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Poultry litter ash as a phosphorus source for greenhouse crop production

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POULTRY LITTER ASH AS A PHOSPHORUS SOURCE FOR GREENHOUSE CROP PRODUCTION

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ABSTRACT

Phosphorus (P) is an essential nutrient for all life forms, including plants, but is a limited agricultural resource whose future availability is in question. Therefore, identification of alternative forms of P fertilizers is important. Poultry litter ash (PLA), a byproduct of bioenergy production, contains high concentrations of P comparable to conventional fertilizers. Forms of P contained in PLA have been characterized as having low water solubility. Nutrient losses during containerized plant production are high due to excessive inputs of water and nutrients and low nutrient sorption capacities of common horticultural substrate components. Environmental concerns over reduced water quality intensify this problem. Use of low soluble P sources has been recommended as a potential means of reducing P losses. Experiments were conducted to determine effects of PLA application on growth, quality, and nutrient uptake of two greenhouse crops (*Verbena canadensis* Britton 'Homestead Purple' and *Lantana camara* L.'New Gold'), substrate chemical properties, and P losses during greenhouse crop production. In the first experiment, substrate leachate-pH increased 25% when PLA was applied instead of superphosphate (SP). Foliar P concentrations of verbena and lantana also increased 27 and 62%, respectively. Application of PLA did not reduce biomass of verbena or lantana. In a subsequent experiment, leachate-dissolved reactive phosphorus (DRP) and effluent-total phosphorus (TP) concentrations were reduced >92% and 69%, respectively, through PLA application, however, plant growth and landscape establishment was not deleteriously affected. Water solubility of PLA-P decreased markedly as combustion temperature increased. Finally, in a third experiment, concentrations of DRP were reduced 24% through reduction of PLA rate, but were reduced 134% when PLA was topdressed instead of incorporated. Plant quality was improved with PLA incorporation. These results indicate that, while P loss reduction can be achieved through PLA application, lower substrate P concentrations do not necessarily reduce plant growth or quality.

CHAPTER 1: LITERATURE REVIEW

Global and Domestic Phosphorus Supply

Phosphorus (P) is the eleventh most abundant element in the earth's crust (Mengel and Kirkby, 1987) and is essential for all life forms, including plants (Smil, 2000). Historic P fertilizer sources have been animal manure (Cordell et al., 2009), other animal byproducts, and superphosphate derived from ground animal bones treated with sulfuric acid (Wines, 1985). The superphosphate fertilizers that were manufactured from animal bones were generally low analysis and low quality products. Nitrogen was introduced to the soil system through animal manures, but P and potassium were simply recycled. Potassium was not typically a limiting nutrient in the soil, but P was. A higher quality P fertilizer was needed (Mikkelsen and Bruulsema, 2005).

In 1867, a solution was identified when phosphate rock deposits were discovered and mined in South Carolina. The phosphate rock contained P in high concentrations that could easily be converted into superphosphate using existing technologies (Wines, 1985). Deposits have since been discovered and mined in other locations throughout the United States including Florida, North Carolina, Idaho, and Tennessee. Soluble phosphate fertilizers are processed and recovered from these phosphate-rich ores (Mikkelsen and Bruulsema, 2005). However, mined phosphate rock is a finite, non-renewable resource (Cordell, 2009).

Moroccan phosphate reserves are the largest globally and account for an estimated 75% of world total reserves (USGS, 2013). The highest producer of phosphate rock is China, followed by the United States and Morocco. Although over 30 countries are currently producing phosphate rock, more than two-thirds of the supply is produced in those three countries.

Phosphate reserves are defined by the U.S. Bureau of Mines and United States Geological Survey (USGS) as deposits that can be economically extracted with current mining practices. For example, in 1998 the USGS defined phosphate reserves as those retrievable at a cost below $35 per ton (Steen, 1998). Likewise, in 2001, phosphate reserves were defined as those extractable for $40 per ton or less (McClellan and Van Kauwenbergh, 2004). As opposed to reserves, resources are defined as reserves plus all other deposits that may be accessed at some point in the future. The reserve base is the part of an identified resource that meets minimum physical and chemical criteria (Roberts and Stewart, 2002).

Calculations of total global phosphate reserves and reserve base are complicated due to many rapidly changing variables. It is generally agreed upon that, at current production levels, global commercial phosphate reserves will last approximately 50-100 years (Cordell et al., 2009). At current production levels, the United States' phosphate ore reserves will last less than 20 years (Roberts and Stewart, 2002). However, since the definition of reserves is based on economics, the time frame could change. The estimated phosphate ore reserve base life of the United States is nearly 100 years, while the global reserve base life is estimated at over 300 years (Roberts and Stewart, 2002). Phosphate resources have been identified on the Atlantic and Pacific continental shelves, but these resources cannot be harvested using current technologies (USGS, 2006).

While the life expectancy of global and domestic phosphate reserves and resources are debatable, the notion that the quality of mined phosphate rock is declining seems to be the consensus (Cordell, 2009; Roberts and Stewart, 2002; Smil, 2000; Steen, 1998). While some phosphate rocks, such as Moroccan reserves, are characterized as high-quality ores, other phosphate rock producers, such as China, are known to produce lower quality phosphate rock (Personal communication, Lucina Lampila, Ph.D., R.D.). When considering the projected phosphate rock shortage and current reduction in quality, it is apparent that discovery and development of renewable, high quality P fertilizer sources is and will continue to be an important endeavor.

Agricultural Applications of Poultry Litter and Associated Concerns

Poultry litter is a biomass source consisting mostly of bird manure and bedding materials (Robinson and Sharpley, 1996) and is a waste product of poultry production. The bedding materials that are typically used include straw, sawdust, wood shavings, shredded paper, peanut hulls, and rice hulls (Kelleher et al., 2002). Poultry litter is in great abundance in several areas of the United States, including the southeast. It contains comparable amounts of nitrogen to ruminant wastes, but often contains higher concentrations of P, since fowls do not share ruminant animals' ability to extract organically bound-P from feeds (Sommers and Sutton, 1980).

Composted poultry litter has been used as a soil amendment and as a substrate amendment in horticultural production (Marble et al., 2010). However, composting takes space and time which limits the application of some composted products. Poultry litter, in its raw form, has been utilized in field and container nursery production. Field applications have been successful, but pasteurization of poultry litter is necessary before usage in container production and problems, such as high rates of P leaching still exist (Broschat, 2008).

While poultry litter has been successfully used in several agricultural fields, its predominant usage, due to its relative low cost and abundance (Jia and Anthony, 2011), is as a soil amendment and fertilizer for agronomic crops and pastures. However, high transportation costs due to the low bulk density of poultry litter (Bernhart et al., 2010) limit the geographical area available for its use as a fertilizer, which has led to environmental concerns associated with agricultural applications of poultry litter.

The primary environmental concern associated with poultry litter is surface and ground water impairment. Years of land application of poultry litter on a nitrogen basis, in relatively small geographical areas, has led to an accumulation of P in soils of poultry producing areas (Maguire and Mullins, 2008). Runoff of P into surface waters has led to accelerated eutrophication of these waters (White et al., 2010).

Nitrogen and P introduction into fresh water systems via surface runoff events has been linked with water quality problems. However, P is often the limiting nutrient in aquatic systems and when it is introduced to these systems, especially as orthophosphate, algae and cyanobacteria, whose growth may have been previously limited, can grow and multiply quickly. This rapid population growth can lead to anoxic or hypoxic conditions which can result in loss of aquatic life. Point sources of P introduction into aquatic systems have been successfully reduced in many cases, but non point sources are much more difficult to identify and limit (Correll, 1998). Sediment runoff from agricultural areas is one potential non-point source of P introduction into aquatic systems.

Nitrates from the poultry litter may also leach into groundwater supplies, raising questions about drinking water safety and quality (Codling and Isensee, 2005). In its report to Congress in 2004, the USEPA (2009) indicated nutrients as one of the top three causal agents of impairment of lakes, ponds, and reservoirs and also listed agriculture as one of the top three sources of impairment of these surface waters.

Nurseries and commercial greenhouse operations have been identified as potential non point sources of nutrients, including P. However, nutrient loss quantities from nurseries have not been well documented (Mangiafico et al., 2008).

Several potential solutions that seek to concentrate nutrients, in order to reduce transportation costs, and to alleviate environmental concerns associated with agricultural applications of poultry litter have been investigated, such as: compaction (Bernhart et al. 2010) pelletization (McMullen, 2005), composting (Brodie et al., 2000), P removal (Szogi et al. 2008), gasification (Priyadarsan et al. 2004), and combustion (Codling et al., 2002; Shiemenz and Eicler-Lobermann, 2010).

Gasification and combustion of poultry litter have the added benefit of energy production compared to the other concentration processes. However, combustion of poultry litter may be the most efficient means available to alleviate environmental concerns over P associated with the litter since all mineral P remains in the ash resulting from the combustion process.

Combustion of Poultry Litter

Recycling of plant nutrients has become a point of interest due to environmental concerns and questions of future, sustainable mineral ore supplies. Uncertainty of the sustainability of the future supply of global and domestic mined phosphate rock has prompted a search for alternative, sustainable P sources. The use of biomass ashes as a nutrient source is one such proposed strategy (Bachmann and Eichler-Lobermann, 2010).

Burning biomass waste materials as a means of disposal has been practiced for centuries. Ashes from the combustion of the biomass materials have historically been utilized as fertilizer sources (Schiemenz and Eicler-Lobermann, 2010). Carbon and nitrogen are lost in the combustion process leaving high concentrations of inorganic plant nutrients such as P, potassium, calcium, and magnesium.

Combustion, however, has not been the historical method of disposal of poultry litter. In a review article, Edwards and Daniel (1992), described in detail many strategies for poultry litter waste management including anaerobic digestion, composting, and land application, but combustion was not mentioned. The inefficiencies and inconsistencies that have historically been associated with burning poultry litter, along with its value as a soil amendment, were factors that likely led to the exclusion of combustion as a disposal technique. More recently, technological advances and increased environmental concerns over land application of poultry litter, have led to the practice of burning poultry litter as a disposal technique as well as a means of heat and energy production (Codling et al., 2002; Habetz and Echols, 2006).

