615	131	188	14.878	24.915
VA	Lower Mattaponi River	156	188	13	16	1.54	1.605
VA	Lower Pamunkey River	374	329	79	61	1.178	1.519
VA	Lower Pocomoke River, VA	388	673	29	32	0.607	0.679
VA	Lower Potomac River, MD	62	77	6	7	0.683	0.683
VA	Lower Potomac River, VA	1,139	1,358	104	135	10.436	10.267
VA	Lower Rappahannock River	1,539	1,936	102	131	29.156	38
VA	Lower York River	268	301	12	17	1.536	2.101
VA	Lynnhaven River	445	1,855	45	123	2.932	7.883
VA	Middle James River	797	964	47	75	5.076	6.691
VA	Middle Pocomoke River, VA	125	185	18	21	1.377	1.692
VA	Middle Potomac River, MD Mainstem	29	33	2	3	0.282	0.375
VA	Middle Potomac River,	546	608	34	38	10.393	17.259

	VA						
VA	Middle Rappahannock River	240	303	20	23	1.108	1.226
VA	Middle York River	531	612	31	39	3.31	4.088
VA	Mobjack Bay	1,288	1,916	95	127	7.472	14.112
VA	Mouth of Chesapeake Bay	722	819	15	30	6,285	7,979
VA	Mouth of James River	1,342	3,471	118	195	3.53	6.505
VA	Mouth to mid Elizabeth River	589	1,294	45	64	1.194	3.056
VA	Piankatank River	441	470	47	49	12.575	13.66
VA	Southern Branch Elizabeth River	271	434	35	68	2.349	4.741
VA	Tangier Sound, VA	313	340	0.48	0.53	7.781	9.344
VA	Upper James River Lower	2,431	3,468	154	132	6.142	9.015
VA	Upper James River Upper	13,850	15,146	1,476	1,977	743.584	1,050.74
VA	Upper Mattaponi River	1,112	1,274	88	103	17.007	20.734
VA	Upper Pamunkey River	1,999	2,128	171	202	62.031	83.168
VA	Upper Potomac River, DC	665	880	33	30	5.635	6.385
VA	Upper Potomac River, MD	12,107	13,647	1,078	1,592	722.107	948.173
VA	Upper Potomac River, VA	3,045	3,697	209	194	59.787	99.787
VA	Upper Rappahannock River	4,196	4,725	730	876	654.056	706.956
VA	Western Branch Elizabeth River	117	176	13	25	1.164	2.637
VA	Western Lower Chesapeake Bay	736	815	2	3	9.007	13.773
WV	Upper James River Upper	18	23	10	14	16.645	28.274
WV	Upper Potomac River, MD	4,667	5,751	737	819	248.106	346.851
All	**All**	**203,10**	**263,11**	**12,52**	**16,46**	**12,580.4**	**15,968.7**

U.S. Evironmental Protection Agency. 2010. Draft Chesapeake Bay total maximum daily load. <http://www.epa.gov/reg3wapd/tmdl/ChesapeakeBay/drafttmdlexec.html>. Section 9. Last accessed 11/15/2010.

Appendix B

Initial Human Subjects Review Board Application

UNIVERSITY OF MARYLAND, COLLEGE PARK
Institutional Review Board
Initial Application for Research Involving Human Subjects
Please complete this cover page AND provide all information requested in the attached instructions.

Name of Principal Investigator (PI) or Project Dr. John Lea-Cox **Tel. No** 301-405-4323
(NOT a student or fellow; must be UMD employee)

Name of Co-Investigator (Co-PI) Dr. Andrew Ristvey **Tel. No** 410-827-8056

Department or Unit Administering the Project Plant Sciences and Landscape Architecture

E-Mail Address jlc@umd.edu **E-Mail Address of Co-** aristvey@umd.edu

Where should the IRB send the approval letter? Dr. John Lea-Cox, PSLA Department, 2120 Plant Sciences, UM College Park, MD 20742-4452

Name of Student Investigator John C. Majsztrik **Tel.** 301-498-7478

E-Mail Address of Student jcmajsz@umd.edu

Check here if this is a student master's thesis ☐ **or a dissertation research project X**

Project Duration (mo/yr – mo/yr) 4/08 **--** 12/09

Project Title Modeling Water and Nutrient Runoff from Nursery and Greenhouse Operations in Maryland

Sponsored Project Data	Funding Agency	N/A	**ORAA Proposal**	N/A

(PLEASE NOTE: Failure to include data above may result in delay of processing sponsored research award at ORAA.)

Vulnerable Populations: The proposed research will involve the following (Check all that apply): pregnant women ☐ , human fetuses ☐ , neonates ☐ , minors/children ☐ , prisoners ☐ , students ☐ , individuals with mental disabilities ☐ , individuals with physical disabilities ☐

Exempt or Nonexempt (Optional): You may recommend your research for exemption or nonexemption by completing the appropriate box below. For exempt recommendation, list the numbers for the exempt category(s)

X☒ Exempt----List Exemption Category 4 ***Or*** ☐ **Non-Exempt**

If exempt, briefly describe the reason(s) for exemption. Your notation is a suggestion to the IRB Manager and IRB Co-Chairs.
The data that will be collected for this project does not involve personal data for the individual. Nursery and greenhouse operators in the state will be supplying information about their operations, not themselves. Operation information will be password protected and aggregated to prevent identification of individual operations.

Date **Signature of Principal Investigator or Faculty Advisor** *(PLEASE NOTE: Person signing above accepts responsibility for the research even when data collection is performed by other*

Date **Signature of Co-Principal Investigator**

Date **Signature of Student Investigator**

Date **REQUIRED** Departmental Signature

Name ______________________________________, Title_______________________________
(Please also print name of person signing above)

(PLEASE NOTE: The Departmental signature block should not be signed by the investigator or the student investigator's advisor.)

***PLEASE ATTACH THIS COVER PAGE TO EACH SET OF COPIES**

---

1. Abstract:

This research seeks to assemble a database of nursery and greenhouse operations in the state of Maryland. This database will include operational information on the approximately 450 farm operations in Maryland. Using this database and other information, we will then develop three decision support tools to help growers and others involved in the green industry make informed management decisions that attempt to reduce nutrient and sediment loading into the Chesapeake Bay and its tributaries. The only personal data that will be collected is the name of the operation, which can be linked to the owner/operator through public records. All data will be kept in a password-protected database, with each operation having a random identification number. Access to the identification key, which will link the random number with the operation, will be limited to those directly involved in the project. Any hard copy data will be kept in a locked cabinet, and destroyed within 5 years of the completion of this project. Any information published from this project will be aggregated, so access to information on individual operations will not be possible.

2. Subject selection:

a. Subjects are owner/operators of field nursery, container nursery, and greenhouse operations in the state of Maryland. Operators will be recruited based on lists of publicly available operations in the state. Growers will be contacted by mailed letters about this project. Included with the letter will be a complete description of the project, including what data will be collected, how it will be used, and how it will be protected (see **Memorandum of Understanding** document included with this application). In addition to the MOU, the consent form included below, and a return envelope will also be included for their convenience.
b. There will be no specific selection apart from owning/operating a field nursery, container nursery, or greenhouse in Maryland.
c. There are no specific selection parameters
d. The number of subjects recruited will depend on the number of respondents of the 450+ operations in Maryland. We hope to recruit at least 100 operations throughout the state.

3. Procedures:

By state law, the subjects are required to submit a nutrient management plan and yearly fertilizer application rates with the Maryland Department of Agriculture (MDA). With operators consent, some of the information reported to the MDA will be collected from the operator's records by conducting site visits. This data is not publicly available. The time requirement for the subject will be the time required for reading and understanding the consent form, and approximately an additional 30 minutes of their time for gathering of required information from their nutrient management plan and yearly application forms. The information that is requested is as follows. From the nutrient management plan: Management units, crop description, container size, number of plants, growing area (sq.ft.), % area under production, production time/goal, irrigation type, and recommended nutrient application rate and type of fertilizer applied. From the annual reporting forms for 2005, 2006, and 2007, data will be gathered for the management units, acres, and total commercial fertilizer applied.

4. Risks and Benefits

A majority of the data for this project is not publicly available. There is a possible risk of the data being collected to be obtained by a third party for malicious reasons including legal ramifications. This risk will be lowered as much as possible by limiting access to the data, and through password protection of all databases.

The grower may benefit by possibly decreasing expenses, identification of additional best management practice to improve efficiency, and potential access to additional cost-share money from the state.

5. Confidentiality

Confidentiality will be maximized through password protection of databases. Access to the identification key will be limited to those faculty at the University of Maryland who are directly involved in this project (Dr. John Lea-Cox, Dr. Andrew Ristvey, Dr. David Ross) and the Ph. D. graduate student conducting the research, Mr. John Majsztrik. In addition, all consent forms and other hard copy data will be secured in a locked filling cabinet, and destroyed (shred) within 5 years of project completion. These measures will minimize the risk of these data being used for purposes other than for this research. Any reported data will be aggregated to protect the identity of individual operators.

6. Information and Consent Forms

See consent form and memorandum of understanding included with this document.

7. Conflict of interest

There is no potential conflict of interest for anyone involved in this project.

8. HIPAA Compliance

No HIPAA protected health information will be used in this project.

9. Research outside of the United States

Not Applicable

10. Research involving prisoners

Not Applicable

CONSENT FORM

Project Title	Modeling Water and Nutrient Runoff from Nursery and Greenhouse Operations in Maryland
Why is this research being done?	This is research project being conducted by Dr. John Lea-Cox and John Majsztrik at the University of Maryland, College Park. We are inviting you to participate in this research project because you own/operate a nursery or greenhouse operation in Maryland. The purpose of this research project is to collect relevant operational data for the development of a statewide database to determine nutrient use in the nursery and greenhouse industry in Maryland and develop decision tools that will help growers reduce their nutrient and sediment loss from their operation.
What will I be asked to do?	We are asking you to grant us permission to access to your Nutrient Management Plan(s) and yearly nutrient reporting form information. This should take less than 30 minutes and all information will be gathered at your operation. From your nutrient management plan, we will collect: Management units, crop description, container size, number of plants, growing area (sq.ft.), % area under production, production time/goal, irrigation type, and recommended nutrient application rate and type of fertilizer applied. From the annual reporting forms for 2005, 2006, and 2007, data will be gathered for the management units, acres, and total commercial fertilizer applied.
What about confidentiality?	We will make every effort to maintain the confidentiality of your personal/operational information. To protect your confidentiality, information will be stored in a password-protected database, with access limited to the six (6) people directly involved in this research. Any paper copies will be stored in a locked filing cabinet in the PI's office at the University of Maryland. Data from your operation will also be given a random identification code that will help protect your identity. In order to access your information, someone would need both the database, and the identification database that contains your code, which will also be password protected. Only four (4) people directly involved in this research will have access to your data and identification key. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Any information that is reported will be aggregated so it can not be traced back to your operation. Your information will only be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.
What are the risks of this research?	The risk of your information being stolen and used for purposes other than those stated for this research project will be minimal based on our security plan, but the potential for abuse does exist. Everything possible will be done to secure the information that you provide to us.

Project Title	Modeling Water and Nutrient Runoff from Nursery and Greenhouse Operations in Maryland	
What are the benefits of this research?	The benefits to you include the possibility of identifying ways for you to reduce costs/increase profit margins through implementing new BMP's, reducing operational overhead, or through cost sharing. This research is also designed to identify ways to improve the health of the Chesapeake Bay and its tributaries through identifying ways to reduce nutrient loading to surface waters.	
Do I have to be in this research? May I stop participating at any time?	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study, or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.	
What if I have questions?	This research is being conducted by Dr. John Lea-Cox, in the Department of Plant Sciences and Landscape Architecture at the University of Maryland, College Park. If you have any questions about the research study itself, please contact Dr. John Lea-Cox at: 2120 Plant Sciences Building University of Maryland College Park MD 20742-4452 Tel: (301) 405-4323 Email: jlc@umd.edu If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: **Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (e-mail) irb@deans.umd.edu; (telephone) 301-405-0678** This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.	
Statement of Age of Subject and Consent	Your signature indicates that: you are at least 18 years of age;, the research has been explained to you; your questions have been fully answered; and you freely and voluntarily choose to participate in this research project.	
Signature and Date ***Please print and sign your name***	**NAME OF SUBJECT**	
	SIGNATURE OF SUBJECT	
	DATE	

<u>Grower packet mailed to each address</u>

Directions for allowing your nutrient management data to be used by The University of Maryland:

PART 1

____ I would like you to access my data from the nutrient management information on file with the MDA

____ I would prefer a site visit for the gathering on my nutrient management information

____ I have no preference for how my data is accessed (either site visit or through MDA records)

____ I would NOT like my data used as part of this project

If you are interested in being part of this study, please provide us with your preferred contact information:

____

Name of Operation

____

Address

__________________ __________________ (_____) __________________

City Zip Code Telephone

PART 2
After completely reading the consent form (first 2 pages following this one)

1. **Initial and date** the first page of the Consent form
2. On the bottom of the second page of the consent form **print and sign your name and date** the form

3. After completely reading the form titled MEMORANDUM OF UNDERSTANDING **please print your name** on the line where it says:

   ______________________________the Owner/Operator (on page 4 of this packet)

4. On page 5 of this packet, **please put the date, and print and sign** in the Owner/Operator section.

5. Once you have completed these steps, please mail this entire packet (5 pages) back in the envelope provided. We thank you for this opportunity to partner with you!

Initials _______ Date ______

CONSENT FORM

Project Title	Modeling Water and Nutrient Efficiencies for Nursery and Greenhouse Operations in Maryland.
Why is this research being done?	This is research project being conducted by Dr. John Lea-Cox and John Majsztrik at the University of Maryland, College Park. We are inviting you to participate in this research project because you own/operate a nursery or greenhouse operation in Maryland. The purpose of this research project is to collect relevant operational data for the development of a statewide database to determine nutrient use in the nursery and greenhouse industry in Maryland and develop decision tools that will help growers reduce their nutrient and sediment loss from their operation.
What will I be asked to do?	We are asking you to grant us permission to access to your Nutrient Management Plan(s) and yearly nutrient reporting form information. This should take less than 60 minutes and all information will be gathered at your operation. From your nutrient management plan, we will collect: Management units, crop description, container size, number of plants, growing area (sq. ft.), % area under production, production time/goal, irrigation type, and recommended nutrient application rate and type of fertilizer applied. From the annual reporting forms for 2005, 2006, and 2007, data will be gathered for the management units, acres, and total commercial fertilizer applied.
What about confidentiality?	We will make every effort to maintain the confidentiality of your personal/operational information. To protect your confidentiality, information will be stored in a password-protected database, with access limited to the six (6) people directly involved in this research. Any paper copies will be stored in a locked filing cabinet in the PI's office at the University of Maryland. Data from your operation will also be given a random identification code that will help protect your identity. In order to access your information, someone would need both the database, and the identification database that contains your code, which will also be password protected. Only two (2) people (Lea-Cox and Majsztrik) will have access to both your data and identification key. If we write a report or article about this research project, your identity or operational data will never be revealed. Any information that is reported will be aggregated so it cannot be traced back to your operation in any way. Your information will only be shared with representatives of the University of Maryland, College Park or governmental authorities in cases of imminent danger, or if we are required to do so by a court judgment.

Project Title	Modeling Water and Nutrient Runoff from Nursery and Greenhouse Operations in Maryland	
What are the benefits of this research?	The benefits to you include the possibility of identifying ways for you to reduce costs/increase profit margins through implementing new BMP's, reducing operational overhead, or through cost sharing. This research is also designed to identify ways to improve the health of the Chesapeake Bay and its tributaries through identifying ways to reduce nutrient loading to surface waters.	
Do I have to be in this research? May I stop participating at any time?	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study, or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.	
What if I have questions?	This research is being conducted by Dr. John Lea-Cox, in the Department of Plant Sciences and Landscape Architecture at the University of Maryland, College Park. If you have any questions about the research study itself, please contact Dr. John Lea-Cox at: 2120 Plant Sciences Building University of Maryland College Park MD 20742-4452 Tel: (301) 405-4323 Email: jlc@umd.edu If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: **Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (e-mail) irb@deans.umd.edu; (telephone) 301-405-0678** This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.	
Statement of Age of Subject and Consent	Your signature indicates that : • you are at least 18 years of age; • the research has been explained to you; • your questions have been fully answered; and • you freely and voluntarily choose to participate in this research project.	
Signature and Date ***Please print and sign your name***	**NAME OF SUBJECT**	
	SIGNATURE OF SUBJECT	
	DATE	

MEMORANDUM OF UNDERSTANDING
among

Owner/Operator of **____**
and
COLLEGE OF AGRICULTURE & NATURAL RESOURCES
Department of Plant Science & Landscape Architecture
regarding

The Release of Data from Nutrient Management Plan and Yearly Reporting Form

This Memorandum of Understanding (MOU) dated ____________________, 2008 is between the University of Maryland, Department of Plant Science & Landscape Architecture (University) and _______________________________the Owner/Operator of the operation named above (Grower).

I. Purpose of the Agreement

This agreement is entered between the “University” and “The Grower” for the purpose of accessing information from the grower for use in a research project being conducted by the University.

The objective of the research is to develop a geographic information system database and decision support management tools that will be used for: a) the evaluation of water and nutrient applications by Maryland Nursery and Greenhouse operations, and b) the evaluation of the effectiveness of the Best Management Practices (BMPs) for these types of operations.

II. Project Description

Almost every commercial nursery and greenhouse operation in the state is required to develop and implement a nutrient management plan. Due to the complex nature of these types of operations, the nutrient management process is based on risk assessment strategy, not on a crop nutrient removal basis as is done for agronomic crops. Since irrigation is the dominant factor in nutrient application and its potential losses, the surface runoff risk assessment is incorporated into the process of writing nutrient management plans.

This research project consists of two phases:

The first phase involves the development of a GIS database of nurseries and greenhouses using information from publicly available sources, along with available nutrient application and irrigation management information provided voluntarily by the grower.

The second phase of the project aims to develop production-specific models and decision support systems that will allow us to increase the water and nutrient use efficiency and profitability of nursery production systems.

III. Conditions and Restriction for the use of Information

The grower is the custodian of all information and protector of its confidentiality.

The use of information by the University is solely for its internal use and conducting the research project specified in this agreement and restricted for any other uses. Aggregated information may be used for the purpose of presenting research results or project reports. Revealing any information on individual operations is prohibited. All information in the possession of the signatory parties will be handled and in a manner that will prevent an unauthorized person from having access to it (see consent form for details).

III. Security

Under no circumstances will individual operation information or records will be made available to other individuals, organizations or other persons for purposes of study, copying or publication.

V. Exception Any exceptions to this agreement must be stated in writing and agreed to in writing by all parties before such exceptions may be considered to be in effect.

____________ ____

Date Owner/Operator signature

____

Owner/Operator printed name

_07/08/2008_ ____

Date University of Maryland, Department of Plant Science & Landscape Architecture, Representative Signature

Dr. John D. Lea-Cox [Principle Investigator]

Representative printed name

IRB APPROVED
VALID UNTIL
MAY 2 0 2009
UNIVERSITY OF MARYLAND
COLLEGE PARK

Postcard Information

Dear Maryland Grower,

A few weeks ago, you should have received a packet of information from the University of Maryland, regarding a modeling and nutrient management project that asked you to partner with us. This project seeks to highlight the progress that the Nursery and Greenhouse industry in the state has made in recent years, and indicate areas where we can improve our efforts as an industry. Your partnership with us is critical to the success of this project, and we are sending this post card to you because we have not heard back from you yet. We know how busy things can get, so we wanted to send a friendly reminder that we would like to hear from you.