Poultry litter is a biomass source that has both theoretical and realized potential for energy production via combustion. According to Habetz and Echols (2006), poultry litter is a viable thermal energy source, since the theoretical combustion of poultry litter could sustain an adiabatic flame temperature of approximately 2000 ˚F. Furthermore, Mukhtar et al. (2002) reported the average heating value of poultry litter is around 4100 Btu/lb. Jia and Anthony (2011) reported that co-firing poultry waste with coal in a circulating fluidized bed combustor did not impede heat and energy production. Even though other combustible feedstock sources have higher heating values, poultry litter is still attractive as a thermal energy source due to its relative abundance and low cost. According to Young et al. (2005), average delivery cost of poultry litter per truck delivered across the state of Arkansas in 2005 was less than $1,000.

While the combustion process is more complicated for poultry litter than for most traditional fuel sources due to inconsistency of litter composition and moisture content, and its relatively high ash content (Baranyai and Bradley, 2008), it has become technologically feasible. For example, by retrofitting a common multiple hearth furnace historically used to burn sewage sludge with new air injectors called circle slot jets, Habetz and Echols (2006) demonstrated that poultry litter could be efficiently burned to produce energy. Annamalai et al. (1985) also demonstrated that poultry litter could successfully produce energy via fluidized bed combustion. A related experiment confirmed that, as long as the moisture content of feedstock poultry litter was maintained below 25%, chicken litter could be utilized as the sole feedstock for a fluidized bed combustor (Abelha et al., 2002). Fortunately, the moisture content of poultry litter can be maintained well below 25% by simply covering stockpiles (Ogejo and Collins, 2009). The potential for energy production via combustion of poultry litter is not only experimentally tested, but is also being practiced on a large scale in the United States.

Fibrominn is a power plant in Benson, Minnesota, operated by an alternative energy company called Fibrowatt, LLC, that is currently providing energy for 40,000 homes by producing 55 MW of energy per year through the co-combustion of poultry litter and wood, with poultry litter constituting more that 60% of the furnace feedstock. The resultant ash is utilized as a nutrient-rich fertilizer for agronomic crops in the Benson, Minnesota area. The vast majority of the ash content of the furnace feedstock is generated from the poultry litter, since wood typically has a very low ash content. Misra and others (1993) reported that the ash content of three commonly burned wood species ranged from only 0.43 – 0.87 percent whereas poultry litter is reported to have an ash content from about 15 percent (IPEP, 2006) to 25 percent (Jia and Anthony, 2011).

Fibrowatt has plans to build and operate several more power plants in other high volume poultry producing areas, such as Mississippi, Georgia, Arkansas, and North Carolina. When these future plants become realities, their ash byproduct may be a valuable fertilizer amendment to agricultural industries including nursery and greenhouse production. Furthermore, due to the rising costs of fossil fuels, combustion of biomass materials, including poultry litter, may be an attractive means of space-heating greenhouses. The resultant ash could potentially be used as a fertilizer amendment for the crops being grown in said greenhouses.

Space heating poultry houses with biomass furnaces is a practice that is being actively researched and implemented in the United States. Although other energy production technologies are attractive such as pyrolysis, anaerobic digestion, and gasification, combustion of biomass materials is currently the technology of choice for space heating poultry houses. Feedstocks that have been evaluated include cord wood, corn, wood pellets, pelletized poultry litter, and raw litter. Raw litter is the most attractive of all the feedstocks, but is also the most problematic. Several factors undermining the potential use of raw litter as a sustainable furnace feedstock for space heating applications include high variability of ash content, ash management considerations, furnace emissions concerns, and storage and handling difficulties. However, raw litter is still being actively evaluated for such operations since its theoretical fuel cost is lowest of all proposed feedstocks, including propane (Wimberly, 2008).

Nursery and Greenhouse Fertilization Practices

Nutrients are typically supplied to containerized plants in water-soluble forms. One common method of nutrient application during containerized plant production is fertilization through irrigation, referred to as fertigation. Applying fertilizers through irrigation allows the fertilizers to be supplied in multiple doses, while minimizing labor costs (Mikkelsen and Bruulsema, 2005). Fertigation has also been reported to improve both irrigation and fertilization efficiencies when monitored correctly (Hagin and Lowengart, 1996).

Another popular fertilization practice has been application of slow-release and controlled-release fertilizers (CRFs). The distinguishing trait between slow-release and CRFs is that controlled-release products have release patterns that are predictable based on several different variables, whereas slow-release fertilizers refer to products or substances that release nutrients into soil solution over time, but whose release pattern is less predictable and is much more generalized. CRFs are generally associated with different types of coating materials which, over time, release nutrients into solution. Some CRFs release nutrients due to chemical degradation of their coating materials via microbes, while others release nutrients due to physical parameters, such as temperature and moisture. Slow-release fertilizer dissolution is typically a function of factors such as particle size, soil moisture, pH, and temperature (Shaviv, 2001). While fertilizer management strategies for containerized plant production seek to maximize plant growth and reduce costs, nutrients, especially P, are often over-applied (Silber et al., 2005).

Phosphorus and Soilless Substrates

The fact that P is readily leached from soilless substrates is well documented. In 1984, when soil-based substrates were beginning to be replaced with soilless components, Marconi and Nelson (1984) reported that more than 33% applied P, as superphosphate [(SP) (8.7% P)], was lost from a peat moss (PM):vermiculite (1:1, v:v) substrate over a nine week period. Less than 5% of applied P leached from a sand:soil:PM (1:1:1, v:v:v) substrate in the same amount of time. Their results indicated that soilless substrate components have low P sorption capacities compared with mineral soil. However, more dramatic results were obtained by others.

Yeager and Barrett (1984) reported on the inefficiency of SP as a fertilizer amendment in soilless culture. In their experiment, between 20% and 37% of P, supplied as SP, leached from substrates composed of different combinations of pine bark (PB), PM, and sand in one day. In all substrates, 55% of supplied P had leached by 7 days, while 66-76% of the P had leached by 21 days. It was concluded that SP was an inefficient source of P in substrates composed of PB, PM, and sand. Despite these recommendations, SP is still used as a starter nutrient in commercial substrate mixes (Ku and Hershey, 1997). Incorporation of starter nutrients into soilless substrates during containerized crop production, however, may lead to unnecessary nutrient losses while not improving or only slightly improving plant growth parameters. Therefore, application of starter nutrients should be questioned as a management strategy (Altland and Buamscha, 2008).

Although application of SP to soilless substrates is no longer recommended, research has shown SP is not the only inefficient P source for soilless container production. In an experiment focused on increasing irrigation efficiency in container-grown plant production, Tyler et al.

(1996) reported that P leaching losses were unaffected by P application rates. Although CRFs were used in the experiment, P leaching losses were affected only by leaching fraction. In a similar experiment, it was reported that the concentration of dissolved reactive P (DRP) in effluent from a PB substrate, amended with a CRF, was independent of the rate of applied P (Owen et al., 2008). CRFs are designed to release a steady, constant stream of nutrients into solution (Shaviv and Mikkelson, 1993). However, if P losses from containers amended with CRFs are unaffected by application rate, CRFs may not be efficient P fertilizers.

Phosphorus uptake efficiencies (PUE) in container production are very low (Lea-Cox and Ristvey, 2003), with values as low as 5% reported (Struve, 1995). One proposed strategy to mitigate nutrient losses from container production is to utilize less soluble fertilizer sources (Lea-Cox and Ristvey, 2003).

Historically, water solubility, especially of P sources, was an important criterion in determining fertilizer application rates and effectiveness. However, water solubility is hardly considered anymore since all commercial P fertilizers are water soluble (Mikkelsen and Bruulsema, 2005). Usage of water soluble fertilizer sources may unintentionally lead to over-application of major nutrients such as nitrogen and P, especially when used in soilless culture. Less soluble P sources have not been historically used in nursery and greenhouse crop production because of an assumed reduction of phosphate availability. Horticultural substrates are typically composed of organic, acidic components such as pine bark and peat moss. Given their acidic nature, these substrates may be able to solubilize phosphates originating from low-soluble sources. Most studies, however, have focused on irrigation, as well as, nutrient use efficiencies in agronomic and horticultural systems, as opposed to solubility to mitigate nutrient losses.

According to Zhu et al. (2007), horticultural substrates have relatively low water and nutrient holding capacities due to their soilless properties and high porosities. It was concluded that container production of ornamental plants is often inefficient due to frequent irrigation and fertilizer applications. Lea-Cox and Ristvey (2003) suggested that several inter-related factors were responsible for low nutrient uptake efficiencies of container-grown plants, including plant genetic factors and poor timing and placement of fertilizers during the growing cycle. By simply reducing the amount of nitrogen and P fertilizers added to a greenhouse grown azalea crop, uptake efficiencies of those nutrients were increased. Nitrogen uptake efficiency was improved from 17% to 60% via a 10-fold reduction of a standard nitrogen application rate. Similar results were achieved for P. By reducing the amount of P supplied by 80%, the P uptake efficiency for azaleas was increased from 30% to 68%. Ku and Hershey (1997) also reported that P supplied through fertigation could be reduced from standard concentrations by up to 80% without sacrificing quality or size of a greenhouse-grown poinsettia crop. Shaviv et al. (1999) reported that by combining controlled-release fertilizer incorporation with fertigation practices, nitrogen leachate losses were reduced.

Poultry Litter Ash as a Fertilizer

Few studies have investigated the potential of poultry litter ash (PLA) as a fertilizer amendment. In a laboratory experiment, Codling (2006) reported that poultry litter ash contained high levels of P, but that most of this P was water-insoluble. However, PLA was successfully used as a P source for wheat in a previous pot study (Codling et al., 2002). Faridullah et al. (2009) reported that chicken and duck litter ashes could be used as nutrient sources for Japanese mustard spinach. Other biomass ashes have also been successfully utilized as nutrient sources for agronomic crops (Schiemenz and Eichler-Lobermann, 2010). In an experiment directed primarily toward altering substrate physical properties, Evans et al. (2011)

reported that incorporation of pulp mill ash into a peat-based substrate increased tomato shoot P concentrations, although available P and total P in the ash were only 0.1% and 0.17%, respectively. Phosphorus recovered from poultry litter has been used as the primary source of P for annual ryegrass (Szogi et al., 2010). No literature exists on PLA as a fertilizer amendment in nursery or greenhouse container production. Although PLA-P has been characterized as primarily water-insoluble, plant P uptake may not be wholly dependent on water-solublity of applied P since organic acids (Bolan et al., 1994) and rhizospheric conditions (Hinsinger, 2001) have been reported to affect phosphate species' solubilities.