Due to an error we made when mailing the packets out, if you choose not to participate in this project, please help us by writing the name of your operation on the return envelope, so we can correctly indicate your preference in our list. If you would like to get in touch with us for a new packet of information or any other reason, please contact John Majsztrik at (301) xxx-xxxx (tel), xxx@umd.edu(email) or by mail c/o PSLA Department, 2102 Plant Science Building, College Park MD, 20742. I look forward to your reply.

Sincerely,
John Majsztrik,
PhD Candidate, PSLA Department.

Grower Interview Form

Internal Reference Code________________________________

Date of interview ____________________On site_____ MDA records_____

Name of Operation ____

Operation

Address____

Name of owner/operator_______________________________

Name of interviewee__________________________________

Operation(s) present greenhouse %_____ Container% _____ Field% _____ Pot in Pot%_____

Date of Plan

Total # of acres of operation_________________ Total # of farmed acres_________________

Is runoff remediated? Yes____ No____ If Yes, how:

Is runoff recycled? Yes____ No____ If Yes, how:

Is additional rainwater captured for irrigation? Yes____ No____

Management unit			
Species of Plant			
Production time/goal			
% area under production			
Growing area sq. ft./acre			
Irrigation type			
gph/gpm per sprinkler			
Sprinklers per MU(spacing)			
Min. of irrigation/day			
Days irrigated per week			
Leaching fraction			
# of Plants in MU			
Substrate used			
Container size			
Container spacing			
# of Fertilzer applied			
N:P:K			
Type of fertilizer			

Notes: terrain, slope, and where runoff goes? How do they schedule irrigation? How often does that change? How much runoff do they have? Any known irrigation problems? (non-uniform application etc.)

Management unit			
Species of Plant			
Production time/goal			
% area under production			
Growing area sq. ft./acre			
Irrigation type			
gph/gpm per sprinkler			
Sprinklers per MU(spacing)			
Min. of irrigation/day			
Days irrigated per week			
Leaching fraction			
# of Plants in MU			
Substrate used			
Container size			
Container spacing			
# of Fertilzer applied			
N:P:K			
Type of fertilizer			

Management unit			
Species of Plant			
Production time/goal			
% area under production			
Growing area sq. ft./acre			
Irrigation type			
gph/gpm per sprinkler			
Sprinklers per MU(spacing)			
Min. of irrigation/day			
Days irrigated per week			
Leaching fraction			
# of Plants in MU			
Substrate used			
Container size			
Container spacing			
# of Fertilzer applied			
N:P:K			
Type of fertilizer			

Notes:

Appendix C

Table C3-1. Abridged greenhouse database based on 27 operations and 169 management units (MUs). All management units are listed, with a number of important variables collected for each MU. Table is arranged by management unit.

reference code	Container size	Number of plants	MU size (ac)/yr	# Plants per acre	Management unit	Production goal	Total N/ acre/ yr	Total P_2O_5 / acre/ yr	Total K_2O / acre/ yr
6087	4"	480,000	1.25	384,353	Annuals	4-8 weeks	53	16	53
4998	4"-4.5" annuals	75,000	0.28	272,727	Annuals	6-12 weeks	137	33	124
2481	4" standard	4,356	0.01	512,052	Annuals	12 weeks	142	39	157
6159	4"	72,000	0.15	489,800	Annuals	11 weeks	154	65	122
8144	4"-4.5" annuals	320,000	1.00	320,000	Annuals	6-8 weeks	683	201	683
7806	4.5" pots	120,060	0.30	402,300	annual turn 2	6-8 weeks	27	10	27
7879	4.5" pots	600,000	1.73	347,281	annuals spring	6-8 wks	42	21	42
2481	4.5" standard	150,000	2.39	62,726	annuals spaced	5 weeks	43	14	43
7879	4.5" pots	15,000	0.10	347,281	annuals Spring (verbena, primrose and petunias)	16-18 wks	51	26	51
2481	4.5" standard	150,000	0.52	287,777	Annuals	5 weeks	51	16	54
7879	4.5" pots	360,000	1.04	347,281	annuals fall	6-8 wks	100	50	100
6766	4.5" pots	3,750	0.01	326,700	Annuals	Jan-July	201	201	201
6159	4.5"	45,000	0.11	409,090	Annuals	11 weeks	227	99	187
6087	5" 8/flat	322,000	1.51	213,816	annuals/petunias	4-8 weeks	53	16	53
7806	6" pots	20,000	0.16	124,460	annual turn 2	6-8 weeks	27	10	27
7806	6" pots	60,000	0.46	130,680	annual turn 1	6-8 weeks	27	10	27
7879	6" pots	37,026	0.22	170,084	Annuals	6-8 wks	34	17	34
2481	6" standard	9,800	0.22	43,560	annuals spaced	6-8 weeks	42	9	50
6087	6" square	196,000	1.12	174,240	Annuals	8 weeks	78	23	78
2481	6" standard	4,200	0.03	154,793	Annuals	6-8 weeks	140	30	166

6159	6"	21,000	0.12	173,554	Annuals	11 weeks	150	66	124
6766	6" squat pots	2,210	0.01	175,000	annuals/foliage	12 months	166	166	166
7882	6" pods	5,500	0.03	174,240	AP3 (annual/perennial)	4 months	236	236	236
2481	8" standard	9,000	0.37	24,503	annuals	8 weeks	51	12	59
6087	8" square	40,000	0.46	87,120	annuals, summer	4-8 weeks	78	20	78
6766	8" pots	390	0.00	85,000	annuals/foliage	12 months	349	349	349
6087	10" square pots	19,250	0.31	62,113	annuals	6-10 weeks	78	23	78
6087	10" square	1,000	0.02	43,560	annuals	6-10 weeks	78	23	78
6766	10" hanging baskets	1,300	0.02	56,600	annuals	Jan-Aug	405	405	405
6087	10.25 square planter	2,880	0.05	54,545	annuals	6-10 weeks	78	23	78
2662	12" pots	7,000	0.16	43,560	annuals	2/1-7/1	44	16	44
6087	12" square	7,200	0.17	41,818	annuals	6-10 weeks	78	23	78
7582	1204 flats	3,600	0.01	315,800	annuals, bedding plants	3/1-6/31	44	44	44
2662	1204	1,000,000	0.66	1,505,434	annuals	2/1-7/1	162	51	162
6087	306 flats	486,000	0.92	529,254	annuals/petunias	6-10 weeks	53	16	53
6087	309 annuals	216,000	0.39	553,468	annuals	4-8 weeks	53	16	53
6087	309 annuals	72,000	0.26	280,029	annuals spring	8 weeks	53	16	53
6087	606 annuals	5,580,000	4.98	1,120,114	annuals	8 weeks	53	16	53
2481	606 cell packs	158,400	0.15	1,024,104	annuals	5 weeks	54	17	57
4998	606 annuals	468,000	0.46	1,017,391	annuals	6 weeks	138	33	125
6159	606	216,000	0.21	1,043,478	Annuals	11 weeks	152	76	127
6766	606 market packs	3,750	0.02	163,350	annuals	Jan-July	383	383	383
3087	market packs 606	21,600	0.04	603,183	annuals, bedding plants	3 months	457	113	577
7882	72 plug tray	10,000	0.00	2,210,644	annuals/foliage	1-2 months	375	375	375
7582	804 flats	9,600	0.12	79,300	annuals, bedding plants	3/1-6/31	21	21	21
2662	804	1,417,000	1.41	1,003,623	annuals	2/1-7/1	109	34	109
2992	806 or 4" pots (# of trays)	750	0.06	13,200	small pot annuals	6-8 weeks	66	66	66

2662	2 qt aquatic	1,400	0.01	174,240	AQ1 aquatic	2/1-7/1	0	0	0
7882	4" pots	1,000	0.00	379,298	Carnivorous	4-6 months	0	0	0
6087	13.3" square	3,600	0.11	31,363	Castella planter	6-10 weeks	78	23	78
3087	4-4.5"	5,000	0.02	227,273	Cool crops	4 months	470	66	579
6087	6" square	25,000	0.15	167,538	Dahlias	4-8 weeks	78	23	78
4095	3-8" pots	12,850	0.11	112,720	F1	12 months	2333	1615	2509
6087	10" square	4,500	0.07	61,256	Garden planter	6-10 weeks	78	23	78
6087	4" 15/flat	120,000	0.31	384,353	Geraniums	4-8 weeks	53	16	53
6159	4"	16,000	0.03	465,116	Geraniums	13 weeks	1017	474	1052
6159	6"	5,000	0.03	145,350	Geraniums	13 weeks	317	148	328
6159	8"	700	0.01	43,478	Geraniums	13 weeks	487	226	496
6159	10"	350	0.01	43,478	Geraniums	13 weeks	383	183	391
6087	12" square	2,400	0.06	41,818	Geranium	6-10 weeks	78	23	78
8144	6" baskets	16,000	0.50	32,000	hanging baskets	6-8 weeks	156	46	156
2792	6" Hanging Basket	5,000	0.03	174,240	hanging basket annuals	8-10 weeks	172	206	172
7582	10" HB	750	0.03	10,560	Hanging Baskets	3/1-6/31	32	32	32
6087	12" hanging basket	27,324	0.69	39,674	hanging baskets	6-10 weeks	60	18	60
6087	10" hanging basket	230,500	5.29	43,560	hanging baskets	6-10 weeks	65	19	65
2481	10" hanging basket	12,000	0.19	62,726	hanging baskets	8 weeks	80	18	94
2792	10" Hanging Basket	10,000	0.17	59,704	hanging baskets	8-10 weeks	140	231	140
2662	10" hanging basket	80,000	1.28	62,726	hanging baskets	1/1-12/31	173	76	173
2992	Hanging baskets	800	0.06	14,000	hanging basket annuals	6-8 weeks	184	51	112
8144	10" baskets	16,000	0.50	32,000	hanging baskets	8-10 weeks	391	115	391
6159	10" Baskets	3,000	0.07	43,478	Hanging baskets	12 weeks	430	200	430
7879	10" hanging baskets	3,145	0.05	59,704	hanging baskets	6-8 wks	516	393	516
4998	10" baskets	13,000	0.30	43,333	hanging baskets	6-12 weeks	621	148	562
3087	10" baskets	325	0.01	23,602	Hanging Baskets	16 weeks	860	332	860
4998	10" baskets	3,500	0.08	43,750	hanging baskets	16-18 weeks	965	230	873
7806	12"	750	0.02	32,680	hanging baskets 1	6-8 weeks	26	10	26

7806	12"	750	0.02	32,680	hanging baskets 2	6-8 weeks	26	10	26
6087	12" hanging basket	33,724	0.92	36,725	hanging baskets	6-10 weeks	55	16	55
7806	14"	1,450	0.05	31,580	hanging baskets 1	6-8 weeks	26	10	26
7806	14"	1,450	0.05	31,580	hanging baskets 2	6-8 weeks	26	10	26
2792	14" Hanging Basket	5,000	0.13	37,116	hanging baskets	8-10 weeks	231	310	231
7882	bare root	24,640	0.02	1,048,162	Harvest beds	4 months	2576	3038	2344
4073	4" pots	9,750	0.02	398,263	herbs	2 months	118	59	118
6766	1 gal	830	0.01	90,387	herb perennials	April-Aug	196	196	196
7879	1 gal (8" pots)	840	0.01	98,118	herbs	6-8 wks	291	146	291
6766	1 qt	830	0.00	180,774	herb perennials	April-Aug	305	305	305
6766	2 gal	40	0.00	43,560	herb perennials	April-Aug	659	659	659
2481	18 plants/tray	576,000	1.21	477,411	herbs	12 weeks	98	20	117
2481	32 plants/tray	384,000	0.45	848,730	herbs	12 weeks	93	19	111
6087	10" square pots	5,000	0.08	62,229	Hydrangeas	6-10 weeks	78	23	78
6159	8"	4,000	0.09	43,573	Kale	14 weeks	481	379	481
2792	3" square	7,000	0.01	737,958	mums and pansies	4 weeks	195	147	195
2792	4.5" square	45,000	0.13	347,281	mums and pansies	8-10 weeks	118	194	118
6159	4.5"	4,000	0.01	347,826	Mums	14 weeks	1478	739	1426
6087	6" round	445,000	2.98	149,109	mums	4-5 months	78	20	78
2792	6" round	40,000	0.24	170,084	mums and pansies	10-12 weeks	274	247	274
6087	8" round	110,880	3.47	31,986	mums	4-5 months	78	20	78
6087	14.5" round	13,200	0.46	28,750	mums	4-5 months	78	20	78
2792	1 gal	10,000	0.10	98,118	mums and pansies	6 months	163	304	163
2792	market pack (1 gal)	40,000	0.32	126,720	mums and pansies	4-6 months	168	319	168
2662	2 gal	5,000	0.46	10,890	mums	6/15-10/1	58	58	58
6159	2 gal	8,000	0.37	21,800	Mums	14 weeks	381	311	381
2792	2 gal	1,000	0.02	43,560	mums and pansies	6 months	481	635	481
2792	2 gal	1,000	0.02	43,560	mums and pansies	6 months	481	635	481
7882	18" diameter 12" deep	450	0.04	10,890	NL (lotus)	1 year	72	101	58

6159	4"	31,500	0.09	362,07 0	Pansies	16 weeks	98	33	76
6159	6"	18,500	0.09	212,64 4	Pansies	16 weeks	115	39	89
6087	1 qt	240,00 0	0.64	373,37 1	Pansies	16 weeks	53	13	53
6159	606	90,000	0.09	1,046,5 10	Pansies	16 weeks	113	38	87
6159	1 gal	7,000	0.16	43,560	perennials	7 weeks	164	82	164
2481	1 quart	105,00 0	0.34	304,34 9	perennials woody	oct-may (8 months)	87	17	104
6159	1 qt	7,500	0.02	326,08 7	perennials	30 weeks	791	396	791
6159	2 gal	1,000	0.05	21,740	perennials	7 weeks	91	46	91
7879	2 gal	1,050	0.01	77,440	perennials	6-8 wks	103	52	103
2662	2 gal	12,000	0.28	43,560	perennials	1/1- 12/31	230	230	230
6159	3"-4"	700	0.01	101,45 0	Poinsettias	16 weeks	145	49	145
2792	4.5" round	4,000	0.01	304,34 9	poinsettia	4 months	138	190	177
2481	4.5" pots	6,200	0.10	62,726	poinsettias	Aug-Dec	132 3	450	132 3
6087	6"	49,000	1.15	42,689	Poinsettia	5-6 months	78	20	78
6087	6"	41,166	1.33	30,917	Poinsettia	5-6 months	78	20	78
2792	6" round	10,000	0.06	170,08 4	poinsettia	4 months	170	279	215
2481	6" pots	15,000	0.61	24,502	poinsettias	June- Dec	541	175	541
8144	6"	7,000	0.16	43,560	poinsettias	16 weeks	263 9	776	263 9
6087	6.5"	98,750	4.13	23,898	Poinsettia	5-6 months	78	20	78
6159	6.5"	1,400	0.01	121,73 9	Poinsettias	16 weeks	661	235	661
2792	7" round	2,000	0.03	62,726	poinsettia	6 months	210	173	284
6087	8"	22,425	1.44	15,555	Poinsettia	5-6 months	78	20	78
2792	8" round	1,000	0.02	43,560	poinsettia	6 months	232	187	315
2481	8" pots	3,000	0.28	10,890	poinsettias	June- Dec	243	78	243
6159	8"-10"	750	0.02	40,760	Poinsettias	16 weeks	440	158	440
6087	10" baskets	24,783	0.80	30,844	Poinsettia	5-6 months	46	12	46
6087	10"	50,180	0.54	92,620	Poinsettia	5-6 months	78	20	78
2481	10" pots	700	0.14	4,840	poinsettias	June- Dec	107	35	107
2792	10" round	500	0.02	32,003	poinsettia	6 months	337	256	458
6766	10" hanging baskets	200	0.00	43,560	poinsettias	Aug-Dec	697	697	697

8144	12"	3,000	0.16	19,354	poinsettias	16 weeks	112 9	332	112 9
2662	2 gal	8,000	0.25	32,003	poinsettia	8/1- 12/24	225	82	225
2662	3 gallon	1,000	0.09	10,890	Poinsettias	4/1- 10/30	115	115	115
7385	3.5"	29,700	0.31	96,803	Propagation	4-6 months	179	59	93
7385	3.5"	29,700	0.31	96,803	Propagation	4-6 months	279	129	204
6087	8" square urns	20,000	0.21	96,800	Roman urn combos	8-10 weeks	78	23	78
4416	1 quart	20,000	0.06	351,12 0	propagation, cuttings and seedlings	3-4 months	0	0	0
2481	105 cell tray	1,995, 000	0.72	2,784,9 05	propagation, herbaceous rooted cuttings	8-10 weeks	23	8	8
6831	36 cell trays	15,000	0.11	43,636	propagation, Junipers and Ilex	1 year	0	0	0
6767	50 plug trays	640,00 0	0.86	1,493,4 86	propagation, Herb. Perenn.	12 weeks	201	63	127
6767	50 plug trays	68,000	0.09	1,493,4 86	propagation, Herb. Perenn.	12 weeks	201	63	127
6767	50 plug trays	272,00 0	0.36	1,493,4 86	propagation, Herb. Perenn.	12 weeks	201	63	127
6767	50 plug trays	19,200	0.03	1,493,4 86	propagation, Herb. Perenn.	12 weeks	201	63	127
10044	18 cell	200,00 0	0.72	280,00 0	Propagation	4-6 months	98	33	43
2792	72 cell plug tray	36,000	0.02	2,210,6 44	rooted cuttings	6 weeks	94	28	133
4073	72 cell plug flats	14,400	0.01	2,210,6 44	root plugs	1 month	276	138	276
10044	32 cell	50,000	0.18	560,00 0	Propagation	4-6 months	55	18	25
9413	32 cell	50,000	0.11	43,560	Propagation	12 months	131	46	92
9413	32 cell	50,000	0.11	43,560	propagation deciduous	12 months	131	46	92
4073	98 cell plug flats	14,700	0.00	3,008,9 32	root plugs	1 month	49	25	49
2662	15 gallon	40	0.01	4,840	roses, tree	2/1-7/1	102	102	102
2662	3 gallon	1,500	0.14	10,890	Roses	2/1-7/1	115	115	115
6087	8" square	11,000	0.11	95,832	Rudbeckia	4-8 weeks	78	23	78
8381	3" square	6,300	0.01	737,95 8	seedling starter	2 months	0	0	0
2792	4.5" round	17,500	0.06	304,34 9	Seedlings	6-8 weeks	26	8	37
2792	6" round	17,500	0.10	170,08 4	Seedlings	6-8 weeks	24	7	34
2792	406 cell tray	60,900	0.01	10,772, 340	Seedlings	1 month	39	11	55

4985	cell tray	350,000	0.00	175,000,000	seedlings, snapdragon	4 weeks	375	113	395
4985	perlite bags	350,000	0.21	422,705	snap dragons	8-24 weeks	551	111	783
6087	14" square	820	0.03	29,766	Urbana planter	6-10 weeks	78	23	78
6087	6" square	7,200	0.05	156,816	Vinca	4-8 weeks	78	23	78
6087	306	81,000	0.16	518,876	Vinca	4-8 weeks	53	16	53
7882	72 plug tray	5,680	0.00	2,210,644	WET (wetland plugs)	1-2 months	375	375	375
6087	15" long	1,800	0.03	52,272	Window box	6-10 weeks	78	23	78

Table C3-2. Rates of N, P_2O_5, and K_2O for 27 greenhouse operations in Maryland based on data collected from site visits.