Leaching is a common practice in the nursery and greenhouse industries because of concerns over potentially hazardous concentrations of salts building up in substrates over time. Greenhouse and nursery substrates, especially those that have been fertigated, are typically leached with water containing no exogenous fertilizer salts often during the growing cycle (Shaviv et al., 1999). Since soilless substrates generally have low nutrient holding capacities (Zhu et al., 2007), the nutrients, including P, contained in the substrate are lost during the leaching process. Rainfall events also leach nutrients from containers that are not covered. The soluble reactive forms of P (SRP) are potentially leached from containers due to these processes and may move offsite.

Experiments conducted to address nutrient loss from nurseries have typically focused on the recapture of lost nutrients or improved cultural practices. Detention basins are one proposed strategy to recapture nutrients lost via leaching and rainfall events from nurseries (Mathers et al., 2005). Mangiafico et al. (2008) assessed the effectiveness and feasibility of constructed detention basins for the recapture of pesticides and nutrients lost from container production nurseries via irrigation or rainfall events. It was concluded that detention basins could be constructed that would capture most, if not all, nutrient runoff from a nursery, but that associated costs may preclude basin construction for small or medium-sized container nurseries. Similarly, Fain et al. (2000) surveyed container production nurseries in Alabama and found that nutrient detention was more prevalent at large nurseries.

Constructed wetlands are another proposed strategy to abate nutrient losses from greenhouse and nursery operations. Three aquatic plant species, [*Thalia geniculata* f. *rheumoides* Shuey, *Oenenathe javanica* Blume DC. 'Flamingo', and *Phyla lanceolata* Michx.] were reported to have high P recovery rates in a laboratory-scale constructed wetland designed for use at a container nursery (Polomski et al., 2008).

The usage of PLA as a fertilizer amendment in nursery and greenhouse container production may reduce the amount of P lost via leaching. In a laboratory study, Codling (2006) characterized the forms of P in poultry litter and PLA. Between 50 and 60 percent of the P contained in the poultry litter was present in water-soluble forms. In contrast, water-soluble P forms constituted an average of only 1.5 percent of the total P in PLA. Most P species (82%) in PLA were soluble only in HCl. The author concluded that P supplied through PLA applications may be less prone to losses via runoff events. Furthermore, PLA could potentially be utilized as a liming amendment because of its high pH and alkalinity (Codling, 2006; Faridullah et al., 2009).

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CHAPTER 2. THE EFFECTS OF PHOSPHORUS SOURCE, PHOSPHORUS RATE, AND LIMING RATE ON GROWTH AND QUALITY OF *Verbena canadensis* Britton 'Homestead Purple' AND *Lantana camara* L. 'New Gold'

Introduction

Phosphorus (P) is the eleventh most abundant element in the earth's crust and is essential for most life forms, including plants (Smil, 2000). Phosphorus fertilizers commonly used in plant production systems, are mined and processed from phosphate-rich ore deposits in the earth's crust (Mikkelsen and Bruulsema, 2005). However, future availability of phosphate rock ore reserves is in jeopardy (Cordell et al., 2009). According to Roberts and Stewart (2002), the United States' phosphate rock ore reserves, at current production, are estimated at less than 20 years. Current global commercial phosphate reserves are estimated to be depleted within 50 to 100 years (Cordell et al., 2009). While expected durations of global and domestic phosphate reserves and resources are only estimates, a decline in phosphare rock ore quality is a consensus among speculators and scientists (Cordell et al., 2009; Roberts and Stewart, 2002; Smil, 2000; Steen, 1998). Therefore, development of renewable, high quality P fertilizer sources is of paramount importance.

Historically, animal manures have been utilized as fertilizers in production of many agricultural commodities. Given concerns regarding phosphate rock ore for P fertilizers, manures have gained interest as potential recycled P sources (Dawson and Hilton, 2011). The rise in poultry production has resulted in significant amounts of waste being produced from these facilities in many areas of the United States, particularly in the southeastern United States. Poultry litter is a biomass source consisting predominantly of bird manure and bedding materials (Robinson and Sharpley, 1996). Bedding materials typically consist of straw, sawdust, wood shavings, shredded paper, peanut hulls, and/or rice hulls, depending on location and availability of materials (Kelleher et al., 2002). Poultry litter contains comparable amounts of nitrogen to ruminant wastes, but higher concentrations of P, since fowls are unable to extract organically bound-P from feeds with the addition of phytase (Sommers and Sutton, 1980). Like most manures, poultry litter application as a fertilizer source is limited due to high transportation costs (Bernhart et al., 2010) and environmental concerns associated with surface water impairment (Sharpley et al., 1994).

To alleviate environmental concerns due to geographically-concentrated poultry litter applications as well as expand the use of poultry litter as a recyclable fertilizer source, several methods have been employed to reduce weight of, or concentrate P within, poultry litter including, compaction (Bernhart et al., 2010), pelletization (McMullen et al., 2005), composting (Brodie et al., 2000), P removal (Szogi et al., 2008), gasification (Priyadarsan et al., 2004), and combustion (Codling et al., 2002; Schiemenz and Eichler-Lobermann, 2010). Of all these methods, combustion of poultry litter may be the most efficient means available because the ash contains inorganic P while energy released during combustion could be used for electricity or heat production (IPEP, 2006). Although the combustion process can be more complicated for poultry litter compared to traditional fuel sources due to inconsistent composition, moisture content, and high ash content (Baranyai and Bradley, 2008), combustion of poultry litter is technologically feasible (Habetz and Echols, 2006). For example, Fibrominn power plant in Benson, Minnesota, an alternative energy plant, co-combusts poultry litter and wood to provide energy to approximately 40,000 homes. Ash from the combustion process is sold as a commercial fertilizer (Misra et al., 1993) with the majority of ash a product of combusted poultry litter (IPEP, 2006; Jia and Anthony, 2011).

With the increase in capability of using poultry litter for ashing or power production the potential of poultry litter ash (PLA) as a fertilizer source needs to be examined for a variety of cropping systems. Limited scientific experiments have reported PLA is a suitable nutrient source for several agronomic crops including wheat (*Triticum aestivum* L.) (Codling et al., 2002), Japanese mustard spinach (*Brassica rapa* L.) (Faridullah et al., 2009), buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), or ryegrass (*Lolium multiflorum westerwoldicum* Gordo) (Bachmann and Eichler-Lobermann, 2010). In each of these experiments, researchers reported increased plant P accumulation for soils amended with PLA even though PLA-P is characterized as having low water solubility (Codling, 2006; Bachmann and Eichler-Lobermann, 2010). No experiments have examined PLA as a P source for containerized horticultural crops.

Given the uncertainty of future P ore based fertilizer availability and quality, low cost alternatives such as PLA may be highly desirable in nursery and greenhouse production systems that require high P fertilization additions with high water usage. Additionally, environmental concerns, due to P losses from highly concentrated production sites, may be reduced by utilizing less soluble, recycled P sources. Therefore, the objective of the experiment was to examine the use of PLA as an alternative P source during the production of two commonly-grown greenhouse crops (*Lantana camara* L. ‘New Gold’ and *Verbena canadensis* Britton ‘Homestead Purple’).

Materials and Methods

Experiment setup

Eighty *Lantana camara* L. ‘New Gold’ and *Verbena canadensis* Britton ‘Homestead Purple’ plants growing in 105-cell trays were selected for uniform quality and size for the experiment initiated 3 February 2012. For each species, two plants were transplanted into 1.6-L containers for a total of 40 containers per species. Containers were filled with a substrate composed of pine bark (<0.38 cm) and peat moss (4:1; v:v) and pre-plant incorporated with 0.89 kg m^{-3} of micronutrient package (Micromax, Scotts Company, Marysville, OH), and 0.25 kg K m^{-3} (0N-0P-35.7K). Remaining pre-plant amendments were superphosphate (SP; 20% P) or poultry litter ash (PLA; 10% P), incorporated at 140 or 280 g P m^{-3}, in combination with pulverized dolomitic limestone (DL) at 1.5 or 3.0 g m^{-3}. Containers filled with the eight pre-plant incorporated combinations were arranged in a completely randomized design with five single-container replications. All plants were maintained under greenhouse conditions at an average temperature of 27.7 ˚C, with no supplemental irradiance, for 42 and 70 d for *Verbena canadensis* and *Lantana camara* , respectively. During the experiment, plants were supplied with 350 ml water d^{-1} including 120 ml aliquots $container^{-1}$ N at 250 mg NH_4NO_3 L^{-1} d^{-1}.

Plant response

Plant growth was measured bi-weekly using a growth index [(height + widest width + perpendicular width) / 3] and flower number was quantified for flower buds showing color. Leaf samples, composed of the most recently matured leaves, were removed, dried at 60 ˚C for 72 hours, and biomass recorded before tissue was milled to <0.5mm using a Thomas Wiley® Mini-Mill (Thomas Scientific, Swedesboro, NJ). Tissue was digested in concentrated nitric acid at an average of 120 ˚C, diluted to 20 ml with deionized water, and filtered prior to analysis of elemental Al, B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, S, and Zn concentrations using inductively coupled plasma optical emission spectroscopy (SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA). At 42 and 70 d, plant shoots were harvested at the substrate surface, dried at 60 ˚C for 72 hours, and biomass recorded.

Leachate collection and analysis

Leachate samples measuring 90 ml, from three containers per treatment for *Lantana camara*, were collected bi-weekly following the Virginia Tech extraction method (Wright, 1986). Leachate samples were transported to the laboratory and allowed to cool to room temperature (21 ˚C) prior to leachate-pH and electrical conductivity (EC) measurement (Orion Star A215 solution analyzer; Thermo Scientific Inc., Beverly, MA).

Statistical analysis

The experiment was a 2 (P source) x 2 (P rate) x 2 (DL rate) factorial, completely randomized design with five replications. Growth index, flower counts, plant dry weight, leachate pH, EC, and tissue nutrient analyses data were analyzed following the mixed procedure in SAS/STAT® statistical software (SAS Institute Inc., 2011). Means for each measurement at each collection interval were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05.

Results

Plant Response

<u>Verbena</u>

Verbena growth was not significantly influenced by P source, P rate, or DL rate at 14 or 28 days after potting (DAP) (Table 2.1). At 42 DAP verbena growth, measured using a growth index, increased 9.5% from 40.0 to 44.2 across both P sources as DL rate increased from 1.5 to 3.0 kg m^{-3}. However, in the case of shoot dry weight, DL affected verbena growth differently depending on P source and rate of application (Table 2.2). Increasing DL rate from 1.5 to 3.0 kg m^{-3} did not increase verbena shoot dry weights at 21.2 g and 23.2 g, respectively, in combination with the lower SP application rate. However, increasing DL application rate at the higher SP application rate of 280 g P m^{-3} resulted in higher dry weight of 30.4 g compared to 19.8 g. For PLA, increasing the DL application rate increased verbena shoot dry weight 5.9 g at the lower PLA application rate. In fact, the combination of DL at 3.0 kg m^{-3} and PLA at 140 g m^{-3} resulted in shoot dry weight of 26.6 g comparable to 27.3 g and 28.1 g as the DL rate increased at 280 g P

Table 2.1. Effects of phosphorus rate and dolomitic limestone rate on growth index of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' over experimental periods of 42 and 70 days, respectively.

P Source[Z]	P Rate ($g\ m^{-3}$)	DL Rate[Y] ($kg\ m^{-3}$)	Verbena Growth Index[X] 14 DAP[W]	Verbena 28 DAP	Verbena 42 DAP	Lantana 14 DAP	Lantana 28 DAP	Lantana 42 DAP	Lantana 56 DAP	Lantana 70 DAP
-	140	-	25.5a[V]	35.9a	42.1a	15.3a	22.9a	36.4a	45.8a	51.3a
-	280	-	26.7a	33.3a	42.1a	16.3a	25.6a	33.1a	42.5b	47.3a
-			*NS*[U]	*NS*	*NS*	*NS*	*NS*	*NS*	*0.029*	*NS*
-	-	1.5	25.1a	33.6a	40.0b	15.3a	24.1a	31.8b	41.1b	46.8b
-	-	3.0	27.1a	35.7a	44.2a	16.3a	24.5a	37.7a	47.2a	51.8a
			NS	*NS*	*0.048*	*NS*	*NS*	*0.013*	*0.001*	*0.047*

[Z]SP = superphosphate; PLA = poultry litter ash.
[Y]DL = pulverized dolomitic limestone.
[X]Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].
[W]Days after potting.
[V]Values in column followed by different letters are significant according to Tukey's Studentized Range Test ($\alpha = 0.05$).
[U]P-value derived from analysis of variance; NS = not significant.

m^{-3} of PLA. An increasing effect of DL on plant dry weight was not evident at the higher PLA application rate.

Phosphorus application rate, regardless of P source, had the greatest effect on verbena flower counts throughout the experiment (Table 2.3). Flower counts increased from 7.4 to 12, 12.8 to 19.2, and 11.1 to 13.3, at 14, 28, and 42 DAP, respectively, as the rate of P increased from 140 to 280 g m^{-3}. Over the 42-day experiment, total flower counts increased 42% from 31.3 to 44.5 as P rate increased from 140 to 280 g m^{-3}. In general, verbenas fertilized with 280 g P m^{-3} across all DL rates resulted in greater flowering than verbena fertilized at 140 g P m^{-3}.

Lantana

As noted with verbena, P source did not affect lantana growth. However, lantana growth index was affected by DL rate and P rate (Table 2.1). Lantana growth increased from 31.8 to 37.7, 41.1 to 47.2, and 46.8 to 51.8, at 42, 56, and 70 DAP, respectively, as DL rate increased from 1.5 to 3.0 kg m^{-3}. In general, P application rate did not affect growth index of lantana with the exception of a 7% decrease at 56 DAP when P rate was increased. Shoot dry weight of lantana was not singularly affected by P source, P rate, or DL rate (Table 2.2). However, increasing DL rate from 1.5 to 3.0 kg m^{-3}, increased shoot biomass from 24.9 to 28.9 g, of lantanas fertilized with SP, but did not affect those fertilized with PLA.

Similar to verbena, flower counts of lantana were affected by P application rate throughout the experiment (Table 2.3). Flower counts increased from 48.8 to 66.8, 110.8 to 150.3, 106.8 to 116.3, and 93.8 to 123.7, at 28, 42, 56, and 70 DAP, respectively, when P application rate of either P source was increased from 140 to 280 g P m^{-3}. For the experiment, there was an overall increase of 26%, from 382.8 to 483.5 flowers, when P application rate was increased. Similar to shoot dry weight, increasing DL rate from 1.5 to 3.0 kg m^{-3}, increased total

Table 2.2. Effects of superphosphate or poultry litter ash as phosphorus sources, phosphorus rate, and dolomitic lime rate on shoot dry weights of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' harvested at 42 and 70 days after potting, respectively.

P Source[Z]	P Rate	DL Rate[Y]	Shoot Dry Weight (g)	
	(g m^{-3})	(kg m^{-3})	Verbena	Lantana
SP	-	1.5	20.5c	24.9b
SP	-	3.0	26.8a	28.9a
PLA	-	1.5	23.9b	29.2a
PLA	-	3.0	27.3a	26.6ab
			0.0217	*0.0029*
SP	140	1.5	21.2c	25.9ab
SP	280	1.5	19.8c	24.0b
SP	140	3.0	23.2bc	27.9ab
SP	280	3.0	30.4a	29.8ab
PLA	140	1.5	20.6c	26.9ab
PLA	280	1.5	27.3a	31.6a
PLA	140	3.0	26.5ab	25.4ab
PLA	280	3.0	28.1a	27.9ab
			<0.0001	*NS*

[Z]SP = superphosphate; PLA = poultry litter ash.

[Y]DL = pulverized dolomitic limestone.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test ($\alpha = 0.05$).

[W]P-value derived from analysis of variance; NS = not significant.

Table 2.3. Effects of superphosphate or poultry litter ash as phosphorus sources, phosphorus rate, and dolomitic limestone rate on bi-weekly and cumulative flower counts of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' over experimental periods of 42 and 70 days, respectively.

			Flower Count[Z]									
P Source[Y]	P Rate	DL Rate[X]	Verbena				Lantana					
	(g m^{-3})	(kg m^{-3})	14 DAP[W]	28 DAP	42 DAP	Total	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	Total
-	140	-	7.4b[V]	12.8b	11.1b	31.3b	22.8a	48.8b	110.8b	106.8b	93.8b	382.8b
-	280	-	12.0a	19.2a	13.3a	44.5a	26.5a	66.8a	150.3a	116.3a	123.7a	483.5a
			<0.0001[U]	*<0.0001*	*0.0492*	*<0.001*	*NS*	*<0.0001*	*<0.0001*	*0.0391*	*0.0012*	*<0.0001*
SP	-	1.5	9.0a	13.5a	10.7a	33.2b	18.8b	52.2b	113.8b	102.0a	100.8a	387.7b
SP	-	3.0	11.0a	15.7a	12.8a	39.5ab	32.0a	65.5a	147.0a	114.0a	111.3a	469.8a
PLA	-	1.5	10.2a	17.3a	12.7a	40.2a	23.8b	57.2ab	118.8b	114.8a	114.3a	429.0ab
PLA	-	3.0	8.7a	17.3a	12.7a	38.7ab	23.8b	56.2ab	142.3a	115.3a	108.3a	446.0a
			0.0311	*NS*	*NS*	*0.0276*	*0.0276*	*0.0259*	*NS*	*NS*	*NS*	*0.0105*
SP	140	1.5	7.0c	11.0d	10.3a	28.3b	17.7b	47.3cd	96.3d	98.3a	94.7a	354.3c
SP	280	1.5	11.0abc	16.0abcd	11.0a	38.0ab	20.0b	57.0bcd	131.3c	105.7a	107.0a	421.0bc
SP	140	3.0	7.7bc	12.3cd	13.0a	33.0b	29.7ab	53.7bcd	128.0c	114.0a	97.3a	422.7bc
SP	280	3.0	14.3a	19.0abc	12.7a	46.0a	34.3a	77.3a	166.0a	114.0a	125.3a	517.0a
PLA	140	1.5	8.0bc	13.3bcd	11.7a	33.0b	23.7ab	49.3bcd	94.0d	106.7a	98.0a	371.7c
PLA	280	1.5	12.3ab	21.3a	13.7a	47.3a	24.0ab	65.0abc	143.7bc	123.0a	130.7a	486.3ab
PLA	140	3.0	7.0c	14.3abcd	9.3a	30.7b	20.0b	44.7d	124.7c	108a	85.0a	382.3c
PLA	280	3.0	10.3abc	20.3ab	16.0a	46.7a	27.7ab	67.7ab	160.0ab	122.7a	131.7a	509.7a
			NS	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

[Z]Flower buds showing color at the time of data collection.
[Y]SP = superphosphate; PLA = poultry litter ash.
[X]DL = pulverized dolomitic limestone.
[W]Days after potting.
[V]Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).
[U]P-value derived from analysis of variance; NS = not significant.

flower counts of lantana fertilized with SP from 387.7 to 469.8, but did not affect flower counts of lantanas fertilized with PLA.

Substrate leachate-pH and EC from *Lantana camara*

Substrate leachate-pH was affected at every measurement date by P source and DL rate (Table 2.4). Average leachate-pH increased from pH 5.18±0.63 to 6.48±0.33, when the P source was changed from SP to PLA, and from pH 5.57±0.81 to 6.09±0.74, when DL rate was increased 1.5 to 3.0 kg DL m^{-3}. As DL rate increased from 1.5 to 3.0 kg DL m^{-3}, substrate leachate-pH increased an average of 11%, from 4.87±0.53 to 5.48±0.55, for plants fertilized with SP, but only 6%, from 6.27±0.27 to 6.69±0.29, for those fertilized with PLA.