Plant type and pot size	Number of MU's represented		Lb N/ acre/yr	Lb P_2O_5/ acre/yr	Lb K_2O /acre/yr
Annuals 4"-4.5"	13	Minimum	27	10	27
		Lower quartile	51	16	51
		Middle quartile	100	33	100
		Average	147	61	142
		Upper quartile	154	65	157
		Maximum	683	201	683
Annuals 5"-6"	10	Minimum	27	9	27
		Lower quartile	36	12	38
		Middle quartile	65	20	65
		Average	95	58	96
		Upper quartile	148	57	155
		Maximum	236	236	236
Annuals 8"-12"	9	Minimum	44	12	44
		Lower quartile	78	20	78
		Middle quartile	78	23	78
		Average	138	99	139
		Upper quartile	78	23	78
		Maximum	405	405	405
Annuals flats (ie 606, 1204 etc)	15	Minimum	21	16	21
		Lower quartile	53	16	53
		Middle quartile	66	34	66
		Average	145	85	150
		Upper quartile	157	71	144
		Maximum	457	383	577
Geraniums 4"-12"	6	Minimum	53	16	53
		Lower quartile	138	54	141
		Middle quartile	350	165	360
		Average	389	178	400
		Upper quartile	461	215	470
		Maximum	1017	474	1052
10" hanging baskets	13	Minimum	32	18	32
		Lower quartile	80	32	94
		Middle quartile	184	115	173
		Average	347	143	331
		Upper quartile	516	230	516

		Maximum	965	393	873
12"-14" Hanging baskets	6	Minimum	26	10	26
		Lower quartile	26	10	26
		Middle quartile	26	10	26
		Average	65	61	65
		Upper quartile	48	15	48
		Maximum	231	310	231
Herbaceous Perennials flats - 2 gal	7	Minimum	93	19	111
		Lower quartile	108	39	117
		Middle quartile	196	146	196
		Average	251	200	257
		Upper quartile	298	251	298
		Maximum	659	659	659
mums 3"-8"	6	Minimum	78	20	78
		Lower quartile	88	51	88
		Middle quartile	156	170	156
		Average	370	228	362
		Upper quartile	255	234	255
		Maximum	1478	739	1426
Mums 1-2 gal	7	Minimum	58	20	58
		Lower quartile	121	181	121
		Middle quartile	168	311	168
		Average	259	326	259
		Upper quartile	431	477	431
		Maximum	481	635	481
Pansies flats - 6"	4	Minimum	53	13	53
		Lower quartile	87	28	70
		Middle quartile	105	36	82
		Average	95	31	76
		Upper quartile	113	39	88
		Maximum	115	39	89
Perennials 1 qt - 2 gal	6	Minimum	87	17	91
		Lower quartile	94	47	104
		Middle quartile	134	67	134
		Average	244	137	247
		Upper quartile	214	193	214
		Maximum	791	396	791
Poinsettias 3"-7"	11	Minimum	78	20	78
		Lower quartile	108	34	111
		Middle quartile	170	175	215
		Average	551	217	565

		Upper quartile	601	257	601
		Maximum	2639	776	2639
Poinsettias 8"-12"	12	Minimum	46	12	46
		Lower quartile	100	31	100
		Middle quartile	229	98	234
		Average	311	166	328
		Upper quartile	363	205	445
		Maximum	1129	697	1129
Propagation flats - 8"	17	Minimum	0	0	0
		Lower quartile	55	23	43
		Middle quartile	131	46	92
		Average	129	47	94
		Upper quartile	201	63	127
		Maximum	279	138	276
Seedling flats - 6"	5	Minimum	0	0	0
		Lower quartile	24	7	34
		Middle quartile	26	8	37
		Average	93	28	104
		Upper quartile	39	11	55
		Maximum	375	113	395

Table C3-3. Abridged container

reference code	container size	number of plants	mu size (acres)	Plant spacing	Irrigation type	Type of fertilizer	management unit	N lbs/acre/yr	P2O5/ac/yr	K2O/ac/yr
8144	.5 gal	10,000	0.13	pot tight	overhead	CRF	<1 gal perennials	198	82	93
8144	1 gal	64,000	2.07	10"	overhead	CRF	1 gal perennials	174	72	82
8381	1 gal	1,000	0.01	pot tight	hand	CRF	1 gallon	907	907	907
8381	2 quart	1,000	0.01	pot tight	hand	CRF	1/2 gallon	604	604	604
6831	10 gal	500	0.08	32" centers	overhead	CRF incorporated	10 gal 1st year	826	229	505
8144	10 gal	100	0.03	48"	drip	CRF	10 gal woody	173	58	77
6831	10 gal	1,000	0.16	32" centers	overhead	CRF incorporated	10 gal year 2-3	831	231	508
6831	15 gal	150	0.02	30" centers	drip	CRF incorporated	15 gal 1st year	1263	351	772
8144	15 gal	3,800	0.53	48"	drip	CRF	15 gal woody	641	214	285
6831	15 gal	250	0.04	30" centers	drip	CRF incorporated	15 gal year 2-3	1286	357	786
8144	2 gal	16,400	0.44	16	overhead	CRF	2 gal perennials	423	174	199
8144	3 gal	6,000	0.11	21"	overhead	CRF	3 gal perennials	903	372	425
8144	3 gal	57,000	4.97	24"	drip	CRF	3 gal roses	205	68	91
8144	5 gal	70	0.02	30"	overhead	CRF	5 gal perennials	119	49	56
8144	5 gal	3,700	0.43	30"	overhead	CRF	5 gal woody	253	84	113
8144	7 gal	250	0.07	36"	drip	CRF	7 gal woody	158	53	70
8993	1 quart	168	0.00	pot tight	hand	CRF top dressed	Annual/perennials	353	118	235
7882	4" pots	66,900	0.19	pot tight	hand	CRF	Annual/perennials	59	59	59
7882	1 gallon	38,000	0.39	pot tight	hand	5g aquatic tablets	Annual/perennials	241	284	219
8762	1-3 gal	7,000	2.00	2' centers	overhead	varies	Azaleas	4	6	4
2808	b and b	500	1.00	varies	overhead gun	soluble	balled and burlap	10	10	10
7582	4.5"	1,800	0.04	varies	hand	soluble	Bedding plants	18	18	18
3058	7.5 qt	550	0.10	varies	hand	varies	bog plants	13	18	10
3058	3.5 qt	550	0.07	varies	hand	varies	bog plants	18	25	14
6029	7 gal	14,000	2.89	36" centers	overhead	CRF incorporated	conifer	407	170	204
6029	5 gal	14,000	1.29	24" centers	overhead	CRF incorporated	conifer	695	290	347
6029	1 gal	28,000	0.45	10" centers	overhead	CRF incorporated	conifer	1067	445	533
6029	3 gal	84,000	3.01	15" centers	overhead	CRF incorporated	conifer	1297	540	648

2808	1-5 gal	varies	0.50	varies	overhead	varies	container stock	.	.	.
6029	5 gal	47,250	4.34	24" centers	overhead	CRF incorporated	deciduous	697	290	349
6029	3 gal	57,750	2.07	15" centers	overhead	CRF incorporated	deciduous	1295	540	648
6029	1 gal	112,500	2.58	12" centers	overhead	CRF incorporated	early can	309	95	214
6029	5 gal	7,500	0.69	24" centers	overhead	CRF incorporated	early can	472	145	327
6029	3 gal	30,000	0.69	15" centers	overhead	CRF incorporated	early can	1370	422	949
6029	1 gal	18,750	0.43	12" centers	overhead	CRF incorporated	ericacious	251	84	167
6029	5 gal	16,750	1.54	24" centers	overhead	CRF incorporated	ericacious	383	128	256
6029	3 gal	37,500	1.35	15" centers	overhead	CRF incorporated	ericacious	712	237	475
8144	1 gal	5,000	0.26	18"	drip	CRF	Fall Mums	109	45	51
6029	3 gal	46,000	1.06	12" centers	overhead	CRF incorporated	garden roses	1349	843	1012
10044	3 gal	8,000	0.51	18-20"	overhead	CRF incorporated	grasses	601	200	267
4543	cell pack	1,000	0.00	pot tight	hand	CRF	ground cover and woody	5386	5386	5386
6029	7 gal	3,200	0.07	36" centers	overhead	CRF incorporated	hollies	4068	1695	2034
6029	5 gal	32,000	2.94	24" centers	overhead	CRF incorporated	hollies	697	290	349
6029	3 gal	128,000	4.59	15" centers	overhead	CRF incorporated	hollies	1295	540	648
8993	1 gal	3,000	0.03	pot tight	hand	CRF	HP1 1 gal	230	138	184
8993	3"	500	0.00	pot tight	hand	CRF	HP1 3"x3.5"	287	172	230
8993	105 cell/tray	500	0.00	pot tight	hand	CRF	HP1 tall plugs	610	366	488
3058	19 qt	220	0.04		hand	varies	lilies	77	108	62
3058	7.5 qt	880	0.13		hand	varies	lilies	92	129	74
7882	1 gallon	900	0.01	pot tight	hand	5g aquatic tablets	LL (lily-like)	314	371	286
6767	7 gal	485	0.06	28"	overhead	CRF incorporated	Long woody rows	505	168	337
6767	3 and 5 gal	2,347	0.12	18"	overhead	CRF incorporated	Long woody rows	674	225	449
6767	1 and 2 gal	31,650	0.30	pot tight	overhead	CRF incorporated	Long woody rows	1331	444	887
3058	17.5 qt	100	0.07		hand	varies	lotus	19	27	15
3058	30 qt	100	0.07		hand	varies	lotus	19	27	15
2992	1 gal	500	0.06		drip	varies	Mums	55	15	34
7582	2 gal	2,000	0.28		hand	CRF	Mums	4	4	4

7882	1 gal	6,700	0.07	pot tight	hand	5g aquatic tablets	NYM (Water lily)	241	284	219
6767	50 cell tray	361,600	0.24	pot tight	overhead	CRF incorporated	outdoor herbaceous	669	211	423
6767	1 quart	13,500	0.04	pot tight	overhead	CRF incorporated	outdoor herbaceous	1086	343	686
6767	1 gal	1,270	0.01	pot tight	overhead	CRF incorporated	outdoor herbaceous	1405	444	887
2992	2 gal	2,400	0.13	8"-18"	overhead	varies	perennials	239	66	146
6029	5 gal	69,000	6.34	15" centers	overhead	CRF incorporated	perennials	697	407	407
6029	3 gal	161,000	5.78	12" centers	overhead	CRF incorporated	perennials	1295	756	756
5430	5	2,500	1.50	3'	drip	CRF	Pot in pot	56	19	38
3720	4x4x1 2”	7,500	0.02	pot tight	overhead	CRF	rooting containers	1941	799	1599
7582	1 and 2 gal	800	0.10		hand	CRF	Roses and shrubs	7	7	7
6767	98 cell trays	44,100	0.02	pot tight	overhead	CRF incorporated	seedlings	444	148	296
6767	1 gal	4,315	0.04	pot tight	overhead	CRF incorporated	seedlings	1331	444	887
6767	2 gal	1,880	0.23	pot tight	overhead	CRF incorporat	seedlings	162	54	108
6767	3 gal	100	0.01	18"	overhead	CRF incorporated	short rows	675	225	450
6767	1 gal	2,623	0.03	pot tight	overhead	CRF incorporated	short rows	1331	444	888
6767	2 gal	1,690	0.02	pot tight	overhead	CRF incorporated	short rows	1617	539	1078
6029	3 gal	184,000	4.22	12" centers	overhead	CRF incorporated	shrub roses	1686	675	1181
9413	15 gal	2,600	0.80	44" centers	overhead	CRF incorporated	shrubs and trees	83	42	56
9413	7 gal	9,000	0.83	24" centers	overhead	CRF incorporated	shrubs and trees	114	57	76
4472	72 cell/tra y	40,320	0.02	pot tight	hand	soluble	spartina alterniflora	1634	1002	686
4472	72 cell/tra y	20,160	0.01	pot tight	hand	soluble	Spartina patens	1635	1003	687
3720	1 gal	12,000	0.11	pot tight	overhead	CRF	woody	626	258	516
3720	2 gal	4,000	0.05	pot tight	overhead	CRF	woody	1044	430	860
3720	3 and 5 gal	500	0.01	pot tight	overhead	CRF	woody	1458	600	1201
2481	2 gal	5,000	0.05	pot tight	hand	soluble	woody and grasses	30	6	36
2481	1 gal	15,000	0.12	pot tight	hand	soluble	woody	42	8	50
4543	2 gal	20	0.00	pot tight	hand	CRF incorporated	woody	108	108	108

4543	1 gal	400	0.01	pot tight	hand	CRF incorporated	woody	143	143	143
4998	3 gal	3,000	0.19	20" centers	overhead	CRF	woody	20	6	10
4998	2 gal	6,500	0.27	16" centers	overhead	CRF	woody	31	8	15
4998	1 gal	5,000	0.08	10" centers	overhead	CRF	woody	128	36	64
4998	5 gal	200	0.02	24" centers	overhead	CRF	woody	276	77	138
4998	15 gal	200	0.07	48" centers	overhead	CRF	woody	377	105	189
4998	7 gal	150	0.02	30" centers	overhead	CRF	woody	1547	430	774
4998	10 gal	160	0.03	36" centers	overhead	CRF	woody	2184	607	1092
10044	25 gal	50	0.02	48"	overhead	CRF incorporated	woody	1471	490	654
10044	1 gal	42,000	0.35	pot tight	overhead	CRF incorporated	woody	1045	348	465
10044	15 gal	2,000	0.48	36-39"	overhead	CRF incorporated	woody	700	233	311
10044	10 gal	3,000	0.62	36"	overhead	CRF incorporated	woody	601	200	267
10044	2 gal	39,000	1.21	14"	overhead	CRF incorporated	woody	698	233	310
10044	7 gal	14,000	2.01	30"	overhead	CRF incorporated	woody	483	161	215
10044	20 gal	1,100	3.09	42"	overhead	CRF incorporated	woody	1093	364	486
10044	5 gal	61,000	5.14	23"	overhead	CRF incorporated	woody	626	209	278
10044	3 gal	128,000	8.16	18-20"	overhead	CRF incorporated	woody	601	200	267
10107	1 gal	200	0.01	2' centers	overhead	CRF	woody	107	107	107
10107	3 gal	1,300	0.22	2' centers	overhead	CRF	woody	136	136	136
10107	3 gal	1,300	0.22	2' centers	overhead	CRF	woody	135	135	135
1284	7 gal	21	0.00	24" centers	overhead	CRF	woody	83	34	39
1284	5 gal	6,560	0.60	24" centers	overhead	CRF	woody	82	34	39
1284	3 gal	3,200	0.17	18" centers	overhead	CRF	woody	146	60	69
1284	2 gal	3,892	0.05	pot tight	overhead	CRF	woody	584	241	275
1284	1 gal	4,138	0.04	pot tight	overhead	CRF	woody	788	324	371
1284	1 quart	840	0.00	pot tight	overhead	CRF	woody	2651	1092	1248
5430	5	800	0.14	3'	overhead	CRF	woody perennial	193	64	129
5430	3	1,200	0.14	3'	overhead	CRF	woody perennial	193	64	129

5585	B and B	100	0.05	various	drip	CRF	woody perennial	115	23	46
5585	5 gal	7,500	0.39	18" centers	overhead	CRF	woody perennial	546	109	219
5585	1 gal	10,000	0.07	pot tight	overhead	CRF	woody perennial	716	143	287
5585	3 gal	7,500	0.17	12" centers	overhead	CRF	woody perennial	768	154	307
6831	1 gal	10,000	0.44	2 rows pot tight, 1 pot space	overhead	CRF incorporated	woody perennial	247	69	151
4073	1 gal	3,000	0.07	12" centers	hand	agritabs slow release	woody perennials	192	96	48
4073	2 gal	2,000	0.08	16" centers	hand	agritabs slow release	woody perennials	227	113	57
4073	5 gal	300	0.03	24" centers	hand	agritabs slow release	woody perennials	303	151	76
7360	1.5-7 gal	1,000	0.23	1-2'	overhead	foliar urea	woody perennials	7	0	0
7385	1 gal	18,900	0.31	12"	overhead	CRF	woody perennials	204	54	97
7385	3 gal	6,480	3.52	21"	overhead	CRF	woody perennials	216	57	102
7385	7 gal	2,800	1.02	32"	overhead	CRF	woody perennials	230	60	109
7385	10 gal	1,800	0.15	40"	overhead	CRF	woody perennials	281	74	133
7385	1 gal	18,900	0.46	12"	overhead	CRF	woody perennials	307	81	145
7385	5 gal	4,050	2.15	27"	overhead	CRF	woody perennials	332	87	157
7385	5 gal	4,050	7.23	27"	overhead	CRF	woody perennials	215	89	152
7385	2 gal	12,690	0.15	15"	overhead	CRF	woody perennials	266	110	188
7385	1 gal	39,375	0.77	pot tight	overhead	CRF	woody perennials	426	112	202
7385	5 gal	4,050	6.01	27"	overhead	CRF	woody perennials	452	119	214
7385	7 gal	2,800	1.08	32"	overhead	CRF	woody perennials	492	129	233
7385	3 gal	6,480	5.90	21"	overhead	CRF	woody perennials	334	138	236
7385	7 gal	2,800	2.32	32"	overhead	CRF	woody perennials	352	145	249
7385	3 gal	18,900	0.42	pot tight	overhead	CRF	woody perennials	630	166	298
7385	1 gal	39,375	0.31	pot tight	overhead	CRF	woody perennials	638	168	302
7385	3 gal	6,480	3.79	21"	overhead	CRF	woody perennials	444	183	313
7385	2 gal	29,138	0.15	pot tight	overhead	CRF	woody perennials	611	251	431

7385	5 gal	14,000	0.35	pot tight	overhead	CRF	woody perennials	745	307	526
7385	1 gal	39,375	0.77	pot tight	overhead	CRF	woody perennials	825	340	583
7385	3 gal	18,900	0.15	pot tight	overhead	CRF	woody perennials	975	402	688
7385	5 gal	14,000	0.25	pot tight	overhead	CRF	woody perennials	1564	412	741
3720	32 cell tray	64,000	0.08	pot tight	overhead	CRF	woody seedlings	497	205	409
3720	25 cell tray	37,500	0.06	pot tight	overhead	CRF	woody seedlings	696	287	573
3720	15 cell tray	12,000	0.03	pot tight	overhead	CRF	woody seedlings	845	348	696
9413	2 gal	30,000	1.08	15" centers	overhead	CRF incorporated	woody shrubs	91	46	61
9413	1 gal	100,000	2.30	1' centers	overhead	CRF incorporated	woody shrubs	92	46	62
9413	5 gal	32,000	2.94	24" centers	overhead	CRF incorporated	woody shrubs	87	44	58
9413	3 gal	100,000	8.43	23" centers	overhead	CRF incorporated	woody shrubs	69	34	46
6831	7 gal	800	0.13	32" centers	overhead	CRF incorporated	WP 4 year 2-5	400	111	245
6831	3 gal	200,000	11.00	18" centers	overhead	CRF incorporated	WP2 1st year	589	163	360
6831	3 gal	450,000	22.00	18" centers	overhead	CRF incorporated	WP2 year 2-3	662	184	405
6831	5 gal	800	0.16	32" centers	overhead	CRF incorporated	WP3 1st year	205	57	125
6831	5 gal	1,700	0.36	32" centers	overhead	CRF incorporated	WP3 year 2-3	196	55	120
6831	7 gal	200	0.07	32" centers	overhead	CRF incorporated	WP4 1st year	177	49	108

Table C3-4. Application rates of N, P_2O_5 and K_2O based on information gathered from site visits to 27 container operations in Maryland.

	N lb/acre/yr	P_2O_5/acre/yr	K_2O /acre/yr
Minimum	4	0	0
Lower Quartile	164	61	92
Middle Quartile	415	147	234
Average	607	263	372
Upper Quartile	762	336	488
Maximum	5386	5386	5386

Table C3-5. Fertilizer rates based on similar management units from information from 27 container operations in Maryland.