Substrate leachate-EC was also affected by P source at 0, 7, 14, 21, 49, and 63 DAP (Table 2.5). Leachate-EC was highest when plants were fertilized with PLA at 0, 7, 49, and 63 DAP, but was higher for SP-fertilized plants 14 and 21 DAP. Increasing the P application rate from 140 g P m^{-3} to 280 g P m^{-3} than for at every measurement date and was increased by an average of 33% for the 70 d experiment. While leachate-EC was affected by both P source and P application rate, increasing P rate from 140 to 280 g P m^{-3} increased leachate-EC for plants fertilized with PLA by a higher margin than for those fertilized with SP at 21, 28, 35, 42, 49, and 56 DAP.

Foliar nutrient concentrations

Verbena

Foliar concentrations of Ca, Mn, and P were affected by P source for verbenas (Table 2.6). Foliar Ca and P concentrations increased from 0.61±0.10 to 0.78±0.16% and 0.26±0.04 to 0.33±0.03%, respectively, when verbena were fertilized with PLA compared to SP, while Mn concentrations decreased from 122.97±23.22 to 65.01±16.83 mg kg^{-1}. A similar trend was also exhibited, across both P sources, as foliar P increased from 0.27±0.05 to 0.31±0.04%, and foliar Mn decreased from 106.01±36.43 to 81.96±31.79 mg kg^{-1} with P application rate increase from

Table 2.4. Effects of superphosphate or poultry litter ash as phosphorus sources, phosphorus rate, and dolomitic lime rate on substrate leachate-pH measured weekly from *Lantana camara* 'New Gold' over an experimental period of 63 days.

P Source[Z]	P Rate	DL Rate[Y]	Substrate Leachate-pH										
	(g m^{-3})	(kg m^{-3})	0 DAP[X]	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
SP	-	-	4.33b[W]	4.65b	4.79b	4.89b	5.03b	5.17b	5.49b	5.69b	5.82b	5.89b	5.18b
PLA	-	-	5.93a	6.27a	6.31a	6.52a	6.59a	6.68a	6.68a	6.57a	6.57a	6.65a	6.48a
			<0.0001[V]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
-	-	1.5	4.93b	5.19b	5.30b	5.44b	5.53b	5.63b	5.81b	5.86b	5.90b	6.06b	5.57b
-	-	3.0	5.32a	5.72a	5.80a	5.97a	6.10a	6.22a	6.36a	6.39a	6.49a	6.48a	6.09a
			<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
SP	-	1.5	4.05d	4.30d	4.44d	4.62d	4.74d	4.87d	5.16d	5.36d	5.48d	5.65d	4.87d
SP	-	3.0	4.61c	4.99c	5.14c	5.17c	5.33c	5.46c	5.82c	6.03c	6.16c	6.13c	5.48c
PLA	-	1.5	5.81b	6.08b	6.16b	6.27b	6.33b	6.39b	6.46b	6.37b	6.32b	6.47b	6.27b
PLA	-	3.0	6.05a	6.45a	6.45a	6.77a	6.87a	6.97a	6.90a	6.77a	6.82a	6.84a	6.69a
			0.0004	*<0.0001*	*<0.0001*	*NS*	*NS*	*NS*	*0.028*	*0.0001*	*0.0035*	*NS*	NS
SP	140	1.5	4.17e	4.41f	4.49f	4.70d	4.74c	4.94f	5.22f	5.58d	5.62d	5.84f	4.97ef
SP	280	1.5	3.94e	4.19f	4.38f	4.52d	4.74e	4.80f	5.10f	5.13e	5.33e	5.46g	4.76f
SP	140	3.0	4.78c	5.16d	5.44d	5.57c	5.54c	5.69d	6.00d	6.22b	6.25bc	6.07ef	5.67d
SP	280	3.0	4.43d	4.83e	4.85e	4.78d	5.11d	5.23e	5.65e	5.84c	6.07c	6.18de	5.30e
PLA	140	1.5	5.78b	6.02c	6.11c	6.16b	6.27b	6.21c	6.33c	6.38b	6.23bc	6.39cd	6.19c
PLA	280	1.5	5.83ab	6.13bc	6.22bc	6.37ab	6.38b	6.56b	6.60bc	6.36b	6.41b	6.55bc	6.34bc
PLA	140	3.0	6.06a	6.33ab	6.34b	6.77a	6.84a	6.89a	6.85ab	6.71a	6.88a	6.78ab	6.64ab
PLA	280	3.0	6.04a	6.58a	6.57a	6.76a	6.91a	7.05a	6.94a	6.83a	6.76a	6.89a	6.73a
			NS	*NS*	*0.0002*	*NS*	*0.0152*	*NS*	*NS*	*NS*	*0.0012*	*0.0011*	*NS*

[Z]SP = superphosphate; PLA = poultry litter ash.
[Y]DL = pulverized dolomitic limestone.
[X]Days after potting.
[W]Values in column followed by different letters are significant according to Tukey's Studentized Range Test ($\alpha = 0.05$).
[V]P-value derived from analysis of variance; NS = not significant.

Table 2.5. Effects of superphosphate or poultry litter ash as phosphorus sources and phosphorus rate on substrate leachate-EC measured from *Lantana camara* 'New Gold' over an experimental period of 63 days.

P Source[Z]	P Rate	Substrate Leachate-EC										
	(g m^{-3})	0 DAP[Y]	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
SP	-	2.24b[X]	2.51b	2.48a	1.98a	1.38a	1.10a	0.85a	0.66b	0.66a	0.57b	1.44a
PLA	-	2.92a	2.99a	2.36b	1.86b	1.39a	1.09a	0.82a	0.73a	0.70a	0.66a	1.55a
		<0.0001[W]	*<0.0001*	*0.0017*	*0.04*	*NS*	*NS*	*NS*	*0.0043*	*NS*	*0.0112*	*NS*
-	140	2.36b	2.34b	2.10b	1.60b	1.13b	0.91b	0.74b	0.59b	0.58b	0.56b	1.29b
-	280	2.80a	3.16a	2.75a	2.25a	1.64a	1.28a	0.93a	0.80a	0.78a	0.67a	1.71a
		<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0031*	0.0015
SP	140	2.04d	2.12d	2.14c	1.77b	1.29c	0.99c	0.79bc	0.59c	0.59c	0.52b	1.28b
SP	280	2.44c	2.91b	2.84a	2.20a	1.49b	1.20b	0.90ab	0.74b	0.73b	0.62ab	1.60ab
PLA	140	2.68b	2.56c	2.06c	1.43c	0.97d	0.82d	0.68c	0.59c	0.57c	0.60ab	1.30b
PLA	280	3.16a	3.42a	2.66b	2.30a	1.80a	1.36a	0.96a	0.86a	0.82a	0.71a	1.81a
		NS	*NS*	*NS*	*0.001*	*<0.0001*	*0.0001*	*0.0312*	*0.0036*	*0.0027*	*NS*	NS

[Z]SP = superphosphate; PLA = poultry litter ash.

[Y]Days after potting.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test ($\alpha = 0.05$).

[W]P-value derived from analysis of variance; NS = not significant.

140 to 280 g P m^{-3}. Across both P sources and P rates, increasing DL rate from 1.5 to 3.0 kg m^{-3} decreased foliar Mn concentrations from 100.21±34.11 to 87.77±37.48 mg kg^{-1}. At the high DL rate, increasing P rate from 140 to 280 g m^{-3} decreased foliar Mn concentration from 145.53±9.44 to 88.16±10.23 mg kg^{-1} for verbenas fertilized with SP, but did not affect foliar Mn concentrations of verbenas fertilized with PLA.

Lantana

For lantanas, foliar Ca, Mg, Mn, and P concentrations were affected by P source and P application rate (Table 6). When PLA was used as the P source, foliar Ca, Mg, and P increased from 0.56 to 0.80%, 0.32 to 0.38%, and 0.21 to 0.34%, respectively. However, similar to verbena, foliar Mn concentrations were decreased from 257.5±25.2 to 130.02±21.1 mg kg^{-1} when PLA was the P source. The same general trend existed for P application rate. As P rate increased from 140 to 280 g m^{-3} foliar Ca, Mg, and P concentrations increased from 0.65±0.13 to 0.71±0.16%, 0.31±0.05 to 0.40±0.04%, and 0.24±0.08 to 0.31±0.07%, respectively, while foliar Mn concentrations decreased from 204.67±68.35 to 182.84±70.83 mg kg^{-1}. When P source was SP and the DL rate was highest, foliar Mn concentrations decreased from 291.06±17.24 to 241.70±20.99 mg kg^{-1} as P rate increased from 140 to 280 g m^{-3}, but Mn concentrations were not affected when PLA was applied.

Discussion

Poultry litter ash is an acceptable P source for verbena and lantana greenhouse container production compared to water-soluble, phosphate rock ore-based fertilizers such as SP. Verbena and lantana growth, measured using a growth index, and in terms of biomass, exhibited similar patterns to plants fertilized using SP. Codling (2002) reported similar results for wheat (*Triticum aestivum* L.) grown on two differing soil types when comparing PLA to potassium phosphate as P fertilizer sources. Similarly, in an experiment conducted to determine the effects of PLA on

Table 2.6. Effects of superphosphate or poultry litter ash as phosphorus sources, phosphorus rate, and dolomitic lime rate on foliar nutrient concentrations of *Verbena canadensis* 'Homestead Purple' and *Lantana camara* 'New Gold' over an experimental period of 70 days.

P Source[Z]	P Rate	DL Rate[Y]	Verbena					Lantana				
	(g m^{-3})	(kg m^{-3})	Ca[X]	Mg	Mn	P	K	Ca	Mg	Mn	P	K
SP	-	-	0.61b[W]	0.52a	122.97a	0.26b	1.89a	0.56b	0.32b	257.50a	0.21b	1.24a
PLA	-	-	0.78a	0.49a	65.01b	0.33a	1.90a	0.80a	0.38a	130.02b	0.34a	1.46a
			0.0072[V]	*NS*	*<0.0001*	*<0.0001*	*NS*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*NS*
-	140	-	0.68a	0.52a	106.01a	0.27b	1.88a	0.65b	0.31b	204.67a	0.24b	1.43a
-	280	-	0.71a	0.48a	81.96b	0.31a	1.92a	0.71a	0.40a	182.84b	0.31a	1.27a
			NS	*NS*	*<0.0001*	*0.0014*	*NS*	*0.0021*	*<0.0001*	*0.0024*	*0.0003*	*NS*
-	-	1.5	0.69a	0.49a	100.21a	0.29a	1.88a	0.64b	0.33b	184.54b	0.28a	1.38a
-	-	3.0	0.70a	0.51a	87.77b	0.29a	1.92a	0.73a	0.37a	202.98a	0.27a	1.32a
			NS	*NS*	*0.0063*	*NS*	*NS*	*0.0001*	*<0.0001*	*0.0077*	*NS*	*NS*
SP	140	1.5	0.51a	0.50a	131.66a	0.26bc	1.98ab	0.45e	0.22e	241.36b	0.18c	1.56a
SP	280	1.5	0.60a	0.48a	126.53a	0.27bc	2.02ab	0.53de	0.36bcd	255.88ab	0.25bc	1.22a
SP	140	3.0	0.71a	0.61a	145.53a	0.22c	1.71ab	0.66bc	0.32d	291.06a	0.16c	1.09a
SP	280	3.0	0.64a	0.47a	88.16b	0.31ab	1.86ab	0.60cd	0.38bc	241.70b	0.26bc	1.07a
PLA	140	1.5	0.82a	0.52a	87.61b	0.32ab	1.84ab	0.71bc	0.33d	138.70cd	0.29b	1.32a
PLA	280	1.5	0.84a	0.46a	55.04c	0.33ab	1.67b	0.85a	0.40b	102.20d	0.39a	1.41a
PLA	140	3.0	0.69a	0.45a	59.26c	0.30ab	1.99ab	0.77ab	0.35cd	147.58c	0.33ab	1.75a
PLA	280	3.0	0.77a	0.51a	58.13c	0.35a	2.11a	0.88a	0.45a	131.58cd	0.33ab	1.37a
			NS	*NS*	*<0.0001*	*NS*	*NS*	*NS*	*0.0006*	*0.0031*	*0.0416*	*NS*

[Z]SP = superphosphate; PLA = poultry litter ash.
[Y]DL = pulverized dolomitic limestone.
[X]Macronutrients reported as percentage of dry matter. Mn reported in mg·kg^{-1} dry matter.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

soil-P pools and P uptake, Bachmann and Eichler-Lobermann (2010) reported no differences in biomass per species of buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), or ryegrass (*Lolium multiflorum westerwoldicum* Gordo) when comparing PLA and potassium phosphate. In addition, flower count, a common measurement used for ornamental plant quality, increased as P rate increased for PLA and SP. James and Van Iersel (2001) reported flower numbers, of other ornamental species, to be positively affected by increasing P fertility. Bi et al. (2010) reported increased flower numbers for marigold with increasing poultry litter application rates. Therefore, under the conditions tested for ornamental plant production, PLA, a low water soluble P source, was able to provide adequate P concentrations throughout the 42 and 70 d production cycles to result in marketable quality plants without any observable deleterious effects.Although PLA was primarily examined for its suitability as a P source, PLA also affected substrate pH known to influence nutrient availability and uptake. Research has shown substrate amendments such as fertilizers and pH-adjusting materials can greatly affect plant growth and quality as a direct result of changes in substrate chemical properties (Altland and Buamscha, 2008; Argo and Biernbaum, 1996; Smith et al., 2004). Unlike SP, which is known to reduce substrate pH (Huang and Nelson, 2001) and require higher lime additions to maintain a range of optimal pH, PLA did not lower substrate pH. In fact, verbena and lantana growth, within species, was similar for PLA across both the lower and higher DL rates.

Poultry litter ash contains a high concentration of Ca as a result of litter composition prior to ashing that can result in a high alkaline compound (Codling, 2006). Although substrate leachate-pH often exceeded the recommended range of 5.4 to 6.8 for proper plant growth (Fonteno et al., 1996) during the experiment, P plant uptake was not negatively affected at the higher DL in combination with PLA. Solution pH-dependent dissociation constants for H_3PO_4 of 2.1 and 7.2 suggest the monovalent P species ($H_2PO_4^-$) available for plant uptake would not be affected within the pH ranges measured for PLA-fertilized plants during the course of the experiment (Schachtman et al., 1998). Therefore, PLA has the added benefit of adjusting media pH while supplying P that should reduce liming requirements of soilless substrates.

Because PLA is not a pure P source and contains constituents that can affect substrate chemical properties and crop nutrition (Codling, 2006; Bachmann and Eichler-Lobermann, 2010), effects of PLA incorporation on salt leaching and ancillary nutrient uptake should be characterized. Substrate EC was not affected by DL rate, but was affected by P source and P rate, with P rate having the most consistent effect. Exceedingly high substrate EC was not observed with PLA incorporation. Leachate-EC measurements generally remained within an optimal range of 0.5 to 3.0 mS cm^{-1} (Raviv and Lieth, 2008; Robbins and Evans, 2005) throughout the experiment, with the only exceptions occurring at the highest rate of PLA at 0 and 7 DAP. In general, PLA did not affect the availability or uptake of required nutrients other than P. However, Ca uptake was increased and Mn uptake was decreased for plant fertilized with PLA. Increased Ca uptake was most likely due to increased Ca concentrations as a result of PLA application. More interesting were the changes in foliar Mn across P sources, P rates, and DL rates. In the case of SP-fertilized plants, Mn uptake increased due to higher Mn availability at lower substrate pH compared to plants fertilized with the more alkaline PLA. Although plant Mn toxicities occur in organic soils and soilless substrates, toxicity levels have been shown to be ameliorated with applications of Fe (Handreck, 1997), K (Alam et al., 2005), Ca (Alam et al., 2006), or Mg (Le Bot et al., 1990). Manganese toxicity symptoms were not observed in this experiment likely due to Fe, Ca, K, and Mg being supplied in adequate concentrations.

Substrate pH was affected throughout the experiment and substrate EC was increased for the first week due to PLA incorporation, but adequate concentrations of P were supplied to plants verbena and lantana. However, based on data recorded for this experiment, it is unknown what salts contributed to leachate-EC. High concentrations of P have been shown to be rapidly released from SP in soilless substrates (Yeager and Barrett, 1984), but P dissolution rates from PLA in a soilless substrate have not previously been reported. Continued research should determine the rate and concentration of P dissolution from PLA when used as a P source in a soilless substrate.

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CHAPTER 3: PHOSPHORUS SOURCE AFFECTS PHOSPHORUS LOSSES FROM GREENHOUSE CROP PRODUCTION

Introduction

Soilless substrates commonly used in nursery and greenhouse production are characterized as having high percolation rates (Zhu et al., 2007) and low phosphorus (P) sorption capacities (Yeager and Barrett, 1984; Bilderback, 2001). As a result, nursery and greenhouse operations have been identified as contributors to non-point nutrient pollution (Mangifiaco et al., 2008); especially in P-accelerated eutrophication of adjacent surface waters. Mitigating P losses during nursery and greenhouse production poses a significant challenge to responsible growers (Bilderback, 2001) to comply with legislation enacted in a number of states regulating nutrient loading (Lea-Cox et al., 2010).

Research has clearly indicated increased P leaching can be directly affected by water-solubility of P sources applied during container production (Yeager and Wright, 1982; Yeager and Barrett, 1984; Cole and Dole, 1997). Many growers compensate for low P retention of soilless substrates through higher fertilizer application rates and frequencies (Silber et al., 2005). However, management practices that rely on high, frequent fertility rates have been shown to increase nutrient leaching losses (Zhu et al., 2007). Reductions in water-solubility of fertilizer sources is a proposed strategy to reduce unnecessary nutrient losses from soilless substrates during container production (Lea-Cox and Ristvey, 2003). Controlled-released fertilizer (CRF) technologies, including coated or granulated fertilizers, release P over time for plant uptake (Shaviv, 2001). In many cases, CRFs are less economical compared to uncoated, water-soluble fertilizers and vary in efficacy with regard to stemming nutrient leaching losses (Tyler et al., 1996; Bilderback, 2001; Ristvey et al., 2007; Zhang et al., 2007).

Reduction of P losses continues to be an important research endeavor given the levels of surface water impairment across the United States associated with P-enriched water bodies (Correll, 1998). Recycling nutrients, mainly in the form of manures, has been researched extensively in recent years as a means to mitigate unnecessary P inputs and losses during crop production cycles (Dawson and Hilton, 2011; Bachmann and Eichler-Lobermann, 2010). One recycled P source in great abundance due to rise in poultry production, particularly in the southeastern United States, is poultry litter (USDA, 2000). Poultry litter contains comparable amounts of nitrogen to ruminant wastes, but higher concentrations of P, since fowls are unable to extract organically bound-P from feeds without the addition of phytase (Somers and Sutton, 1980). However, poultry litter application has been reported as a P source for surface water impairment due to concentrated land applications (Sharpley et al., 1994). Attempts to increase the acreage for poultry litter application must be accompanied with reduced costs associated with transportation (Bernhart et al., 2010). Processes to concentrate P from manures have included compaction (Bernhart et al. 2010), pelletization (McMullen, 2005), composting (Brodie et al., 2000), P extraction (Szogi et al. 2008), gasification (Priyadarsan et al. 2004), or combusting (Codling et al., 2002; Shiemenz and Eicler-Lobermann, 2010) poultry litter.