Container size and plant type	MU's in value	Statistical value	Lb N/ acre/yr	Lb P_2O_5/ acre/yr	Lb K_2O / acre/yr
1-7 gal aquatic	8	Minimum	13	18	10
		Lower quartile	19	26	15
		Average	99	124	87
		Middle quartile	48	67	38
		Upper Quartile	130	168	110
		Maximum	314	371	286
98 cell flats to 2 gal cuttings	9	Minimum	162	54	108
		Lower quartile	444	172	296
		Average	757	314	587
		Middle quartile	610	287	488
		Upper Quartile	845	366	696
		Maximum	1941	799	1599
1-5 gal ericaceous	4	Minimum	4	6	4
		Lower quartile	189	64	126
		Average	338	114	225
		Middle quartile	317	106	211
		Upper Quartile	466	155	310
		Maximum	712	237	475
1-2 gal mums	3	Minimum	4	4	4
		Lower quartile	30	10	19
		Average	56	21	30
		Middle quartile	55	15	34
		Upper Quartile	82	30	42
		Maximum	109	45	51
50 cell flats to 5 gal herbaceous perennials	14	Minimum	18	18	18
		Lower quartile	206	74	106
		Average	861	599	684
		Middle quartile	297	175	227
		Upper Quartile	989	391	620
		Maximum	5386	5386	5386
.25- 1 gal woody perennials	22	Minimum	42	8	48
		Lower quartile	195	84	116
		Average	609	269	363
		Middle quartile	515	143	250

		Upper Quartile	816	346	529
		Maximum	2651	1092	1248
2 gal woody perennials	12	Minimum	30	6	15
		Lower quartile	104	92	60
		Average	477	188	301
		Middle quartile	344	144	193
		Upper Quartile	633	243	341
		Maximum	1617	539	1078
3 gal woody perennials	22	Minimum	20	6	10
		Lower quartile	196	85	130
		Average	607	224	359
		Middle quartile	595	165	303
		Upper Quartile	870	335	444
		Maximum	1686	675	1181
5 gal woody perennials	21	Minimum	82	34	39
		Lower quartile	205	64	120
		Average	485	166	277
		Middle quartile	332	109	157
		Upper Quartile	674	225	347
		Maximum	1564	600	1201
7 gal woody perennials	12	Minimum	83	34	39
		Lower quartile	172	56	100
		Average	412	131	221
		Middle quartile	376	120	209
		Upper Quartile	485	163	246
		Maximum	1547	430	774
10 gal woody perennials	6	Minimum	173	58	77
		Lower quartile	361	106	167
		Average	816	233	430
		Middle quartile	713	215	386
		Upper Quartile	830	230	507
		Maximum	2184	607	1092
15 gal woody perennials	6	Minimum	83	42	56
		Lower quartile	443	132	213
		Average	725	217	400
		Middle quartile	671	224	298
		Upper Quartile	1122	321	657
		Maximum	1286	357	786

Table C3-6. All Field management units with abridged information about each unit.

Reference code	Produc-tion goal (years)	In row spacing (ft)	Between row spacing (ft)	MU size (acres)	Plants per acre	Lb N/ acre / year	Lb P2O5 / acre/ year	Lb K2O / acre/ year	gallon/ acre	L/ha	irrigation type
1284	5-6	8	8	55	680	21	0	0	1143	10696	pressure compensated
1284	5-6	5	5	95	1742	21	0	0	1830	17113	pressure compensated
1284	1-2	1	2	5	21780	21	0	0	4574	42783	pressure compensated
2479	5-10	6	6	0.8	750	16	16	16	0	0	none
2479	10-12	6	6	1.3	1000	16	16	16	0	0	none
2479	8-10	6	6	1.6	1000	16	16	16	0	0	None
2808	2-4	6	11	120	660	122	27	102	3600	33674	overhead gun
2808	2-4	3	6	30	2420	143	30	95	3600	33674	overhead gun
3325	1-2	6	10	6	726	25	0	0	5227	48895	pressure compensated
3325	3-6	6	10	3	726	25	0	0	3485	32597	pressure compensated
3325	1-2	6	10	6	726	25	0	0	5227	48895	pressure compensated
3325	3-6	6	10	3	726	25	0	0	3485	32597	pressure compensated
3714	3-5	0	0	112.5	5000000	65	39	39	10667	99775	traveling gun
4416	8-16	5	5	22	2150	0	0	0	25607	239530	drip emitters
4416	8-16	5	5	1.7	2150	0	0	0	25607	239530	drip emitters
5081	7	6	6	0.86	1210	0	0	0	varies	varies	overhead
5081	13	5	5	2.875	1740	0	0	0	varies	varies	overhead
5081	10	5	5	2.01	1740	0	0	0	varies	varies	overhead
5081	2-3	1	1	0.1	30000	0	0	0	varies	varies	overhead
5430	2-3	7	10	30	600	24	12	12	3267	30559	drip
5430	2-3	5	10	30	870	34	17	17	3267	30559	drip
5585	2-3	3	10	7	1750	2	0	0	13721	128349	pressure compensated

5585	3-5	8	10	14	550	4	0	0	137 21	128 349	pressure compensated
5585	2-3	5	10	14	870	4	0	0	137 21	128 349	pressure compensated
5833	7-8	6	6	5	1210	6	2	3	0	0	none
6290	6	2	3	0.0 5	135	1	1	1	400 0	374 16	hose
7360	6-8	6	7	12	1037	2	0	0	0	0	none
7385	4-8	6	10	9	726	26	4	4	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	26	4	4	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	26	4	4	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	26	4	4	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	26	4	4	290 40	271 638	pressure compensated
7385	4-8	6	10	5	726	30	6	6	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	33	7	7	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	33	7	7	290 40	271 638	pressure compensated
7385	4-8	6	10	8.5	726	34	8	8	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	35	8	8	290 40	271 638	pressure compensated
7385	4-8	6	10	8	726	38	9	9	290 40	271 638	pressure compensated
7385	4-8	6	10	13	726	38	9	9	290 40	271 638	pressure compensated
7385	4-8	6	10	4	726	40	10	10	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	42	11	11	290 40	271 638	pressure compensated
7385	4-8	6	10	4.5	726	42	11	11	290 40	271 638	pressure compensated
7385	4-8	6	10	10	726	45	12	12	290 40	271 638	pressure compensated
7385	4-8	6	10	6	726	49	13	13	290 40	271 638	pressure compensated
7385	4-8	6	10	10	726	51	14	14	290 40	271 638	pressure compensated
7385	4-8	6	10	3	726	51	14	14	290 40	271 638	pressure compensated
7385	4-8	6	10	10	726	55	16	16	290 40	271 638	pressure compensated

7385	4-8	6	10	4	726	55	16	16	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	55	16	16	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	60	18	18	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	60	18	18	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	60	18	18	290 40	271 638	pressure compensated
7385	4-8	6	10	8	726	69	21	21	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	71	22	22	290 40	271 638	pressure compensated
7385	4-8	6	10	9	726	71	22	22	290 40	271 638	pressure compensated
7385	4-8	6	10	8.7 5	726	72	23	23	290 40	271 638	pressure compensated
7385	4-8	6	10	7	726	72	23	23	290 40	271 638	pressure compensated
7385	4-8	6	10	8.5	726	74	24	24	290 40	271 638	pressure compensated
7385	4-8	6	10	7	726	78	25	25	290 40	271 638	pressure compensated
7385	4-8	6	10	7.5	726	80	26	26	290 40	271 638	pressure compensated
7385	4-8	6	10	6	726	82	27	27	290 40	271 638	pressure compensated
7385	4-8	6	10	3	726	82	27	27	290 40	271 638	pressure compensated
7385	4-8	6	10	6	726	82	27	27	290 40	271 638	pressure compensated
7385	4-8	6	10	6	726	89	29	29	290 40	271 638	pressure compensated
7385	4-8	6	10	4	726	90	30	30	290 40	271 638	pressure compensated
7385	4-8	6	10	4	726	90	30	30	290 40	271 638	pressure compensated
7385	4-8	6	10	2	726	95	32	32	290 40	271 638	pressure compensated
7385	4-8	6	10	5	726	95	32	32	290 40	271 638	pressure compensated
7385	4-8	6	10	5	726	95	32	32	290 40	271 638	pressure compensated
7385	4-8	5	10	5	871	110	8	8	348 48	325 966	pressure compensated
7385	4-8	5	10	12	871	115	10	10	348 48	325 966	pressure compensated
7385	4-8	6	10	4	726	115	40	40	290 40	271 638	pressure compensated

7385	4-8	5	10	12	871	123	13	13	34848	325966	pressure compensated
7385	4-8	5	10	9.5	871	132	17	17	34848	325966	pressure compensated
7385	4-8	5	10	7	871	133	17	17	34848	325966	pressure compensated
7385	4-8	5	10	7	871	133	17	17	34848	325966	pressure compensated
7385	4-8	5	10	9	871	134	18	18	34848	325966	pressure compensated
7385	4-8	5	10	8.75	871	136	18	18	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	137	19	19	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	137	19	19	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	137	19	19	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	137	19	19	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	139	20	20	34848	325966	pressure compensated
7385	4-8	5	10	8.5	871	142	21	21	34848	325966	pressure compensated
7385	4-8	6	10	7	726	165	60	60	29040	271638	pressure compensated
7603	5	7	8	0.386	800	32	19	19	4356	40746	drip
7603	5	7	8	0.257	800	39	58	39	4356	40746	drip
7603	5	3	4	0.055	3600	182	272	182	8712	81492	drip
9168	1-8	1-3	3	4	4500	69	67	225	varies	varies	overhead
9168	1-8	1-5	3	0.4	4500	69	67	225	53434	499815	drip
9237	8	6	6	7.5	1210	0	0	0	0	0	none
9237	8	8	8	7.5	680	0	0	0	0	0	none
9237	8	6	6	1	1210	0	0	0	varies	varies	drip
9237	8	8	8	1	680	0	0	0	varies	varies	drip
9237	1-2	1	2	0.1	30000	0	0	0	varies	varies	drip
9413	3	6	6	1.5	1210	86	8	16	600	5612	pressure compensated

Table C3-7. Fertilizer application rates reported by 17 growers during site visits, representing 92 management units.

Plant grown	MU's represented		N/acre/yr	P_2O_5/acre/yr	K_2O /acre/yr
Deciduous	6	Minimum	0	0	0
		lower quartile	18	0	0
		middle quartile	25	8	8
		Average	37	10	23
		upper quartile	31	19	19
		Maximum	122	27	102
Evergreen	13	Minimum	0	0	0
		lower quartile	0	0	0
		middle quartile	6	0	0
		average	25	6	11
		upper quartile	25	8	16
		maximum	143	30	95
Mixed	73	minimum	0	0	0
		lower quartile	34	8	8
		middle quartile	60	17	17
		average	69	21	24
		upper quartile	95	23	23
		maximum	182	272	225

Appendix D

Equations used in Stella Greenhouse model

N_container_capacity_in_mg(t) = N_container_capacity_in_mg(t - dt) + (N_mg_of__applied_N - N_leachate_in_mg - N_Plant_uptake_in_mg_per_week - N_mg_denitirification) * dt
INIT N_container_capacity_in_mg = Container_size__in_Liters*10

INFLOWS:
N_mg_of__applied_N =
PULSE((((N_mg_per_plant_per_application*Interception__efficiency))+N_from_recycling), 0.2 , (1/Days_fertigated_per_week))

OUTFLOWS:
N_leachate_in_mg = IF (N_container_capacity_in_mg >= N_holding_capacity) THEN (PULSE(N_container_capacity_in_mg-N_holding_capacity)) ELSE (N_mg_per_plant_per_application*(1-Interception__efficiency))
N_Plant_uptake_in_mg_per_week = GRAPH(TIME)
(0.00, 10.0), (1.00, 11.0), (2.00, 13.0), (3.00, 14.0), (4.00, 18.0), (5.00, 25.0), (6.00, 36.0), (7.00, 47.0), (8.00, 61.0), (9.00, 74.0), (10.0, 87.0), (11.0, 100), (12.0, 111), (13.0, 120), (14.0, 120), (15.0, 101), (16.0, 112), (17.0, 123), (18.0, 135), (19.0, 147), (20.0, 147)
N_mg_denitirification = (microorganisms+N_overfertilization_factor)
N_mg_denit_accumulation(t) = N_mg_denit_accumulation(t - dt) + (N_mg_denitirification) * dt
INIT N_mg_denit_accumulation = 0

INFLOWS:
N_mg_denitirification = (microorganisms+N_overfertilization_factor)
N_mg_leachate_accumulation(t) = N_mg_leachate_accumulation(t - dt) + (N_leachate_in_mg) * dt
INIT N_mg_leachate_accumulation = 0

INFLOWS:
N_leachate_in_mg = IF (N_container_capacity_in_mg >= N_holding_capacity) THEN (PULSE(N_container_capacity_in_mg-N_holding_capacity)) ELSE (N_mg_per_plant_per_application*(1-Interception__efficiency))
N_mg_plant_accumulation(t) = N_mg_plant_accumulation(t - dt) + (N_Plant_uptake_in_mg_per_week) * dt
INIT N_mg_plant_accumulation = 0

INFLOWS:
N_Plant_uptake_in_mg_per_week = GRAPH(TIME)
(0.00, 10.0), (1.00, 11.0), (2.00, 13.0), (3.00, 14.0), (4.00, 18.0), (5.00, 25.0), (6.00, 36.0), (7.00, 47.0), (8.00, 61.0), (9.00, 74.0), (10.0, 87.0), (11.0, 100), (12.0, 111), (13.0, 120), (14.0, 120), (15.0, 101), (16.0, 112), (17.0, 123), (18.0, 135), (19.0, 147), (20.0, 147)
P_container_capacity_in_mg(t) = P_container_capacity_in_mg(t - dt) + (P_mg_applied - P_mg_leachate - P_mg_uptake_per_week - P_Microbial_uptake_in_mg_per_week) * dt
INIT P_container_capacity_in_mg = Container_size__in_Liters*2

INFLOWS:
P_mg_applied = PULSE ((((P2O5_mg_per__plant_per_application*.4324)*Interception__efficiency))+P_mg_from_recycling, 0.2, 1/Days_fertigated_per_week)

OUTFLOWS:
P_mg_leachate = IF (P_container_capacity_in_mg >= P_holding_capacity) THEN (PULSE(P_container_capacity_in_mg - P_holding_capacity)) ELSE (P2O5_mg_per__plant_per_application* (1-Interception__efficiency))
P_mg_uptake_per_week = GRAPH(TIME)
(0.00, 2.00), (1.00, 2.00), (2.00, 2.50), (3.00, 3.00), (4.00, 4.00), (5.00, 5.00), (6.00, 6.00), (7.00, 8.00), (8.00, 10.0), (9.00, 13.0), (10.0, 15.0), (11.0, 18.0), (12.0, 21.0), (13.0, 25.0), (14.0, 53.0), (15.0, 16.0), (16.0, 19.0), (17.0, 23.0), (18.0, 27.0), (19.0, 32.0), (20.0, 32.0)
P_Microbial_uptake_in_mg_per_week = P_container_capacity_in_mg*.075
P_mg_leachate_accumulation(t) = P_mg_leachate_accumulation(t - dt) + (P_mg_leachate) * dt
INIT P_mg_leachate_accumulation = 0

INFLOWS:
P_mg_leachate = IF (P_container_capacity_in_mg >= P_holding_capacity) THEN (PULSE(P_container_capacity_in_mg - P_holding_capacity)) ELSE (P2O5_mg_per__plant_per_application* (1-Interception__efficiency))
P_mg_microbial_accumulation(t) = P_mg_microbial_accumulation(t - dt) + (P_Microbial_uptake_in_mg_per_week) * dt
INIT P_mg_microbial_accumulation = 0

INFLOWS:
P_Microbial_uptake_in_mg_per_week = P_container_capacity_in_mg*.075
P_mg_plant_accumulation(t) = P_mg_plant_accumulation(t - dt) + (P_mg_uptake_per_week) * dt
INIT P_mg_plant_accumulation = 0

INFLOWS:
P_mg_uptake_per_week = GRAPH(TIME)
(0.00, 2.00), (1.00, 2.00), (2.00, 2.50), (3.00, 3.00), (4.00, 4.00), (5.00, 5.00), (6.00, 6.00), (7.00, 8.00), (8.00, 10.0), (9.00, 13.0), (10.0, 15.0), (11.0, 18.0), (12.0, 21.0), (13.0, 25.0), (14.0, 53.0), (15.0, 16.0), (16.0, 19.0), (17.0, 23.0), (18.0, 27.0), (19.0, 32.0), (20.0, 32.0)
Water_leached_L_accumulation(t) = Water_leached_L_accumulation(t - dt) + (Water_leaching_in_L) * dt
INIT Water_leached_L_accumulation = 0

INFLOWS:
Water_leaching_in_L = (IF (W_container__capacity>water_capacity_in_L) THEN (PULSE (W_container__capacity-water_capacity_in_L)) ELSE(0))+ (PULSE((Liters_of_water_per_plant_per_application*(1-Interception__efficiency)),0,(1/(Days_fertigated_per_week))))+ (PULSE((Liters_of_water_per_plant_per_application*(1-Interception__efficiency)),0,(1/(Days_irrigated_per_week))))
W_container__capacity(t) = W_container__capacity(t - dt) + (W_Liters_per_irrigation - Water_leaching_in_L - W_plant_ET_in_L_per_week) * dt
INIT W_container__capacity = .1*Container_size__in_Liters

INFLOWS:
W_Liters_per_irrigation = Pulse (((Liters_of_water_per_plant_per_application*Interception__efficiency)), 0, (1/(Days_fertigated_per_week)))+ Pulse (((Liters_of_water_per_plant_per_application*Interception__efficiency)), 0, (1/(Days_irrigated_per_week)))

OUTFLOWS:
Water_leaching_in_L = (IF (W_container__capacity>water_capacity_in_L) THEN (PULSE (W_container__capacity-water_capacity_in_L)) ELSE(0))+ (PULSE((Liters_of_water_per_plant_per_application*(1-Interception__efficiency)),0,(1/(Days_fertigated_per_week))))+ (PULSE((Liters_of_water_per_plant_per_application*(1-Interception__efficiency)),0,(1/(Days_irrigated_per_week))))
W_plant_ET_in_L_per_week = GRAPH(TIME)
(0.00, 0.2), (1.00, 0.22), (2.00, 0.25), (3.00, 0.28), (4.00, 0.35), (5.00, 0.45), (6.00, 0.5), (7.00, 0.55), (8.00, 0.65), (9.00, 0.7), (10.0, 0.75), (11.0, 0.8), (12.0, 0.85), (13.0, 0.9), (14.0, 0.218), (15.0, 0.226), (16.0, 0.228), (17.0, 0.244), (18.0, 0.256), (19.0, 0.26), (20.0, 0.26)

W_Plant_L_ET_accumulation(t) = W_Plant_L_ET_accumulation(t - dt) + (W_plant_ET_in_L_per_week) * dt
INIT W_Plant_L_ET_accumulation = 0