Unlike many processes used to concentrate P, combustion of poultry litter can be used in energy production (Habetz and Echols, 2006). For example, Fibrominn power plant in Benson, Minnesota, is an alternative energy plant that co-combusts poultry litter and wood to provide 55 MW of energy for 40,000 homes. Combustion of poultry litter converts P from 50 to 60% water-soluble forms, found in raw poultry litter, to 1.5% water soluble P in poultry litter ash (PLA). More than 80% of the P species in PLA are soluble in hydrochloric acid (Codling, 2006) and as a result less prone to movement via surface runoff. Although PLA-P is present in low-soluble compounds, PLA has been reported to be a suitable P source for wheat [(*Triticum aestivum* L) (Codling et al., 2002)], Japanese mustard spinach [(*Brassica rapa* L.) (Faridullah et al., 2009)], buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), and ryegrass [(*Lolium multiflorum westerwoldicum* Gordo) (Bachmann and Eichler-Lobermann, 2010)].

To date, no published research on PLA's effects on reducing P leaching from soilless substrates is available. Therefore, experiments were conducted to determine the effect of PLA application on P losses from a soilless substrate during containerized plant production and combustion temperature's effect on PLA-P solubility.

Materials and Methods

Experiment I

Setup

Sixty *Lantana camara* L. 'New Gold' plants growing in a 105-cell tray were selected for uniform quality and size prior to the initiation of studies 6 September 2011 and 2 March 2012. Two plants were transplanted into 30 1.6-L containers for a total of 60 containers. Substrate was composed of amended pine bark (<0.38 cm) and peat moss (4:1; v:v) amended with 0.89 kg m^{-3} micronutrient package (Micromax, Scotts Company, Marysville, OH), 0.25 kg K m^{-3} (0N-0P-35.7K), and 2.97 kg m^{-3} of pulverized dolomitic limestone. Pre-plant P treatment sources were either superphosphate (20% P) or PLA (10% P) incorporated as a single source or at ratios of 25:75, 50:50 or 75:25 SP:PLA at 280 g P m^{-3} with controls receiving no P fertilizer. Poultry litter ash used in this experiment was the product of commercial energy production via combustion of poultry litter and was obtained courtesy of North American Fertilizer, LLC.

Plants were maintained under greenhouse conditions at averages of 23.7 °C and 28.4 °C in 2011 and 2012, respectively, with no supplemental irradiance, for 84 d. During the experiment, plants were supplied with 350 ml water d^{-1} including 120 ml aliquots $container^{-1}$ of N at 250 mg NH_4NO_3 L^{-1} d^{-1}.

In 2012, *Lantana camara* L. 'New Gold', grown on an adjacent greenhouse bench according to previously outlined procedures, were transplanted into a raised bed to simulate post-transplant field conditions at the end of the 84-d experimental period. A linear bed, measuring 120 m long and 1 m wide was amended with pine bark, milled to <0.95 cm (Phillips Bark Processing Co., Brookhaven, MS) and granular fertilizer (12N-2.6P-4.9K) was pre-plant applied to the surface of the soil at 0.97 kg N 100 m^{-2}. Lantana were planted into the raised bed 1.2 m apart in a randomized complete block design with five replications. Plants were mulched with pine bark <1.6 cm (Phillips Bark Processing Co., Brookhaven, MS) at a depth of 5 cm. The planted bed was overhead irrigated with 0.4 cm water d^{-1}.

Data Collection

Lantana growth was measured bi-weekly using a growth index [(height + widest width + perpendicular width) / 3]. In 2012, flowers showing color were quantified bi-weekly. At 84 days after planting (DAP), lantana shoots and roots were harvested and separated. Roots were washed with a gentle stream of water to remove attached soilless substrate before being dried at 60 °C for 72 hours and biomass recorded. Lantana leaf and root samples were also collected. Samples with a mass of 0.5 g were milled to <0.5-mm, digested in concentrated nitric acid at 120 °C for 4 hours. Concentrated samples were diluted with 20 ml deionized water, filtered (Whatman 42) before being analyzed for elemental Al, B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, S, and Zn (using inductively coupled plasma optical emission spectroscopy (ICP-OES) (SPECTRO

Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA).

Leachate from three containers per P treatment was collected weekly following the Virginia Tech extraction method (Wright, 1986). Leachate samples were cooled to room temperature (21 ˚C) and leachate-pH and EC measured (Orion Star A215 solution analyzer, Thermo Scientific Inc., Beverly, MA). In the laboratory, 15 ml of leachate was filtered through a 0.45 µm disposable nylon filter (22 mm diameter, Whatman™; GE Healthcare UK Limited, Buckinghamshire) in preparation for dissolved reactive phosphorus (DRP) analysis using the molybdate colorimetric method developed by Murphy and Riley (1962) and modified by Pote and Daniel (2000a). Dissolved reactive P was quantified at 880 nm using a spectrophotometer (Spectronic 20, Bausch and Lomb, Rochester, NY).

Once planted into a simulated landscape, lantana growth was measured weekly using a growth index [(height + widest width + perpendicular width) / 3] and flowers showing color were quantified for the first 28 d. At the end of the 49-d experimental period, lantana shoots were harvested at the soil surface, dried at 60 °C for 96 hours and biomass recorded. Prior to shoot harvest, leaf samples, composed of the most recently-matured leaves, were collected. Samples with a mass of 0.5 g were milled to <0.5-mm and digested in concentrated nitric acid at 120 °C for 4 hours. Concentrated samples were diluted with 20 ml deionized water, and filtered (Whatmann No. 42) before being analyzed for elemental Al, B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, S, and Zn using inductively coupled plasma optical emission spectroscopy (ICP-OES) (SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA).

Statistical Analysis

Lantana were arranged in a completely randomized design with five replicates in the greenhouse, and as a randomized complete block design with five blocks in the landscape evaluation. Growth index, flower counts, plant dry weight, leachate-pH and EC, and tissue nutrient concentrations were analyzed using the mixed procedure in SAS/STAT® statistical software (SAS Institute Inc., 2011). Where appropriate, means for each measurement at each collection interval were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05. Leachate-DRP data were fitted to appropriate models using regression techniques. All data were analyzed using SAS/STAT® statistical software (SAS Institute Inc., 2011).

Experiment II

Setup

In 2012, lantana were grown in soilless substrate and P-treatments were prepared following the procedures outline in Experiment I. However, these containerized lantana plants were used to quantify effluent-total P (effluent-TP) during the 84-d experimental period. Effluent from growing containers was continuously collected in 18.9-L polypropylene buckets. In order to capture growing container effluent and prevent evaporative losses, a 15-cm diameter opening was fashioned in each lid to allow the 1.6 L containers to empty directly into the collection bucket. A silicone caulk sealant was placed applied to seal the container-bucket junction. Lantana were maintained under the same conditions and protocols previously described in Experiment I.

Data Collection

Total leachate volume was quantified bi-weekly with 120-ml aliquots collected for total P (TP) analysis. The procedure for TP analysis included digestion of 25 mL sub-samples in 1 ml and 5 ml concentrated sulfuric and nitric acids, respectively, at 145 ˚C for 6 hrs on a digestion block (Bran + Luebbe BD-40) controlled with a BD-20/40 controller (Bran + Luebbe, Vallejo, California) (Pote and Daniel, 2000b). Post digestion, TP was quantified at 880 nm using a spectrophotometer (Spectronic 20, Bausch and Lomb, Rochester, NY).

At 84 DAP, lantana shoots and roots were harvested and separated. Roots were washed with a gentle stream of water to remove attached soilless substrate. Shoot and root tissues were dried at 60 °C for 72 hours and biomasses recorded. Lantana shoot and root samples were also collected. Samples with a mass of 0.5 g were milled to <0.5-mm, digested in concentrated nitric acid at 120 °C for 4 hours. Concentrated samples were diluted with 20 ml with deionized water, and filtered before being quantified for elemental P concentration using inductively coupled plasma optical emission spectroscopy (ICP-OES) (SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA). Effluent-P and plant accumulated P analyses were used to calculate a mass balance of P.

Statistical Analysis

Lantana were arranged in a completely randomized design with three replicates. Growth index, flower count, plant dry weight, tissue P concentration, and effluent-TP were analyzed using the mixed procedure in SAS/STAT® statistical software (SAS Institute Inc., 2011). Where appropriate, means for each measurement at each collection interval were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05. All data were analyzed using SAS/STAT® statistical software (SAS Institute Inc., 2011).

Experiment III

Setup

Poultry broiler litter was collected in 2011 from a poultry house located at Ben Hur Research Farm (Louisiana State University, Baton Rouge, LA). The primary bedding material was composed of sawdust exposed to a single crop of chickens. Poultry litter was air-dried on a tarpaulin on a greenhouse floor for seven days to reduce excess moisture. Samples weighing 300 g were combusted in a muffle furnace at 500, 750, or 1000 C for two hours. Ash was cooled and weight recorded.

Ash samples, with a mass of 20-g, including a commercially produced PLA (NAFmicro; North American Fertilzers, Inc., Benson, MN) were placed into 150 ml deionized water and shaken at 250 rpm for 96 hours (New Brunswick Scientific Co.). Each ash treatment was replicated three times.

Data Collection

At 3, 6, 12, 24, 48, and 96 hours after initiation, shaking ceased and suspended particulates were allowed to settle prior to extraction of 15-ml aliquots using a graduated, disposable syringe. No solid ash material was removed. Aliquots were filtered through 0.45 µm disposable nylon filters (22 mm diameter, Whatman™; GE Healthcare UK Limited, Buckinghamshire) and analyzed for P using inductively coupled plasma optical emission spectroscopy (ICP-OES) (SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA).

Statistical Analysis

Ash samples were arranged as a completely randomized design with three replicates. Solution P concentrations were regressed for each combustion temperature over time using linear regression. All data were analyzed using SAS/STAT® statistical software (SAS Institute Inc., 2011).

Results

Experiment I

Plant Response in Container

Application of P, regardless of source, increased growth index of lantana at 42, 56, and 70 days after potting (DAP) in 2011, and at all measurement dates in 2012 (Table 3.1). When applied as a singular P source, PLA increased growth index compared to the control, 75, 157, and 178% at 42, 56, and 70 DAP in 2011, and an average of 73% throughout the experimental period in 2012. In 2011, excluding the control, between 28 and 70 DAP, lantana growth exhibited a slight pattern of slower growth as PLA composition increased. However, no effect of PLA compared to SP on lantana growth was observed in 2012. Similar to growth index, shoot biomass slightly decreased to 17.4, 14.6, 12.0, and 10.8 g as PLA percentage increased in 2011 compared to 18.2 g for 100% SP-fertilized lantana (Table 3.2). However, much smaller shoot biomass differences were detected in 2012. Shoot:root biomass was increased by P application, regardless of source or combination of sources in both years, illustrating a larger disparity in shoot mass than root mass based on P application. Flower counts did not differ between P fertilizer treatments with the exception of the first two measurement dates (Table 3.3).