INFLOWS:
W_plant_ET_in_L_per_week = GRAPH(TIME)
(0.00, 0.2), (1.00, 0.22), (2.00, 0.25), (3.00, 0.28), (4.00, 0.35), (5.00, 0.45), (6.00, 0.5), (7.00, 0.55), (8.00, 0.65), (9.00, 0.7), (10.0, 0.75), (11.0, 0.8), (12.0, 0.85), (13.0, 0.9), (14.0, 0.218), (15.0, 0.226), (16.0, 0.228), (17.0, 0.244), (18.0, 0.256), (19.0, 0.26), (20.0, 0.26)
Container_size__in_Liters = 0.5
Cost_of_fertilzer_per_cycle = Fertilizer_price_per_lb*Fert_lbs_per_cycle
Days_fertigated_per_week = GRAPH(TIME)
(0.00, 2.00), (1.00, 2.00), (2.00, 2.00), (3.00, 2.00), (4.00, 2.00), (5.00, 2.00), (6.00, 2.00), (7.00, 2.00), (8.00, 2.00), (9.00, 2.00), (10.0, 2.00), (11.0, 2.00), (12.0, 2.00), (13.0, 2.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00)
Days_irrigated_per_week = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00)
emitters_per_management_unit = 10000
Fertilizer_price_per_lb = 1
Fert_lbs_per_cycle = N_lbs_per_cycle/(Percent_N_of_fertilizer/100)
Interception__efficiency = 0.9
lbs_of_N_per_week = mg_of_N_per_week/453592.4
lbs_of_P2O5_per_week = P2O5_mg_per_week/453592.4
Liters_of_water_per_plant_per_application = (Liters_per__minute*Minutes_of_irrigation_per_day)/Number_of_plants_in_management__unit
Liters_per__minute = (emitters_per_management_unit*(LPH_per_emitter/60))
LPH_per_emitter = 0.375
mg_of_N_per_week = N_mg_per_plant_per_application*Days_fertigated_per_week*Number_of_plants_in_management__unit
microorganisms = IF ((N_container_capacity_in_mg/N_holding_capacity)>.2) THEN (((5.1*Container_size__in_Liters)*Temperature_effect)*((N_container_capacity_in_mg/N_holding_capacity)*5)) ELSE ((5.1*Container_size__in_Liters)*Temperature_effect)
Minutes_of_irrigation_per_day = GRAPH(TIME)

(0.00, 30.0), (1.00, 30.0), (2.00, 30.0), (3.00, 30.0), (4.00, 60.0), (5.00, 60.0), (6.00, 60.0), (7.00, 60.0), (8.00, 60.0), (9.00, 60.0), (10.0, 90.0), (11.0, 90.0), (12.0, 90.0), (13.0, 90.0), (14.0, 60.0), (15.0, 60.0), (16.0, 60.0), (17.0, 60.0), (18.0, 60.0), (19.0, 60.0), (20.0, 60.0)
number_of__weeks_in_cycle = 13
Number_of_plants_in_management__unit = 10000
N_from_recycling = N_leachate_in_mg*Percent_of__runoff_recycled
N_holding_capacity = Container_size__in_Liters*N_holding_capacity_in_mg_per_L
N_holding_capacity_in_mg_per_L = 100
N_lbs_per_acre_per_cycle = ((((N_mg_per_plant_per_application/453592.4)*Number_of_plants_in_management__unit*(number_of__weeks_in_cycle*Days_fertigated_per_week))/(Sq_ft_of_management_unit/43560)))
N_lbs_per_cycle = (N_lbs_per_acre_per_cycle*(Sq_ft_of_management_unit/43560))
N_mg_per_plant_per_application = N_mg_per_L_or_PPM_of_solution*Liters_of_water_per_plant_per_application
N_mg_per_L_or_PPM_of_solution = 200
N_overfertilization_factor = (N_mg_per_plant_per_application/Container_size__in_Liters)/10
P2O5_lbs_per_acre_per_cycle = ((Number_of_plants_in_management__unit*(P2O5_mg_per__plant_per_application/453592.4)*(number_of__weeks_in_cycle*Days_fertigated_per_week))/(Sq_ft_of_management_unit/43560))
P2O5_lbs_per_cycle = Fert_lbs_per_cycle*(Percent_P2O5_of_fertilizer/100)
P2O5_mg_per__plant_per_application = (N_mg_per_L_or_PPM_of_solution*(Percent_P2O5_of_fertilizer/Percent_N_of_fertilizer))*Liters_of_water_per_plant_per_application
P2O5_mg_per_week = P2O5_mg_per__plant_per_application*Number_of_plants_in_management__unit*Days_fertigated_per_week
Percent_N_of_fertilizer = 20
Percent_of__runoff_recycled = 0
Percent_P2O5_of_fertilizer = 10
P_holding_capacity = Container_size__in_Liters*P_holding_capacity_in_mg_per_L
P_holding_capacity_in_mg_per_L = 50
P_mg_from_recycling = P_mg_leachate*Percent_of__runoff_recycled
Sq_ft_of_management_unit = 1000
Substrate_water_holding_capacity = 0.3
Temperature_effect = GRAPH(TIME)

(0.00, 1.80), (1.00, 1.70), (2.00, 1.60), (3.00, 1.50), (4.00, 1.45), (5.00, 1.40), (6.00, 1.35), (7.00, 1.30), (8.00, 1.25), (9.00, 1.20), (10.0, 1.15), (11.0, 1.10), (12.0, 1.05), (13.0, 1.00), (14.0, 0.95), (15.0, 0.95), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00)
water_capacity_in_L = Container_size__in_Liters*Substrate_water_holding_capacity
W_Leaching_fraction = IF (W_Liters_per_irrigation=0) THEN (0) ELSE (Water_leaching_in_L/W_Liters_per_irrigation)

Appendix E

Equations used in Stella Container model

Initial_CRF_N(t) = Initial_CRF_N(t - dt) + (CRF_N_added - CRF_mg_N_out) * dt
INIT Initial_CRF_N = 0

INFLOWS:
CRF_N_added = PULSE ((grams_of_CRF_fertilizer_per_plant*1000)*(percent_N_CRF/100),0,0)

OUTFLOWS:
CRF_mg_N_out = PULSE (((((grams_of_CRF_fertilizer_per_plant*1000)*(percent_N_CRF/100))/(Release_time_in_weeks))*Air_Temperature_factor),0, 1)
Initial_CRF_P(t) = Initial_CRF_P(t - dt) + (CRF_P_added - CRF_P_out) * dt
INIT Initial_CRF_P = 0

INFLOWS:
CRF_P_added = PULSE ((grams_of_CRF_fertilizer_per_plant*1000)*(Percent_P_CRF/100),0,0)

OUTFLOWS:
CRF_P_out = PULSE (((((grams_of_CRF_fertilizer_per_plant*1000)*(Percent_P_CRF/100))/Release_time_in_weeks)*Air_Temperature_factor),0,1)
N_accumulation_surface_water(t) = N_accumulation_surface_water(t - dt) + (N_runoff_loss) * dt
INIT N_accumulation_surface_water = 0

INFLOWS:
N_runoff_loss = (IF (N_in_Root__zone>Container_N_storage__capacity) THEN (PULSE(N_in_Root__zone-Container_N_storage__capacity)) ELSE (0)) +F_mg_N_OH_unintercepted+(F_mg_N_drip_per_application*W_F_Leaching_fraction) +(F_mg_N_OH_per_application*W_F_Leaching_fraction)
N_Denitrified_N_accumulation(t) = N_Denitrified_N_accumulation(t - dt) + (N_denitirification) * dt
INIT N_Denitrified_N_accumulation = 0

INFLOWS:

N_denitirification = In_pot_denitrification
N_initial_biosolid(t) = N_initial_biosolid(t - dt) + (N_bioavailable - N_g_Plant_available) * dt
INIT N_initial_biosolid = 0

INFLOWS:
N_bioavailable = N_g_incorporated

OUTFLOWS:
N_g_Plant_available = PULSE ((N_g_incorporated/G_Number_of_weeks_in_growing_year),0,1)
N_in_Root__zone(t) = N_in_Root__zone(t - dt) + (N_to_Plant - N_runoff_loss - N_Leaf_uptake_in_mg_per_week - N_denitirification - N_Woody_uptake_in_mg) * dt
INIT N_in_Root__zone = Container_N_storage__capacity/10

INFLOWS:
N_to_Plant = (N_g_Plant_available*1000)+F_mg_N_OH_per_application+CRF_mg_N_out+F_mg_N_drip_per_application+((N_runoff_loss*.8)*(percent_of_runoff_recycled/100))

OUTFLOWS:
N_runoff_loss = (IF (N_in_Root__zone>Container_N_storage__capacity) THEN (PULSE(N_in_Root__zone-Container_N_storage__capacity)) ELSE (0)) +F_mg_N_OH_unintercepted+(F_mg_N_drip_per_application*W_F_Leaching_fraction) +(F_mg_N_OH_per_application*W_F_Leaching_fraction)
N_Leaf_uptake_in_mg_per_week = GRAPH(TIME)
(0.00, 100), (4.00, 100), (8.00, 100), (12.0, 100), (16.0, 25.0), (20.0, 15.0), (24.0, 15.0), (28.0, 5.00), (32.0, 5.00), (36.0, 0.00), (40.0, 0.00)
N_denitirification = In_pot_denitrification
N_Woody_uptake_in_mg = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 5.00), (16.0, 7.00), (20.0, 9.00), (24.0, 15.0), (28.0, 23.0), (32.0, 50.0), (36.0, 50.0), (40.0, 50.0)
N_Leaf_N_accumulation(t) = N_Leaf_N_accumulation(t - dt) + (N_Leaf_uptake_in_mg_per_week) * dt
INIT N_Leaf_N_accumulation = 0

INFLOWS:
N_Leaf_uptake_in_mg_per_week = GRAPH(TIME)
(0.00, 100), (4.00, 100), (8.00, 100), (12.0, 100), (16.0, 25.0), (20.0, 15.0), (24.0, 15.0), (28.0, 5.00), (32.0, 5.00), (36.0, 0.00), (40.0, 0.00)

N_Woody_N_accumulation(t) = N_Woody_N_accumulation(t - dt) + (N_Woody_uptake_in_mg) * dt
INIT N_Woody_N_accumulation = 0

INFLOWS:
N_Woody_uptake_in_mg = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 5.00), (16.0, 7.00), (20.0, 9.00), (24.0, 15.0), (28.0, 23.0), (32.0, 50.0), (36.0, 50.0), (40.0, 50.0)
P_leaf_accumulation(t) = P_leaf_accumulation(t - dt) + (P_leaf_uptake) * dt
INIT P_leaf_accumulation = 0

INFLOWS:
P_leaf_uptake = GRAPH(TIME)
(0.00, 11.0), (4.00, 11.0), (8.00, 12.0), (12.0, 12.0), (16.0, 8.00), (20.0, 4.00), (24.0, 4.00), (28.0, 2.00), (32.0, 2.00), (36.0, 0.00), (40.0, 0.00)
P_surface_water_accumulation(t) = P_surface_water_accumulation(t - dt) + (R_P_Surface_water) * dt
INIT P_surface_water_accumulation = 0

INFLOWS:
R_P_Surface_water = (IF (Root_zone_P>Container_P_storage_capacity) THEN (PULSE(Root_zone_P-Container_P_storage_capacity)) ELSE (0))+F_mg_P_OH_unintercepted+(W_F_Leaching_fraction*F_mg_drip_P_per_application)+(W_F_Leaching_fraction*F_mg_P_OH_per_application)
P_woody_accumulation(t) = P_woody_accumulation(t - dt) + (P_woody_uptake) * dt
INIT P_woody_accumulation = 0

INFLOWS:
P_woody_uptake = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 0.00), (16.0, 1.00), (20.0, 2.00), (24.0, 3.00), (28.0, 5.00), (32.0, 6.00), (36.0, 5.00), (40.0, 5.00)
Root_zone_P(t) = Root_zone_P(t - dt) + (P_to_Container - R_P_Surface_water - P_woody_uptake - P_leaf_uptake) * dt
INIT Root_zone_P = Container_P_storage_capacity/10

INFLOWS:
P_to_Container = (((P_g_incorporated_per_plant*1000)+(F_mg_P_OH_per_application+F_mg_drip_P_per_application))*.4324)+((R_P_Surface_water*.1)*(percent_of_runoff_recycled/100))+CRF_P_out

OUTFLOWS:
R_P_Surface_water = (IF (Root_zone_P>Container_P_storage_capacity) THEN (PULSE(Root_zone_P-Container_P_storage_capacity)) ELSE (0))+F_mg_P_OH_unintercepted+(W_F_Leaching_fraction*F_mg_drip_P_per_application)+(W_F_Leaching_fraction*F_mg_P_OH_per_application)
P_woody_uptake = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 0.00), (16.0, 1.00), (20.0, 2.00), (24.0, 3.00), (28.0, 5.00), (32.0, 6.00), (36.0, 5.00), (40.0, 5.00)
P_leaf_uptake = GRAPH(TIME)
(0.00, 11.0), (4.00, 11.0), (8.00, 12.0), (12.0, 12.0), (16.0, 8.00), (20.0, 4.00), (24.0, 4.00), (28.0, 2.00), (32.0, 2.00), (36.0, 0.00), (40.0, 0.00)
R_N_Containment__basin_accumulation(t) = R_N_Containment__basin_accumulation(t - dt) + (R_N_containment_basin) * dt
INIT R_N_Containment__basin_accumulation = 0

INFLOWS:
R_N_containment_basin = IF (R_Presence_of_Containment_basin=1)THEN (N_runoff_loss*.1) ELSE (0)
R_N_in_MU_soil_accumlation(t) = R_N_in_MU_soil_accumlation(t - dt) + (R_N_in_MU_soil) * dt
INIT R_N_in_MU_soil_accumlation = 0

INFLOWS:
R_N_in_MU_soil = N_runoff_loss*.1
R_N_veg_buffer__accumulation(t) = R_N_veg_buffer__accumulation(t - dt) + (R_N_Vegetative_Buffer) * dt
INIT R_N_veg_buffer__accumulation = 0

INFLOWS:
R_N_Vegetative_Buffer = IF (R_presence_of_vegetative_buffer=1) THEN (R_Sediment_trapping*N_runoff_loss) ELSE 0
R_P_containment_basin_accumulation(t) = R_P_containment_basin_accumulation(t - dt) + (R_P_Overland_flow) * dt
INIT R_P_containment_basin_accumulation = 0

INFLOWS:
R_P_Overland_flow = IF (R_Presence_of_Containment_basin=1) THEN (R_P_Surface_water*.9) ELSE (0)

R_P_in_MU_soil_accumulation(t) = R_P_in_MU_soil_accumulation(t - dt) + (R_P_in_MU_soil) * dt
INIT R_P_in_MU_soil_accumulation = 0

INFLOWS:
R_P_in_MU_soil = R_P_Surface_water*.05
R_P_veg_buffer_accumulation(t) = R_P_veg_buffer_accumulation(t - dt) + (R_P_Containment__basin_outflow) * dt
INIT R_P_veg_buffer_accumulation = 0

INFLOWS:
R_P_Containment__basin_outflow = IF (R_presence_of_vegetative_buffer=1) THEN (R_Sediment_trapping*R_P_Surface_water) ELSE (0)
Water_in_substrate(t) = Water_in_substrate(t - dt) + (W_Liters_applied_to_container - Water_leached - W_Evapotranspiration) * dt
INIT Water_in_substrate = W_Container_water_volume*.5

INFLOWS:
W_Liters_applied_to_container = W_drip_irrigation_L_applied+W_drip_fertigation_L_applied+(W_OH_irrigation_L_applied*Overhead_Interception_efficiency)+(W_OH_fertigation_L_applied*Overhead_Interception_efficiency)+(W_L_rain_to_pot_area*Overhead_Interception_efficiency)

OUTFLOWS:
Water_leached = (IF (Water_in_substrate>W_Container_water_volume) THEN (PULSE (Water_in_substrate-W_Container_water_volume)) ELSE (0))+(W_drip_fertigation_L_applied*W_F_Leaching_fraction)+(W_drip_irrigation_L_applied*W_F_Leaching_fraction)+(W_F_Leaching_fraction*W_OH_fertigation_L_applied)+(W_OH_irrigation_L_applied*W_F_Leaching_fraction)
W_Evapotranspiration = ((W_Crop_factor_Kc*((W_Evapotranspiration_ETo/10)*7))*((PI*((Diameter_of_canopy_in_feet/2)^2))*929.0304))/1000
W_Accumulated_leached_water(t) = W_Accumulated_leached_water(t - dt) + (Water_leached) * dt
INIT W_Accumulated_leached_water = 0

INFLOWS:
Water_leached = (IF (Water_in_substrate>W_Container_water_volume) THEN (PULSE (Water_in_substrate-W_Container_water_volume)) ELSE (0))+(W_drip_fertigation_L_applied*W_F_Leaching_fraction)+(W_drip_irrigation_L_a

pplied*W_F_Leaching_fraction)+(W_F_Leaching_fraction*W_OH_fertigation_L_applied)+(W_OH_irrigation_L_applied*W_F_Leaching_fraction)
W_ET_loss(t) = W_ET_loss(t - dt) + (W_Evapotranspiration) * dt
INIT W_ET_loss = 0

INFLOWS:
W_Evapotranspiration = ((W_Crop_factor_Kc*((W_Evapotranspiration_ETo/10)*7))*((PI*((Diameter_of_canopy_in_feet/2)^2))*929.0304))/1000
W_infiltration_accumulation(t) = W_infiltration_accumulation(t - dt) + (W_infiltration) * dt
INIT W_infiltration_accumulation = 0

INFLOWS:
W_infiltration = ((Water_leached*.1)+(((1-Overhead_Interception_efficiency)*W_L_rain_to_pot_area)*.1)+(((1-Overhead_Interception_efficiency)*W_L_OH_Irrigation_per_plant)*.1))+(((1-Overhead_Interception_efficiency)*F_OH_L_fert_per_application)*.1)
W_unintercepted__water_accumulation(t) = W_unintercepted__water_accumulation(t - dt) + (W_unintercepted_water) * dt
INIT W_unintercepted__water_accumulation = 0

INFLOWS:
W_unintercepted_water = (W_L_rain_to_pot_area*(1-Overhead_Interception_efficiency))+(W_L_OH_Irrigation_per_plant*(1-Overhead_Interception_efficiency))+((1-Overhead_Interception_efficiency)*F_OH_L_fert_per_application)
Air_Temperature_factor = GRAPH(TIME)
(0.00, 1.00), (5.00, 1.50), (10.0, 2.50), (15.0, 3.00), (20.0, 3.00), (25.0, 2.50), (30.0, 1.00), (35.0, 0.5), (40.0, 0.5)
Container_N_storage__capacity = N_holding_capacity_in_mg_per_L*G_Container_size_in_LIters
Container_P_storage_capacity = G_Container_size_in_LIters*P_holding_capacity_in_mg_per_L
Denitrification_rate_in_mg_per_sqM_per_week = GRAPH(TIME)
(0.00, 75.0), (4.00, 75.0), (8.00, 125), (12.0, 125), (16.0, 150), (20.0, 150), (24.0, 200), (28.0, 200), (32.0, 175), (36.0, 100), (40.0, 100)
Diameter_of_canopy_in_feet = GRAPH(TIME)
(0.00, 1.00), (4.00, 1.00), (8.00, 1.00), (12.0, 1.00), (16.0, 1.00), (20.0, 1.00), (24.0, 1.00), (28.0, 1.00), (32.0, 1.00), (36.0, 1.00), (40.0, 1.00)

F_cost_of_CRF_and_incorporated =
(F_CRF_cost_per_pound*(G_Number_of_plants_in_MU*(grams_of_CRF_fertilizer_per_plant/453.5924)))+(F_Incorporated_fertilizer_cost_per_pound*F_lbs_incorporated_for_MU)
F_Cost_of__fertilizer_per_week =
(((((F_mg_N_drip_per_application/(F_percent_N_drip_fertilizer/100))/1000)*G_Number_of_plants_in_MU)/453.5924)*F_soluble_fertilizer_cost_per_pound)+((((F_mg_N_OH_per_application/(F_percent_N_OH_fertilizer/100))*G_Number_of_plants_in_MU)/453592.4)*F_soluble_fertilizer_cost_per_pound)
F_CRF_cost_per_pound = 2
F_drip_PPM_or_mg_per_L = GRAPH(TIME)
(0.00, 0.00), (5.00, 0.00), (10.0, 0.00), (15.0, 0.00), (20.0, 0.00), (25.0, 0.00), (30.0, 0.00), (35.0, 0.00), (40.0, 0.00)
F_Incorporated_fertilizer_cost_per_pound = 0.5
F_lbs_incorporated_for_MU = 0
F_mg_drip_P_per_application = IF (F_percent_N_drip_fertilizer>0) THEN (F_mg_N_drip_per_application*(F_percent_P_drip_fertilizer/F_percent_N_drip_fertilizer)) ELSE (0)
F_mg_N_drip_per_application =
W_drip_fertigation_L_applied*F_drip_PPM_or_mg_per_L
F_mg_N_OH_per_application =
F_OH_L_fert_per_application*F_OH_PPM_or_mg_per_L
F_mg_N_OH_unintercepted = F_mg_N_OH_per_application*(1-Overhead_Interception_efficiency)
F_mg_P_OH_per_application =
F_mg_N_OH_per_application*(F_percent_P_OH_fertilizer/F_percent_N_OH_fertilizer)
F_mg_P_OH_unintercepted = (F_mg_P_OH_per_application*.4324)*(1-Overhead_Interception_efficiency)
F_number_of_drip_fertigations_per_week = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 0.00), (16.0, 0.00), (20.0, 0.00), (24.0, 0.00), (28.0, 0.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
F_OH_fertigations_per_week = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 0.00), (16.0, 0.00), (20.0, 0.00), (24.0, 0.00), (28.0, 0.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
F_OH_L_fert_per_application =
((W_OH_fertigation_min_per_run_for_MU*W_OH_liters_per_minute_per_emitter)*W_OH_emitters_per_MU)/G_Number_of_plants_in_MU
F_OH_PPM_or_mg_per_L = GRAPH(TIME)
(0.00, 0.00), (40.0, 0.00)
F_percent_N_drip_fertilizer = 7.5

F_percent_N_OH_fertilizer = 75
F_percent_P_drip_fertilizer = 48.5
F_percent_P_OH_fertilizer = 1.5
F_soluble_fertilizer_cost_per_pound = 1
grams_of_CRF_fertilizer_per_plant = 0
G_Container_size_in_LIters = 3.5
G_management_unit_size_in_acres = 0.02
G_Number_of_plants_in_MU = 1500
G_Number_of_weeks_in_growing_year = 40
Infiltration_Clay = GRAPH(TIME)
(0.00, 0.8), (0.003, 0.155), (0.006, 0.115), (0.009, 0.1), (0.012, 0.1), (0.015, 0.075), (0.018, 0.05)
Infiltration_loamy_clay = GRAPH(TIME)
(0.00, 1.50), (0.003, 0.9), (0.006, 0.75), (0.009, 0.75), (0.012, 0.75), (0.015, 0.7), (0.018, 0.7)
Infirltration_sandy_loam = GRAPH(TIME)
(0.00, 2.00), (0.003, 1.50), (0.006, 1.40), (0.009, 1.40), (0.012, 1.40), (0.015, 1.40), (0.018, 1.40)
In_pot_denitrification =
((((((M_Container_diameter_in_inches)*2.54)^2)*PI)/10000)*Denitrification_rate_in_mg_per_sqM_per_week)*(Air_Temperature_factor)*(N_in_Root__zone/Container_N_storage__capacity)
Linear_feet_of_MU =
(G_management_unit_size_in_acres*43560)/M_Spacing_between_rows_in_feet
M_Container_diameter_in_inches = 9
M_Spacing_between_rows_in_feet = 0.75
M_spacing_in_rows_in_feet = 0.75
N_g_incorporated = PULSE
((((F_lbs_incorporated_for_MU*N_incorporated_Percent_N)*453.5924)/G_Number_of_plants_in_MU),0,0)
N_holding_capacity_in_mg_per_L = 90
N_incorporated_Percent_N = 5
N_lbs_of_fert_per_week =
G_management_unit_size_in_acres*N_lbs_per_acre_per_week
N_lbs_per_acre_per_week =
(((((F_mg_N_drip_per_application+F_mg_N_OH_per_application)/1000)*G_Number_of_plants_in_MU))/453.5924)/G_management_unit_size_in_acres
N_lbs_per_acre_per_year_CRF_and_incorporated =
((((grams_of_CRF_fertilizer_per_plant*(percent_N_CRF/100))+N_g_incorporated)/453.592)*G_Number_of_plants_in_MU)/G_management_unit_size_in_acres

Overhead_Interception_efficiency =
(((((M_Container_diameter_in_inches/2)/12)^2)*(22/7))/(M_Spacing_between_rows_in_feet*M_spacing_in_rows_in_feet))*Plant_architecture_factor
percent_N_CRF = 19
percent_of_runoff_recycled = 0
Percent_P_CRF = 5
Plant_architecture_factor = 1
P_g_incorporated_per_plant = PULSE
((N_g_incorporated*(P_Percent_P_incorporated_fert/N_incorporated_Percent_N)), 0,0)
P_holding_capacity_in_mg_per_L = 15
P_lbs_of_fertilizer_per_week =
P_lb_per_acre_per_week*G_management_unit_size_in_acres
P_lbs_per_acre_per_year_CRF_and_incorporated =
((((grams_of_CRF_fertilizer_per_plant*(Percent_P_CRF/100))+P_g_incorporated_per_plant)/453.592)*G_Number_of_plants_in_MU)/G_management_unit_size_in_acres
P_lb_per_acre_per_week =
((((F_mg_drip_P_per_application+F_mg_P_OH_per_application)/1000)*G_Number_of_plants_in_MU)/453.5924)/G_management_unit_size_in_acres
P_Percent_P_incorporated_fert = 46
Release_time_in_weeks = 40
R_Buffer_width_in_feet = 50
R_Presence_of_Containment_basin = 0
R_presence_of_vegetative_buffer = 1
R_Sediment_trapping =
(53.77+(1.58*(R_Buffer_width_in_feet*0.3048))+(5.67*R_Slope_percent_of_buffer)-(.314*(R_Slope_percent_of_buffer^2)))/100
R_Slope_percent_of_buffer = 4
W_avg_rainfall_amount_in_cm_per_week = GRAPH(TIME)
(0.00, 2.50), (5.20, 2.50), (10.4, 2.50), (15.6, 2.50), (20.8, 2.50), (26.0, 2.50), (31.2, 2.50), (36.4, 2.50), (41.6, 2.50), (46.8, 2.50), (52.0, 2.50)
W_Container_water_volume =
G_Container_size_in_LIters*(W_Substrate_water_holding_capacity_in_ml_per_L/1000)
W_Crop_factor_Kc = 0.5
W_drip_fertigation_L_applied = IF (F_number_of_drip_fertigations_per_week>0)
THEN (PULSE(W_drip_fertigation_L_per_application,
.142,1/F_number_of_drip_fertigations_per_week)) ELSE (0)
W_drip_fertigation_L_per_application =
(W_Drip_liters_per_hour_per_emitter*W_drip_number_of_emitters_per_pot)*(W_Drip_min_of_fertigation_per_application/60)

W_drip_irrigation_L_applied =
PULSE(W_drip_irrigation_L_per_application,0,1/W_Irrigations_per_week_drip)
W_drip_irrigation_L_per_application =
(W_Drip_liters_per_hour_per_emitter*W_drip_number_of_emitters_per_pot)*(W_Drip_min_of_irrigation_per_application/60)
W_Drip_liters_per_hour_per_emitter = 0.14
W_Drip_min_of_fertigation_per_application = GRAPH(TIME)
(0.00, 60.0), (4.00, 60.0), (8.00, 60.0), (12.0, 60.0), (16.0, 60.0), (20.0, 60.0), (24.0, 60.0), (28.0, 60.0), (32.0, 60.0), (36.0, 60.0), (40.0, 60.0)
W_Drip_min_of_irrigation_per_application = GRAPH(TIME)
(0.00, 240), (4.00, 240), (8.00, 240), (12.0, 240), (16.0, 240), (20.0, 240), (24.0, 240), (28.0, 240), (32.0, 240), (36.0, 240), (40.0, 240)
W_drip_number_of_emitters_per_pot = 1
W_Evapotranspiration_ETo = GRAPH(TIME)
(0.00, 1.90), (4.00, 3.00), (8.00, 4.25), (12.0, 4.75), (16.0, 5.75), (20.0, 6.00), (24.0, 5.00), (28.0, 4.10), (32.0, 2.90), (36.0, 2.10), (40.0, 2.10)
W_F_Leaching_fraction = .1
W_Infiltration_rate_in_cm_per_hr = 2
W_Irrigations_per_week_drip = GRAPH(TIME)
(0.00, 0.00), (1.00, 1.00), (2.00, 2.00), (3.00, 3.00), (4.00, 4.00), (5.00, 5.00), (6.00, 6.00), (7.00, 7.00), (8.00, 0.00), (9.00, 1.00), (10.0, 2.00), (11.0, 3.00), (12.0, 4.00), (13.0, 5.00), (14.0, 6.00), (15.0, 7.00), (16.0, 5.00), (17.0, 5.00), (18.0, 5.00), (19.0, 5.00), (20.0, 5.00), (21.0, 5.00), (22.0, 5.00), (23.0, 5.00), (24.0, 5.00), (25.0, 5.00), (26.0, 5.00), (27.0, 5.00), (28.0, 5.00), (29.0, 5.00), (30.0, 5.00), (31.0, 5.00), (32.0, 5.00), (33.0, 5.00), (34.0, 5.00), (35.0, 5.00), (36.0, 5.00), (37.0, 5.00), (38.0, 5.00), (39.0, 5.00), (40.0, 5.00)
W_L_OH_Irrigation_per_plant =
((W_OH_irrigation_min_per_run_for_MU*W_OH_liters_per_minute_per_emitter)*W_OH_emitters_per_MU)/G_Number_of_plants_in_MU
W_L_rain_to_pot_area =
(((M_spacing_in_rows_in_feet*M_Spacing_between_rows_in_feet)*929.0304)*W_rainfall_depth_in_cm)/1000
W_OH_Coefficient_of_uniformity = 0.9
W_OH_emitters_per_MU = 0
W_OH_fertigation_L_applied = IF (F_OH_fertigations_per_week>0) THEN
(PULSE(F_OH_L_fert_per_application,0,1/F_OH_fertigations_per_week)) ELSE (0)
W_OH_fertigation_min_per_run_for_MU = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 0.00), (12.0, 0.00), (16.0, 0.00), (20.0, 0.00), (24.0, 0.00), (28.0, 0.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
W_OH_irrigation_L_applied = IF (W_OH_irrigations_per_week>0) THEN
(PULSE(W_L_OH_Irrigation_per_plant,0,1/W_OH_irrigations_per_week)) ELSE (0)

W_OH_irrigation_min_per_run_for_MU = GRAPH(TIME)
(0.00, 5.00), (4.00, 5.00), (8.00, 120), (12.0, 240), (16.0, 240), (20.0, 120), (24.0, 120), (28.0, 5.00), (32.0, 5.00), (36.0, 5.00), (40.0, 5.00)
W_OH_irrigations_per_week = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 2.00), (12.0, 3.00), (16.0, 4.00), (20.0, 4.00), (24.0, 2.00), (28.0, 2.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
W_OH_liters_per_minute_per_emitter = 0.5
W_rainfall_depth_in_cm = (W_rainfall_duration*W_rainfall_intensity__in_cm_per_hr)
W_rainfall_duration = IF (W_rainfall_events_per_month)>0 THEN (((W_avg_rainfall_amount_in_cm_per_week*4)/W_rainfall_events_per_month)/W_rainfall_intensity__in_cm_per_hr) ELSE (1)
W_rainfall_events_per_month = IF (ABS(ROUND (NORMAL (5,2, 300)>.5))) THEN (ABS (ROUND (NORMAL (3,2, 300)))) ELSE (1)
W_rainfall_intensity__in_cm_per_hr = .75
W_Substrate_water_holding_capacity_in_ml_per_L = 200

Table E 5.1. Graphical values used for model calibration and validation. All values (except canopy diameter) were not changed during subsequent runs. Canopy diameter increased for each dataset, to factor in plant growth.

Canopy diameter (feet)	Denitrification (mg/sqM/week)	Air Temp factor	Avg weekly rainfall (cm)	Evapotranspiration (Eto)
0.9	100	0.64	2.6	1.9
1	150	0.94	2.3	3
1.1	200	1.6	3.0	4.25
1.2	250	1.9	2.5	4.75
1.3	300	2.08	2.6	5.75
1.3	300	2.05	2.3	6
1.4	225	1.75	2.9	5
1.4	150	1	2.3	4.1
1.5	100	1	2.3	2.9
1.5	75			2.1
1.5	75			2.1

Table E 5.2. Variable values used for model calibration, based on information provided in Ristvey (2004). For subsequent runs, plant uptake values were changed to match reported values.

N leaf uptake	N woody uptake	P leaf uptake	P woody uptake
100	0	11	0
100	5	11	0
100	7	12	1
100	9	12	2
25	15	8	3
15	23	4	5
15	50	4	6
5	50	2	5
5	50	2	5
0	0	0	0
0	0	0	0

Table E 5.3. Variable values used for model calibration, based on information provided in Ristvey (2004).

Week	Irrigations per week drip	Min of drip irrigation per application	Fertigations per week	Min of drip fertigation per application	Drip PPM or mg/L
1	7	30	0	30	0
2	7	30	0	30	0
3	7	30	0	30	0
4	7	30	0	30	0
5	5	30	2	30	150
6	5	30	2	30	150
7	5	30	2	30	150
8	5	30	2	30	150
9	5	30	2	30	150
10	5	30	2	30	150
11	5	30	2	30	150
12	5	30	2	30	150
13	5	30	2	30	150
14	5	30	2	30	150
15	5	30	2	30	150
16	5	30	2	30	150
17	5	30	2	30	150
18	5	30	2	30	150
19	5	30	2	30	150
20	5	30	2	30	150
21	5	40	2	40	150
22	5	40	2	40	150
23	5	40	2	40	150
24	5	40	2	40	150
25	5	40	2	40	75
26	5	40	2	40	75
27	5	40	2	40	75
28	5	40	2	40	75
29	5	40	2	40	75
30	5	40	2	40	75
31	5	40	2	40	75
32	7	40	0	40	75
33	7	40	0	40	0
34	7	40	0	40	0
35	7	40	0	40	0
36	7	40	0	40	0

37	7	40	0	40	0
38	7	40	0	40	0
39	7	40	0	40	0
40	7	40	0	40	0

Table E 5.4. Constant inputs for model validation, based on informaiton from Ristvey (2004).

Variable	Dataset 1 Overhead	Dataset 2 Drip	Dataset 2 Overhead	Dataset 3 Drip	Dataset 3 Overhead
MU size (acres)	0.26	0.26	0.26	0.26	0.26
# of plants in MU	1792	896	896	560	280
Between row spacing (ft)	0.75	1	1	1.45	1.45
In row spacing (ft)	0.75	1.25	1.25	1.45	1.45
Container diameter (in)	9	9	9	14	14
Container size (L)	11.7	11.7	11.7	19.4	19.4
# of weeks in growing year	40	40	40	40	40
N holding capacity (mg/L)	75	75	75	75	75
P holding capacity (mg/L)	10	10	10	10	10
Plant architecture factor	1	1	1	1	1
Crop factor Kc	0.8	0.8	0.8	0.8	0.8
Substrate water holding cap. (ml/ L)	200	200	200	200	200
OH emitters per MU	24	0	24	0	24
OH L/ min per emitter	0.5	0.5	0.5	0.5	0.5
OH Coefficient of uniformity	0.9	0.9	0.9	0.9	0.9
Drip L/ hr per emitter	1.2	1.2	1.2	1.2	1.2
Drip # of emitters per pot	0	2	0	2	0
grams of SRF fertilizer per plant	51.7	32.21	32.21	0	0
SRF cost per lb	2	2	2	2	2
SRF N %	19	19	19	19	19
SRF P %	5	5	5	5	5
SRF release time in weeks	40	40	40	40	40
Drip fertilizer % N	75	50	0	75	75
Drip fertilizer % P	1.5	1.5	0	9	9
OH fertilizer % N	75	50	100	75	75
OH fertilizer %P	1.5	1.5	2.5	9	9
Soluble fert. $/ pound	1	1	1	1	1
Buffer width (ft)	50	50	50	50	50
Slope of buffer (%)	4	4	4	4	4

Table E 5.5. Constant input values used for validation of model, based on information from Cabrera (2003).

Variable	**Value**
G management unit size in acres	0.02
G number of plants in MU	1500
M spacing between rows in feet	0.75
M spacing in rows in feet	0.75
M Container diameter in inches	9
G container size in Liters	3.5
G Number of weeks in growing year	40
N holding capacity in mg per L	90
P holding capacity in mg per L	15
Plant architecture factor	1
W Crop factor Kc	0.5
W substrate water holding capacity in ml per L	200
W OH emitters per MU	0
W OH liters per minute per emitter	0.5
W OH Coefficient of uniformity	0.9
W drip liters per hour per emitter	0.14
W drip number of emitters per pot	1
F lbs incorporated for MU	0
F Incorporated fertilizer cost per pound	0.5
N incorporated Percent N	5
P Percent P incorporated fert	46
grams of CRF fertilizer per plant	0
F CRF cost per pound	2
Percent N CRF	19
Percent P CRF	5
Release time in weeks	40
F percent N drip fertilizer	7.5
F percent P drip fertilizer	48.5
F percent N OH fertilizer	75
F percent P OH fertilizer	1.5
F soluble fertilizer cost per pound	1
R Buffer width in feet	50
R Slope percent of buffer	4

Table E 5.6. Graphical variables used as model inputs for model calibration, based on information from Cabrera (2003).

Canopy diameter in feet	Denitrification in mg/sqM/week	Air Temp factor	Avg weekly rainfall in cm	Evapotranspiration (Eto)
0.4	100	0.500	0	1.9
0.5	150	0.805	0	3
0.6	200	1.489	0	4.25
0.7	250	1.786	0	4.75
0.7	300	1.973	0	5.75
0.8	300	1.935	0	6
0.8	225	1.675	0	5
0.8	150	0.917	0	4.1
0.9	100	0.917	0	2.9
0.9	75			2.1
0.9	75			2.1

Table E 5.7. Graphical irrigation values used to validate models, based on information from Cabrera (2003). All columns remained the same except drip mg/ L, which was changed to 15, 30, 60, 120, 210 and 300 mg/ L for subsequent runs.

Week	irrigations per month drip	Min of drip irrigation per application	Fertigations per month	Min of drip fertigation per application	Drip PPM or mg/ L
1	0	60	2	60	15
2	0	60	2	60	15
3	0	60	2	60	15
4	0	60	2	60	15
5	0	60	2	60	15
6	0	60	2	60	15
7	0	60	3	60	15
8	0	60	3	60	15
9	0	60	3	60	15
10	0	60	3	60	15
11	0	60	3	60	15
12	0	60	3	60	15
13	0	60	4	60	15
14	0	60	4	60	15
15	0	60	4	60	15
16	0	60	4	60	15
17	0	60	4	60	15
18	0	60	4	60	15
19	0	60	4	60	15
20	0	60	4	60	15
21	0	60	4	60	15
22	0	60	4	60	15
23	0	60	4	60	15
24	0	60	4	60	15
25	0	60	3	60	15
26	0	60	3	60	15
27	0	60	3	60	15
28	0	60	3	60	15
29	0	60	3	60	15
30	0	60	3	60	15
31	0	60	3	60	15
32	0	60	3	60	15
33	0	60	3	60	15
34	0	60	3	60	15

35	0	60	2	60	15
36	0	60	2	60	15
37	0	60	2	60	15
38	0	60	2	60	15
39	0	60	2	60	15
40	0	60	2	60	15

Table E.8. Graphical input variables for N and P uptake, based on information from Cabrera (2003). N values are based on published data, while P values were assumed to be 10% of N values. Values for 15 mg/ L rate are shown below.

Root: shoot ratio is 1:1 for 15 mg/L only, all others are 3:1-5:1 (figure 1)			
N leaf uptake	N woody uptake	P leaf uptake	P woody uptake
3	0	0.4	0
5	0	0.4	0
3	0	0.5	0
1.6	0	0.3	0
1	0	0.2	0
0.4	1	0.1	0.1
0.2	2	0	0.3
0.1	2.5	0	0.3
0	5	0	0.4
0	4	0	0.3
0	4	0	0.3

Table E.9. Constants values for what if scenarios. Unless discussed, values for each run were not changed between subsequent runs.

G management unit size in acres	1
G number of plants in MU	75000
M spacing between rows in feet	0.75
M spacing in rows in feet	0.75
M Container diameter in inches	9
G container size in Liters	6
G Number of weeks in growing year	40
N holding capacity in mg per L	75
P holding capacity in mg per L	10
Plant architecture factor	1
W Crop factor Kc	0.8
W substrate water holding capacity in ml per L	200
W OH emitters per MU	100
W OH liters per minute per emitter	1
W OH Coefficient of uniformity	0.9
W drip liters per hour per emitter	1.2
W drip number of emitters per pot	0
F lbs incorporated for MU	0
F Incorporated fertilizer cost per pound	0.5
N incorporated Percent N	5
P Percent P incorporated fert.	46
grams of CRF fertilizer per plant	45
F CRF cost per pound	2
Percent N CRF	20
Percent P CRF	3
Release time in weeks	40
F percent N drip fertilizer	20
F percent P drip fertilizer	10
F percent N OH fertilizer	20
F percent P OH fertilizer	10
F soluble fertilizer cost per pound	1
R Buffer width in feet	50
R Slope percent of buffer	5

Appendix F

Stella equations for Field model

N_accumulation_surface_water(t) = N_accumulation_surface_water(t - dt) + (N_erossion_loss) * dt
INIT N_accumulation_surface_water = 0

INFLOWS:
N_erossion_loss = IF (R_Presence_of_erosion=1) THEN ((N_to_Plant*R_Erosion_factor)-(R_N_containment_basin+R_N_in_row_buffer+R_N_Vegetative_Buffer)) ELSE (0)
N_accumulation__in_groundwater(t) = N_accumulation__in_groundwater(t - dt) + (N_leached__beyond_rootzone) * dt
INIT N_accumulation__in_groundwater = 0

INFLOWS:
N_leached__beyond_rootzone = CONVEYOR OUTFLOW
N_Denitrified_N_accumulation(t) = N_Denitrified_N_accumulation(t - dt) + (N_denitirification) * dt
INIT N_Denitrified_N_accumulation = 0

INFLOWS:
N_denitirification = In_row_denitrification
N_in_Root__zone(t) = N_in_Root__zone(t - dt) + (N_to_Plant + N_plant_available - N_erossion_loss - N_beyond_root_zone - N_Leaf_uptake_in_mg - N_denitirification - N_Woody_uptake_in_mg - R_N_in_row_buffer - R_N_containment_basin - R_N_Vegetative_Buffer) * dt
INIT N_in_Root__zone = N_Soil_storage_in_mg_per_tree/10

INFLOWS:
N_to_Plant = ((N_g_of_liquid_N_per_plant+g_of_solid_N_per_plant)*1000)+F_mg_fertigation_N_per_application
N_plant_available = PULSE (((N_g_incorporated_per_plant*1000)/G_Number_of_weeks_in_growing_year),0,1)

OUTFLOWS:
N_erossion_loss = IF (R_Presence_of_erosion=1) THEN
((N_to_Plant*R_Erosion_factor)-
(R_N_containment_basin+R_N_in_row_buffer+R_N_Vegetative_Buffer)) ELSE (0)
N_beyond_root_zone = IF (N_in_Root__zone>N_Soil_storage_in_mg_per_tree) THEN
(PULSE (N_in_Root__zone-N_Soil_storage_in_mg_per_tree)) ELSE (0)
N_Leaf_uptake_in_mg = GRAPH(TIME)
(0.00, 1200), (4.00, 1200), (8.00, 1200), (12.0, 1200), (16.0, 100), (20.0, 50.0), (24.0, 50.0), (28.0, 25.0), (32.0, 25.0), (36.0, 0.00), (40.0, 0.00)
N_denitirification = In_row_denitrification
N_Woody_uptake_in_mg = GRAPH(TIME)
(0.00, 50.0), (4.00, 50.0), (8.00, 50.0), (12.0, 25.0), (16.0, 25.0), (20.0, 50.0), (24.0, 50.0), (28.0, 360), (32.0, 360), (36.0, 360), (40.0, 360)
R_N_in_row_buffer = IF (R_Presence_of_in_row_buffer=1) THEN
((N_to_Plant*(R_Erosion_factor/2))*R_In_row_sediment_trapping) ELSE (0)
R_N_containment_basin = IF (R_Presence_of_Containment_basin=1)THEN
((N_to_Plant*(R_Erosion_factor))*.5) ELSE (0)
R_N_Vegetative_Buffer = IF (R_presence_of_vegetative_buffer=1) THEN
(R_Sediment_trapping*(N_to_Plant*(R_Erosion_factor/2))) ELSE 0
N_leaching_through_root_zone(t) = N_leaching_through_root_zone(t - dt) +
(N_beyond_root_zone - N_leached__beyond_rootzone) * dt
INIT N_leaching_through_root_zone = 0
TRANSIT TIME = 2
INFLOW LIMIT = INF
CAPACITY = INF

INFLOWS:
N_beyond_root_zone = IF (N_in_Root__zone>N_Soil_storage_in_mg_per_tree) THEN
(PULSE (N_in_Root__zone-N_Soil_storage_in_mg_per_tree)) ELSE (0)

OUTFLOWS:
N_leached__beyond_rootzone = CONVEYOR OUTFLOW
N_Leaf_N_accumulation(t) = N_Leaf_N_accumulation(t - dt) + (N_Leaf_uptake_in_mg) * dt
INIT N_Leaf_N_accumulation = 0

INFLOWS:
N_Leaf_uptake_in_mg = GRAPH(TIME)
(0.00, 1200), (4.00, 1200), (8.00, 1200), (12.0, 1200), (16.0, 100), (20.0, 50.0), (24.0, 50.0), (28.0, 25.0), (32.0, 25.0), (36.0, 0.00), (40.0, 0.00)

N_Slowly_available_in_soil(t) = N_Slowly_available_in_soil(t - dt) + (N_slowly_available - N_plant_available) * dt
INIT N_Slowly_available_in_soil = N_Soil_storage_in_mg_per_tree/10

INFLOWS:
N_slowly_available = PULSE ((N_g_incorporated_per_plant*1000),0,0)

OUTFLOWS:
N_plant_available = PULSE (((N_g_incorporated_per_plant*1000)/G_Number_of_weeks_in_growing_year),0,1)
N_Woody_N_accumulation(t) = N_Woody_N_accumulation(t - dt) + (N_Woody_uptake_in_mg) * dt
INIT N_Woody_N_accumulation = 0

INFLOWS:
N_Woody_uptake_in_mg = GRAPH(TIME)
(0.00, 50.0), (4.00, 50.0), (8.00, 50.0), (12.0, 25.0), (16.0, 25.0), (20.0, 50.0), (24.0, 50.0), (28.0, 360), (32.0, 360), (36.0, 360), (40.0, 360)
P_accumulation_groundwater(t) = P_accumulation_groundwater(t - dt) + (P_leached_beyond_rootzone) * dt
INIT P_accumulation_groundwater = 0

INFLOWS:
P_leached_beyond_rootzone = CONVEYOR OUTFLOW
P_leaching_through_root_zone(t) = P_leaching_through_root_zone(t - dt) + (P_to_root_zone - P_leached_beyond_rootzone) * dt
INIT P_leaching_through_root_zone = 0
TRANSIT TIME = 2
INFLOW LIMIT = INF
CAPACITY = INF

INFLOWS:
P_to_root_zone = IF (Root_zone_P>G_Soil_P_storage_in_mg_per_tree) THEN (Root_zone_P-G_Soil_P_storage_in_mg_per_tree) ELSE (0)

OUTFLOWS:
P_leached_beyond_rootzone = CONVEYOR OUTFLOW
P_leaf_accumulation(t) = P_leaf_accumulation(t - dt) + (P_leaf_uptake) * dt
INIT P_leaf_accumulation = 0

INFLOWS:
P_leaf_uptake = GRAPH(TIME)
(0.00, 120), (4.00, 120), (8.00, 120), (12.0, 120), (16.0, 10.0), (20.0, 5.00), (24.0, 5.00), (28.0, 2.50), (32.0, 2.50), (36.0, 0.00), (40.0, 0.00)
P_slowly_available_in_soil(t) = P_slowly_available_in_soil(t - dt) + (P_slowly_available - P_plant_available) * dt
INIT P_slowly_available_in_soil = 0

INFLOWS:
P_slowly_available = PULSE (((P_g_incorporated_per_plant*.4324)*1000), 0,0)

OUTFLOWS:
P_plant_available = PULSE ((((P_g_incorporated_per_plant*1000)*.4324)/G_Number_of_weeks_in_growing_year), 0,1)
P_woody_accumulation(t) = P_woody_accumulation(t - dt) + (P_woody_uptake) * dt
INIT P_woody_accumulation = 0

INFLOWS:
P_woody_uptake = GRAPH(TIME)
(0.00, 5.00), (4.00, 5.00), (8.00, 5.00), (12.0, 2.50), (16.0, 2.50), (20.0, 5.00), (24.0, 5.00), (28.0, 36.0), (32.0, 36.0), (36.0, 36.0), (40.0, 36.0)
Root_zone_P(t) = Root_zone_P(t - dt) + (P_to_root + P_plant_available - P_to_root_zone - R_P_Surface_water - P_leaf_uptake - P_woody_uptake - P_Overland_flow - R_P_Surface_applied - P_Containment__basin_outflow) * dt
INIT Root_zone_P = G_Soil_P_storage_in_mg_per_tree/10

INFLOWS:
P_to_root = ((P_g_of_solid_P_per_plant*1000)*.4324)+(F_mg_fertigation_P_per_application+(P_g_of_liquid_P_per_plant*1000)*.4324)
P_plant_available = PULSE ((((P_g_incorporated_per_plant*1000)*.4324)/G_Number_of_weeks_in_growing_year), 0,1)

OUTFLOWS:
P_to_root_zone = IF (Root_zone_P>G_Soil_P_storage_in_mg_per_tree) THEN (Root_zone_P-G_Soil_P_storage_in_mg_per_tree) ELSE (0)

R_P_Surface_water = IF (R_Presence_of_erosion=1) THEN
((P_to_root*R_Erosion_factor)-
(P_Containment__basin_outflow+P_Overland_flow+R_P_Surface_applied)) ELSE (0)
P_leaf_uptake = GRAPH(TIME)
(0.00, 120), (4.00, 120), (8.00, 120), (12.0, 120), (16.0, 10.0), (20.0, 5.00), (24.0, 5.00),
(28.0, 2.50), (32.0, 2.50), (36.0, 0.00), (40.0, 0.00)
P_woody_uptake = GRAPH(TIME)
(0.00, 5.00), (4.00, 5.00), (8.00, 5.00), (12.0, 2.50), (16.0, 2.50), (20.0, 5.00), (24.0, 5.00),
(28.0, 36.0), (32.0, 36.0), (36.0, 36.0), (40.0, 36.0)
P_Overland_flow = IF (R_Presence_of_Containment_basin=1) THEN
((P_to_root*R_Erosion_factor)*.9) ELSE (0)
R_P_Surface_applied = If (R_Presence_of_in_row_buffer=1) THEN
(R_In_row_sediment_trapping*(P_to_root*R_Erosion_factor)) ELSE (0)
P_Containment__basin_outflow = IF (R_presence_of_vegetative_buffer=1) THEN
(R_Sediment_trapping*(R_Erosion_factor*P_to_root)) ELSE (0)
R_N_Containment__basin_accumulation(t) = R_N_Containment__basin_accumulation(t
- dt) + (R_N_containment_basin) * dt
INIT R_N_Containment__basin_accumulation = 0

INFLOWS:
R_N_containment_basin = IF (R_Presence_of_Containment_basin=1)THEN
((N_to_Plant*(R_Erosion_factor))*.5) ELSE (0)
R_N_in_row_buffer__accumulation(t) = R_N_in_row_buffer__accumulation(t - dt) +
(R_N_in_row_buffer) * dt
INIT R_N_in_row_buffer__accumulation = 0
INFLOWS:
R_N_in_row_buffer = IF (R_Presence_of_in_row_buffer=1) THEN
((N_to_Plant*(R_Erosion_factor/2))*R_In_row_sediment_trapping) ELSE (0)
R_N_veg_buffer__accumulation(t) = R_N_veg_buffer__accumulation(t - dt) +
(R_N_Vegetative_Buffer) * dt
INIT R_N_veg_buffer__accumulation = 0

INFLOWS:
R_N_Vegetative_Buffer = IF (R_presence_of_vegetative_buffer=1) THEN
(R_Sediment_trapping*(N_to_Plant*(R_Erosion_factor/2))) ELSE 0
R_P_containment_basin_accumulation(t) = R_P_containment_basin_accumulation(t - dt)
+ (P_Overland_flow) * dt
INIT R_P_containment_basin_accumulation = 0

INFLOWS:
P_Overland_flow = IF (R_Presence_of_Containment_basin=1) THEN ((P_to_root*R_Erosion_factor)*.9) ELSE (0)
R_P_in_row_buffer_accumulation(t) = R_P_in_row_buffer_accumulation(t - dt) + (R_P_Surface_applied) * dt
INIT R_P_in_row_buffer_accumulation = 0

INFLOWS:
R_P_Surface_applied = If (R_Presence_of_in_row_buffer=1) THEN (R_In_row_sediment_trapping*(P_to_root*R_Erosion_factor)) ELSE (0)
R_P_surface_water_accumulation(t) = R_P_surface_water_accumulation(t - dt) + (R_P_Surface_water) * dt
INIT R_P_surface_water_accumulation = 0

INFLOWS:
R_P_Surface_water = IF (R_Presence_of_erosion=1) THEN ((P_to_root*R_Erosion_factor)-(P_Containment__basin_outflow+P_Overland_flow+R_P_Surface_applied)) ELSE (0)
R_P_veg_buffer_accumulation(t) = R_P_veg_buffer_accumulation(t - dt) + (P_Containment__basin_outflow) * dt
INIT R_P_veg_buffer_accumulation = 0

INFLOWS:
P_Containment__basin_outflow = IF (R_presence_of_vegetative_buffer=1) THEN (R_Sediment_trapping*(R_Erosion_factor*P_to_root)) ELSE (0)
Water__runoff_accumulation(t) = Water__runoff_accumulation(t - dt) + (Water_Leaching) * dt
INIT Water__runoff_accumulation = 0

INFLOWS:
Water_Leaching = W_OH_water_runoff_per_application+(((((W_Acre_inches_runoff_per_storm/12)*(G_management_unit_size_in_acres*43560))/G_Number_of_plants_in_MU)*7.480519)*3.785412)
Water_in_soil(t) = Water_in_soil(t - dt) + (W_Liters_applied - W_Evapotranspiration - W_Soil_water) * dt
INIT Water_in_soil = .10

INFLOWS:
W_Liters_applied =
W_OH_Irrigation_per_plant+W_Liters_per_plant_per_storm+W_drip_irrigation_L_per_application+W_drip_fertigations_L_per_application

OUTFLOWS:
W_Evapotranspiration =
((W_Crop_factor_Kc*((W_Evapotranspiration_ETo/10)*7))*((PI*((Diameter_of_canopy_in_feet/2)^2))*929.0304))/1000
W_Soil_water = IF (Water_in_soil>W_Soil_water_volume_in_L) THEN (Water_in_soil-W_Soil_water_volume_in_L) ELSE (0)
Water_moving_through_soil_profile(t) = Water_moving_through_soil_profile(t - dt) + (W_Soil_water - Water_past_root_zone) * dt
INIT Water_moving_through_soil_profile = 0
TRANSIT TIME = 2
INFLOW LIMIT = INF
CAPACITY = INF

INFLOWS:
W_Soil_water = IF (Water_in_soil>W_Soil_water_volume_in_L) THEN (Water_in_soil-W_Soil_water_volume_in_L) ELSE (0)

OUTFLOWS:
Water_past_root_zone = CONVEYOR OUTFLOW
W_Accumulated_leached_water(t) = W_Accumulated_leached_water(t - dt) + (Water_past_root_zone) * dt
INIT W_Accumulated_leached_water = 0

INFLOWS:
Water_past_root_zone = CONVEYOR OUTFLOW
W_ET_loss(t) = W_ET_loss(t - dt) + (W_Evapotranspiration) * dt
INIT W_ET_loss = 0

INFLOWS:
W_Evapotranspiration =
((W_Crop_factor_Kc*((W_Evapotranspiration_ETo/10)*7))*((PI*((Diameter_of_canopy_in_feet/2)^2))*929.0304))/1000
Avg_slope_of_MU = 4
Banding_efficiency = .9
Denitrification_rate_in_mg_per_sqM_per_week = GRAPH(TIME)

(0.00, 100), (4.00, 100), (8.00, 150), (12.0, 150), (16.0, 200), (20.0, 200), (24.0, 250), (28.0, 250), (32.0, 250), (36.0, 200), (40.0, 200)
Depth_of_rootzone_in_feet = GRAPH(TIME)
(0.00, 0.8), (4.00, 0.8), (8.00, 0.8), (12.0, 0.8), (16.0, 0.8), (20.0, 0.8), (24.0, 0.8), (28.0, 0.8), (32.0, 0.8), (36.0, 0.8), (40.0, 0.8)
Diameter_of_canopy_in_feet = GRAPH(TIME)
(0.00, 1.00), (4.00, 1.00), (8.00, 1.00), (12.0, 1.00), (16.0, 1.00), (20.0, 1.00), (24.0, 1.00), (28.0, 1.00), (32.0, 1.00), (36.0, 1.00), (40.0, 1.00)
Diameter_of_rootzone_in_feet = GRAPH(TIME)
(0.00, 0.5), (4.00, 0.5), (8.00, 0.5), (12.0, 0.6), (16.0, 0.6), (20.0, 0.6), (24.0, 0.7), (28.0, 0.7), (32.0, 0.8), (36.0, 0.8), (40.0, 0.8)
F_Incorporated_fertilizer_cost_per_pound = 0.1
F_liquid_fertilizer_cost_per_pound = 1
F_mg_fertigation_N_per_application = PULSE ((W_drip_fertigation_L_per_application*F_PPM_or_mg_per_L_fertigation), 0, (4/F_number_of_liquid_fertigations_per_month))
F_mg_fertigation_P_per_application = IF (F_number_of_liquid_fertigations_per_month>0) THEN (PULSE ((F_PPM_or_mg_per_L_fertigation*(P_Liquid_fertilizer_percent_P/N_Liquid_fertilizer_percent_N))*W_drip_fertigation_L_per_application, 0, (4/F_number_of_liquid_fertigations_per_month))) ELSE (0)
F_number_of_liquid_fertigations_per_month = GRAPH(TIME)
(0.00, 2.00), (4.00, 1.00), (8.00, 1.00), (12.0, 0.00), (16.0, 0.00), (20.0, 1.00), (24.0, 2.00), (28.0, 2.00), (32.0, 1.00), (36.0, 0.00), (40.0, 0.00)
F_Pounds_of_incorporated_fertilizer = 200
F_Pounds_of_liquid_fertilizer_for_MU_per_application = 0
F_Pounds_of_solid_fert_applied_to_MU_per_application = 50
F_PPM_or_mg_per_L_fertigation = 0
F_solid_fertilizer_applications_per_month = GRAPH(TIME)
(0.00, 0.00), (4.00, 1.00), (8.00, 0.00), (12.0, 1.00), (16.0, 0.00), (20.0, 0.00), (24.0, 0.00), (28.0, 0.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
F_Solid_fertilizer_cost_per_pound = 0.25
G_Fertilizer_area = (M_In_row_spacing_in_feet*(M_Between_row_spacing_in_feet-M_Width_of_vegetative_buffer_between_rows))
G_management_unit_size_in_acres = 1
G_Number_of_plants_in_MU = 890
G_Number_of_weeks_in_growing_year = 40
g_of_solid_N_per_plant = PULSE ((((F_Pounds_of_solid_fert_applied_to_MU_per_application*(N_Solid_fertilizer_percent_N/100))/ G_Number_of_plants_in_MU)*453.5924), 0, IF

(4/F_solid_fertilizer_applications_per_month<.001) THEN (0) ELSE (4/F_solid_fertilizer_applications_per_month))
G_Soil_P_storage_in_lbs_per_tree = P_soil_storage_in_lbs_per_acre*((M_Between_row_spacing_in_feet*M_In_row_spacing_in_feet)/43560)
G_Soil_P_storage_in_mg_per_tree = G_Soil_P_storage_in_lbs_per_tree*453592.4
Infiltration_Clay = GRAPH(TIME)
(0.00, 0.8), (0.003, 0.155), (0.006, 0.115), (0.009, 0.1), (0.012, 0.1), (0.015, 0.075), (0.018, 0.05)
Infiltration_loamy_clay = GRAPH(TIME)
(0.00, 1.50), (0.003, 0.9), (0.006, 0.75), (0.009, 0.75), (0.012, 0.75), (0.015, 0.7), (0.018, 0.7)
Infirltration_sandy_loam = GRAPH(TIME)
(0.00, 2.00), (0.003, 1.50), (0.006, 1.40), (0.009, 1.40), (0.012, 1.40), (0.015, 1.40), (0.018, 1.40)
In_row_denitrification = (((G_Fertilizer_area*(Denitrification_rate_in_mg_per_sqM_per_week/10.76391))*Soil_water_saturation_percent)*Temperature_effect_of_soil) *(N_in_Root__zone/N_Soil_storage_in_mg_per_tree)
Linear_feet_of_MU = (G_management_unit_size_in_acres*43560)/M_Between_row_spacing_in_feet
M_Between_row_spacing_in_feet = 7
M_In_row_spacing_in_feet = 7
M_Percent_MU_harvested_per_year = 20
M_Width_of_vegetative_buffer_between_rows = 4
N_Cost_of_N_fertilizer_per_week = (((N_g_incorporated_per_plant/(N_Percent_N_incorporated_fert/100))/453.5924*F_Incorporated_fertilizer_cost_per_pound)+(((N_g_of_liquid_N_per_plant/(N_Liquid_fertilizer_percent_N/100))/453.5924)+(((F_mg_fertigation_N_per_application/(N_Liquid_fertilizer_percent_N/100))/453592.4))*F_liquid_fertilizer_cost_per_pound)+((g_of_solid_N_per_plant/(N_Solid_fertilizer_percent_N/100))/453.5924*F_Solid_fertilizer_cost_per_pound))*G_Number_of_plants_in_MU
N_g_incorporated_per_plant = ((((F_Pounds_of_incorporated_fertilizer*453.6)*(N_Percent_N_incorporated_fert/100))*(M_Percent_MU_harvested_per_year/100))/G_Number_of_plants_in_MU)
N_g_of_liquid_N_per_plant = IF (F_number_of_liquid_fertigations_per_month>0) THEN (PULSE ((((F_Pounds_of_liquid_fertilizer_for_MU_per_application*453.5924)*(N_Liquid_fertilizer_percent_N/100))/G_Number_of_plants_in_MU),0,(4/F_number_of_liquid_fertigations_per_month))) ELSE (0)

N_lbs_of_fert_per_week =
G_management_unit_size_in_acres*N_lbs_per_acre_per_week
N_lbs_per_acre_per_week =
((((g_of_solid_N_per_plant+N_g_incorporated_per_plant+N_g_of_liquid_N_per_plant)/453.5924)+(F_mg_fertigation_N_per_application/453592.4))*G_Number_of_plants_in_MU)/G_management_unit_size_in_acres
N_Liquid_fertilizer_percent_N = 20
N_Percent_N_incorporated_fert = 2
N_Soil_storage_in_lbs_per_acre = 50
N_Soil_storage_in_lbs_per_tree =
N_Soil_storage_in_lbs_per_acre*(G_Fertilizer_area/43560)
N_Soil_storage_in_mg_per_tree = N_Soil_storage_in_lbs_per_tree*453592.4
N_Solid_fertilizer_percent_N = 20
P_g_incorporated_per_plant =
((F_Pounds_of_incorporated_fertilizer*453.6)*(P_Percent_P_incorporated_fert/100))*(M_Percent_MU_harvested_per_year/100)/G_Number_of_plants_in_MU
P_g_of_liquid_P_per_plant = IF (F_number_of_liquid_fertigations_per_month>0) THEN (PULSE (((F_Pounds_of_liquid_fertilizer_for_MU_per_application*(P_Liquid_fertilizer_percent_P*.01))*453.5924)/G_Number_of_plants_in_MU, 0, (4/F_number_of_liquid_fertigations_per_month))) ELSE (0)
P_g_of_solid_P_per_plant = IF (F_solid_fertilizer_applications_per_month>0) THEN (PULSE ((((P_Solid_fertilizer_percent_P*.01)*(F_Pounds_of_solid_fert_applied_to_MU_per_application*453.5924))/G_Number_of_plants_in_MU), 0, (4/F_solid_fertilizer_applications_per_month))) ELSE (0)
P_lbs_of_fertilizer_per_week =
P_lb_per_acre_per_week*G_management_unit_size_in_acres
P_lb_per_acre_per_week =
((((P_g_of_liquid_P_per_plant+P_g_of_solid_P_per_plant+P_g_incorporated_per_plant)/453.5924)+(F_mg_fertigation_P_per_application/453592.4))*G_Number_of_plants_in_MU)/G_management_unit_size_in_acres
P_Liquid_fertilizer_percent_P = 20
P_Percent_P_incorporated_fert = 5
P_soil_storage_in_lbs_per_acre = 50
P_Solid_fertilizer_percent_P = 20
Radius_of_throw_in_feet = 80
rainfall__volume = 200

Root_volume_in_Liters =
(((4/3)*PI*((Diameter_of_rootzone_in_feet/2)^2)*(Depth_of_rootzone_in_feet))/2)*28.31685
R_Buffer_width_in_feet = 50
R_Erosion_factor = 0.15
R_In_row_sediment_trapping =
(53.77+(1.58*(M_Width_of_vegetative_buffer_between_rows*0.3048))+(5.67*R_Slope_percent_of_MU)-(.314*(R_Slope_percent_of_MU^2)))/100
R_Presence_of_erosion = 1
R_Presence_of_Containment_basin = 0
R_Presence_of_in_row_buffer = 1
R_presence_of_vegetative_buffer = 1
R_Sediment_trapping =
(53.77+(1.58*(R_Buffer_width_in_feet*0.3048))+(5.67*R_Slope_percent_of_buffer)-(.314*(R_Slope_percent_of_buffer^2)))/100
R_Slope_percent_of_buffer = 3
R_Slope_percent_of_MU = 3
Soil_P_storage__capacity_per_L = 200
Soil_water_saturation_percent = GRAPH(TIME)
(0.00, 1.00), (4.00, 0.9), (8.00, 0.8), (12.0, 0.7), (16.0, 0.6), (20.0, 0.5), (24.0, 0.5), (28.0, 0.6), (32.0, 0.6), (36.0, 0.7), (40.0, 0.7)
Temperature_effect_of_soil = GRAPH(TIME)
(0.00, 0.7), (4.00, 0.8), (8.00, 0.9), (12.0, 1.20), (16.0, 1.50), (20.0, 1.60), (24.0, 1.60), (28.0, 1.50), (32.0, 1.10), (36.0, 0.8), (40.0, 0.8)
width_of_root_area = 3
Width_of_fertilizer__application_in_feet = 3
WOH_irrigations_per_month = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 2.00), (12.0, 3.00), (16.0, 4.00), (20.0, 4.00), (24.0, 2.00), (28.0, 2.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
W_acre_inches_infiltration_per_storm = (W_rainfall_infiltration_in_cm*.3937008)
W_Acre_inches_runoff_per_storm = W_Rainfall_runoff_water*0.3937008
W_avg_rainfall_amount_in_cm_per_week = GRAPH(TIME)
(0.00, 0.00), (5.20, 0.5), (10.4, 1.75), (15.6, 0.00), (20.8, 0.00), (26.0, 0.225), (31.2, 0.3), (36.4, 0.1), (41.6, 0.375), (46.8, 0.35), (52.0, 0.35)
W_Avg_rainfall_intensity__in_cm_per_hr = .75
W_Crop_factor_Kc = 0.3
W_drip_distance_between_emitters_in_feet = 2
W_drip_fertigation_L_per_application =
((W_Drip_liters_per_hour_per_emitter*(Linear_feet_of_MU/W_drip_distance_between_

emitters_in_feet)*(W_Drip_min_of_fertigation_per_application/60))/G_Number_of_plants_in_MU)
W_drip_fertigations_L_per_application = IF
(F_number_of_liquid_fertigations_per_month>0) THEN
(PULSE(((W_Drip_liters_per_hour_per_emitter*(Linear_feet_of_MU/W_drip_distance_between_emitters_in_feet)*(W_Drip_min_of_fertigation_per_application/60))/G_Number_of_plants_in_MU)
,0,(4/F_number_of_liquid_fertigations_per_month))) ELSE (0)
W_drip_irrigation_L_per_application = IF (W_Irrigations_per_month_drip>0) THEN
(PULSE(((W_Drip_liters_per_hour_per_emitter*(Linear_feet_of_MU/W_drip_distance_between_emitters_in_feet)*(W_Drip_min_of_irrigation_per_application/60))/G_Number_of_plants_in_MU),0,1/(4/W_Irrigations_per_month_drip))) ELSE (0)
W_Drip_liters_per_hour_per_emitter = 10
W_Drip_min_of_fertigation_per_application = GRAPH(TIME)
(0.00, 60.0), (4.00, 60.0), (8.00, 60.0), (12.0, 60.0), (16.0, 60.0), (20.0, 60.0), (24.0, 60.0), (28.0, 60.0), (32.0, 60.0), (36.0, 60.0), (40.0, 60.0)
W_Drip_min_of_irrigation_per_application = GRAPH(TIME)
(0.00, 240), (4.00, 240), (8.00, 240), (12.0, 240), (16.0, 240), (20.0, 240), (24.0, 240), (28.0, 240), (32.0, 240), (36.0, 240), (40.0, 240)
W_Evapotranspiration_ETo = GRAPH(TIME)
(0.00, 1.90), (4.00, 3.00), (8.00, 4.25), (12.0, 4.75), (16.0, 5.75), (20.0, 6.00), (24.0, 5.00), (28.0, 4.10), (32.0, 2.90), (36.0, 2.10), (40.0, 2.10)
W_Infiltration_rate_in_cm_per_hr = .6
W_Irrigations_per_month_drip = GRAPH(TIME)
(0.00, 1.00), (4.00, 2.00), (8.00, 3.00), (12.0, 5.00), (16.0, 6.00), (20.0, 6.00), (24.0, 4.00), (28.0, 2.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
W_Liters_per_plant_per_storm =
((((W_acre_inches_infiltration_per_storm/12)*(PI*((Diameter_of_rootzone_in_feet/2)^2))*7.480519)*3.785412))
W_OH_Coefficient_of_uniformity = 0.7
W_OH_emitters_per_MU = 50
W_OH_Irrigation_per_plant = IF
(W_OH_water_application_rate_in_cm_per_hr<W_Infiltration_rate_in_cm_per_hr)
THEN (PULSE
((((W_OH_liters_per_minute_per_emitter*W_OH_emitters_per_MU*W_OH_min_per_run_for_MU)*W_OH_Coefficient_of_uniformity)/(G_Number_of_plants_in_MU)),0,(1/(WOH_irrigations_per_month/4)))) ELSE (PULSE
(((((W_OH_liters_per_minute_per_emitter*W_OH_emitters_per_MU*W_OH_min_per_run_for_MU)*(W_Infiltration_rate_in_cm_per_hr/W_OH_water_application_rate_in_cm

_per_hr))*W_OH_Coefficient_of_uniformity)/(G_Number_of_plants_in_MU)),0,(1/(W
OH_irrigations_per_month/4))))
W_OH_liters_per_minute_per_emitter = 10
W_OH_min_per_run_for_MU = GRAPH(TIME)
(0.00, 0.00), (4.00, 0.00), (8.00, 120), (12.0, 240), (16.0, 240), (20.0, 120), (24.0, 120), (28.0, 0.00), (32.0, 0.00), (36.0, 0.00), (40.0, 0.00)
W_OH_water_application_rate_in_cm_per_hr =
((((W_OH_min_per_run_for_MU*W_OH_liters_per_minute_per_emitter)*W_OH_emitters_per_MU)*1000)/(G_management_unit_size_in_acres*(4.046856*10^7)))/(W_OH_min_per_run_for_MU/60)
W_OH_water_runoff_per_application =
IF(W_OH_water_application_rate_in_cm_per_hr>W_Infiltration_rate_in_cm_per_hr) THEN ((((W_OH_water_application_rate_in_cm_per_hr-W_Infiltration_rate_in_cm_per_hr)*(W_OH_min_per_run_for_MU/60))*(G_management_unit_size_in_acres*(4.046856*10^7))/1000)+((1-W_OH_Coefficient_of_uniformity)*W_OH_Irrigation_per_plant)) ELSE (0)
W_rainfall_infiltration_in_cm = IF
(W_Infiltration_rate_in_cm_per_hr>W_Avg_rainfall_intensity__in_cm_per_hr) THEN (W_Avg_rainfall_intensity__in_cm_per_hr*W_rainfall_duration) ELSE (W_Infiltration_rate_in_cm_per_hr*W_rainfall_duration)
W_Rainfall_runoff_water = PULSE (IF
(W_Avg_rainfall_intensity__in_cm_per_hr<W_Infiltration_rate_in_cm_per_hr) THEN (0) ELSE ((W_Avg_rainfall_intensity__in_cm_per_hr-W_Infiltration_rate_in_cm_per_hr)*W_rainfall_duration), 0,
4/W_rainfall_events_per_month)

W_rainfall_duration = IF (W_rainfall_events_per_month>0) THEN ((W_avg_rainfall_amount_in_cm_per_week/W_rainfall_events_per_month)/W_Avg_rainfall_intensity__in_cm_per_hr) ELSE (0)
W_rainfall_events_per_month = IF (ROUND (NORMAL (5,2, 300))>.5) THEN (ROUND (NORMAL (5,2, 300))) ELSE (1)
W_Soil_water_holding_capacity_per_L = .3
W_Soil_water_volume_in_L =
Root_volume_in_LIters*W_Soil_water_holding_capacity_per_L

Table F 6.1. Graphical parameters for calibration using data from Lea-Cox et al. (2001).

Week	Denitrification rate (mg/m^2/ day)	Temperature effect	Fetigations/ month	Min/ fertigation
0	100	0.7	3	60
4	100	0.8	3	60
8	150	0.9	3	60
12	150	1.2	3	60
16	200	1.5	3	60
20	200	1.6	3	60
24	250	1.6	3	60
28	250	1.5	3	60
32	250	1.1	3	60
36	200	0.8	3	60
40	200	0.7	3	60

Table F 6.2. Graphical parameters for calibration run using data from Lea-Cox et al. (2001).

Week	Soil saturation (%)	irrigations per month	Irrigation (min)	Root diameter (ft)	Root depth (ft)	Canopy diameter (ft)
0	1	8	120	8	0.7	12
4	0.9	8	120	8	0.7	12.5
8	0.8	8	180	8	0.7	13
12	0.7	8	180	8.5	0.8	13
16	0.6	8	240	8.5	0.8	13
20	0.5	8	240	8.5	0.8	13
24	0.5	8	240	9	0.9	13
28	0.6	8	180	9.5	0.9	14
32	0.6	8	180	9.5	1	14
36	0.7	8	120	10	1	14
40	0.7	8	120	10	1	14

Table F 6.3. Graphical parameters for calibration run for leaf and woody N and P uptake rates in mg/week, using data from Lea-Cox et al. (2001).

Week	Leaf N uptake (mg)	Woody N uptake (mg)	Leaf P uptake (mg)	Woody P uptake (mg)
0	1200	50	120	5
4	1200	50	120	5
8	1200	50	120	5
12	1200	25	120	2.5
16	100	25	10	2.5
20	50	50	5	5
24	50	50	5	5
28	25	360	2.5	36
32	25	360	2.5	36
36	0	360	0	36
40	0	360	0	36

Table F 6.4. Constant values for field model what if scenarios.

Variable	Value
G management unit size in acres	1
G Number of plants in MU	890
G Number of weeks in growing year	40
M In row spacing in feet	7
M between row spacing in feet	7
M Width of vegetative buffer between rows	4
R Slope percent of MU	3
W Drip distance between emitters in feet	2
W Drip liters per hour per emitter	10
W OH emitters per MU	0
W OH Coefficient of uniformity	0.9
W OH liters per minute per emitter	0
N Percent N incorporated fert	2
P Percent P incorporated fert	5
F Pounds of incorporated fertilizer	200
M Percent MU harvested per year	20
F Incorporated fertilizer cost per pound	0.1
N Solid fertilizer percent N	20
P Solid fertilizer percent P	20
F Solid fertilizer cost per pound	0.25
F Pounds of solid fert applied to MU per application	50
N Liquid fertilizer percent N	20
P Liquid fertilizer percent P	20
F Pounds of liquid fertilizer for MU per application	0
F liquid fertilizer cost per pound	1
F PPM or mg per L fertigation	0
R Buffer width in feet	50
R Slope percent of buffer	3
R Erosion factor	0.15
N Soil storage in lbs per acre	50
P soil storage in lbs per acre	50
presence of	
Erosion	Y
in row buffer	N
end of row buffer	N
containment basin	N

Table F 6.5. Graphical values for field model what if scenarios. Plant uptake rates were ½ the values used for the Lea-Cox et al. (2001) dataset to represent immature trees.

N leaf uptake (mg)	N woody uptake (mg)	P leaf uptake (mg)	P woody uptake (mg)
600	25	30	2
600	25	30	2
600	25	30	1
600	15	30	1
50	10	4	1
25	25	2	1
25	25	2	2
15	180	1	9
10	180	0.5	9
0	180	0	9
0	180	0	9

Table F 6.6. Graphical values for field model what if scenarios.

Denitrification rate	Temperature effect	Fertigations per month	min per fertigation
100	0.35	0	60
100	0.55	0	60
150	0.75	0	60
150	1.05	0	60
200	1.3	0	60
200	1.45	0	60
250	1	0	60
250	0.7	0	60
250	0.55	0	60
200	0.25	0	60
200	0.25	0	60

Table F 6.7. Graphical values for field model what if scenarios.

soil saturation percent	irrigations per month	min per irrigation
1	0	0
0.9	0	0
0.8	0	0
0.7	8	60
0.6	8	60
0.5	8	60
0.5	8	60
0.6	8	60
0.6	0	0
0.7	0	0
0.7	0	0

Table F 6.8. Graphical values for field model what if scenarios.

Root Diameter (feet)	**Root depth (feet)**	**Diameter of canopy (feet)**	**Solid fertilizer applications per month**
4.0	0.7	4	1
4.0	0.7	4	1
4.5	0.7	4.5	0
4.5	0.8	4.5	0
5.0	0.8	5.0	0
5.0	0.8	5.0	0
5.0	0.9	5.0	1
5.0	0.9	5.0	1
5.5	1.0	5.5	0
5.5	1.0	5.5	0
5.5	1.0	5.5	0

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