Tissue Nutrient Accumulation

As the percentage of PLA increased, foliar P concentrations slightly decreased from 0.37±0.03% for 100% SP-fertilized lantana to 0.33±0.01% for 100% PLA-fertilized lantana (Table 3.4), but all P sources increased foliar P concentrations compared to the control group. Lantanas fertilized

Table 3.1. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on growth index of *Lantana camara* 'New Gold' throughout an 84 day experimental period.

Treatment[Z]	Growth Index[Y]						
	2011						
	14 DAP[X]	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Average
Control	9.45a[W]	9.68c	9.87d	9.38c	8.97c	-	9.47c
100:0 SP:PLA	11.08a	14.63ab	25.63a	30.37a	32.80a	-	22.90a
75:25 SP:PLA	11.15a	15.85a	26.13a	30.42a	32.33a	-	23.18a
50:50 SP:PLA	11.20a	14.68ab	22.67ab	27.23ab	28.87ab	-	20.93ab
25:75 SP:PLA	10.63a	13.28ab	18.63bc	25.20ab	26.67ab	-	18.88ab
0:100 SP:PLA	10.52a	11.83bc	17.27c	24.10b	25.00b	-	17.74b
	NS[V]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	-	*<0.0001*
	2012						
Control	7.53c	12.31b	15.11b	18.81c	22.36b	24.94b	16.84b
100:0 SP:PLA	16.53a	27.44a	31.89a	36.92ab	44.83a	47.94a	34.26a
75:25 SP:PLA	17.39a	26.64a	32.67a	42.53a	46.50a	48.06a	35.63a
50:50 SP:PLA	16.69a	24.17a	28.89a	37.69ab	46.00a	49.14a	33.93a
25:75 SP:PLA	12.47b	24.33a	27.36a	32.22ab	40.94a	43.50a	30.14a
0:100 SP:PLA	13.14b	21.08a	26.00a	31.97b	39.72a	42.72a	29.11a
	<0.0001	*0.0002*	*<0.0001*	*0.0001*	*<0.0001*	*<0.0001*	*0.0001*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].
[X]DAP = days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[V]P-value derived from analysis of variance; NS = not significant.

Table 3.2. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on biomass accumulation of *Lantana camara* 'New Gold' during an 84-d experimental period.

Treatment[Z]	2011			2012		
	Shoot[Y]	Root	Shoot:Root	Shoot	Root	Shoot:Root
Control	2.10d[X]	2.19d	0.99b	8.55c	5.61c	1.51b
100:0 SP:PLA	18.20a	5.55b	3.06a	25.24a	8.26ab	2.99a
75:25 SP:PLA	17.43a	6.88a	2.60a	27.41a	9.87a	2.82a
50:50 SP:PLA	14.62b	5.81ab	2.45a	26.23a	9.36ab	2.82a
25:75 SP:PLA	11.99c	4.69bc	2.65a	21.85b	7.67b	2.73a
0:100 SP:PLA	10.81c	4.00c	2.71a	21.75b	7.93b	2.71a
	<0.0001[W]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

Table 3.3. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on flower counts of *Lantana camara* 'New Gold' in over an 84-d experimental period in 2012.

Treatment[Z]	Flower Counts[Y]						
	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Total
Control	5.67c	8.67c	11.00b	9.33b	13.67b	6.67b	55.00b
100:0 SP:PLA	33.00ab	65.33ab	110.67a	138.00a	114.00a	145.33a	606.33a
75:25 SP:PLA	30.67ab	75.33a	114.33a	145.33a	123.67a	154.33a	643.67a
50:50 SP:PLA	33.67a	72.67ab	115.33a	150.33a	131.33a	157.33a	660.67a
25:75 SP:PLA	29.33ab	58.00ab	104.67a	153.00a	119.00a	160.33a	624.33a
0:100 SP:PLA	22.67b	54.33b	104.33a	152.67a	108.00a	148.33a	590.33a
	<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.004*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Flower buds showing color at the time of data collection.

[X]Days after potting.

[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

[V]P-value derived from analysis of variance; NS = not significant.

Table 3.4. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on foliar and root nutrient concentrations of *Lantana camara* 'New Gold' in 2011.

Treatment[Z]	Foliar mg k					Root				
	Ca[X]	Mg	Mn	P	K	Ca	Mg	Mn	P	K
Control	0.83a	0.49a	226.46a	0.03d	3.24a	0.43a	0.30ab	151.04a	0.02d	0.98a
100:0 SP:PLA	1.04a	0.42abc	225.53a	0.37ab	1.81d	0.25b	0.33a	144.08a	0.33a	0.37cd
75:25 SP:PLA	0.97a	0.45ab	187.94b	0.39a	1.98cd	0.23b	0.33a	104.02ab	0.27ab	0.69b
50:50 SP:PLA	0.94a	0.42abc	158.18bc	0.36abc	2.29bcd	0.24b	0.29ab	79.86bc	0.21c	0.85ab
25:75 SP:PLA	0.85a	0.40bc	147.08cd	0.34bc	2.57abc	0.25b	0.27ab	68.66bc	0.23b	0.61bc
0:100 SP:PLA	0.86a	0.35c	115.97d	0.33c	2.76ab	0.26b	0.26b	51.91c	0.21bc	0.36d
	NS	*0.0066*	*<0.0001*	*<0.0001*	*0.0003*	*<0.0001*	*0.0113*	*0.0001*	*<0.0001*	*<0.0001*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Samples composed of recently matured leaves.

[X]Macronutrients reported as percentage of dry matter. Mn reported in $mg\cdot kg^{-1}$ dry matter.

[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

[V]P-value derived from analysis of variance; NS = not significant.

[U]Sub-sample of entire root system.

with 100% PLA had foliar Mn concentrations reduced by 49%, from 225.53±8.37 to 115.97±11.71 mg·kg^{-1} compared to 100% SP-fertilized lantana. Fertilization with 100% PLA also led to a 52% increase in foliar K concentrations, from 1.81±0.12 to 2.76±0.18%, compared with 100% SP-fertilized plants.

Similar trends were observed for root nutrient concentrations. As the percentage of PLA increased, root P concentrations decreased slightly from 0.33±0.01% for 100% SP-fertilized lantanas to 0.21±0.02% for 100% PLA-fertilized lantanas (Table 3.4). Root Mn concentrations also decreased from 144.08±4.31 to 51.91±2.16 mg Mn kg^{-1} as the percentage of PLA increased from 0 to 100.

Landscape Establishment

Phosphorus source during production affected landscape performance of lantana. Growth index of lantanas fertilized with phosphorus, regardless of source during greenhouse production, increased growth index for the first three measurement intervals (Table 3.5). Similarly, flower numbers were higher for lantanas fertilized with P than for those receiving no exogenous P during greenhouse production for the first two measurement dates (Table 3.6) At the end of the experimental period, there were no differences in foliar concentrations of nutrients that had previously differed during greenhouse production (Table 3.7). Lantanas shoot biomass did not differ due to production P-fertilization treatment at the end of the 49-d experimental period (Table 3.8).

Dissolved Reactive Phosphorus

Application of 100% PLA decreased cumulative DRP losses 93 and 92% in 2011 and 2012, respectively, compared to lantana fertilized with 100% SP during the 84-day production cycles (Figure 3.1). Increasing the percentage of PLA as a component of applied fertilizer, by

Table 3.5. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources during greenhouse production on growth index of *Lantana camara* 'New Gold' grown in a simulated landscape for 49 days in 2012.

Treatment[Z]	Growth Index[Y]							
	0 DAP[X]	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP
Control	38.93b[W]	39.07b	42.60b	48.93a	82.27b	88.93b	90.67b	93.80b
100:0 SP:PLA	67.87a	59.93a	60.47a	61.40ab	99.67a	101.33a	104.20a	109.00a
75:25 SP:PLA	69.87a	61.07a	61.13a	64.07a	90.40ab	94.80ab	97.13ab	101.27ab
50:50 SP:PLA	65.13a	59.20a	59.20a	63.40a	95.40a	97.60ab	100.07ab	103.67ab
25:75 SP:PLA	68.20a	58.93a	59.60a	63.20a	93.80ab	98.00ab	100.73ab	104.67ab
0:100 SP:PLA	61.53a	61.07a	56.67a	60.67ab	93.87ab	97.60ab	100.20ab	103.67ab
	<0.0001[V]	*0.0003*	*0.0032*	*0.0215*	*0.0052*	*0.0434*	*0.0413*	*0.049*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[X]DAP = days after potting.

[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

[V]P-value derived from analysis of variance; NS = not significant.

Table 3.6. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources during greenhouse production on flower number of *Lantana camara* 'New Gold' measured over the course of 28 days in a simulated landscape in 2012.

Treatment[Z]	Flower Count[Y] (number of flowers)				
	0 DAP[X]	7 DAP	14 DAP	21 DAP	28 DAP
Control	5.0b[W]	24.4b	49.4a	71.4a	209.4a
100:0 SP:PLA	51.4ab	110.8a	77.6a	57.4a	301.8a
75:25 SP:PLA	61.4a	94.4a	72.6a	89.2a	292.2a
50:50 SP:PLA	52.0ab	112.0a	77.6a	92.4a	303.4a
25:75 SP:PLA	44.0ab	93.6a	75.0a	55.8a	270.2a
0:100 SP:PLA	27.4ab	88.2a	67.6a	50.4a	290.4a
	0.0172[V]	*<0.0001*	*NS*	*NS*	*NS*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Flower buds showing color.
[X]DAP = days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[V]P-value derived from analysis of variance; NS = not significant.

Table 3.7. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources during greenhouse production on flower number of *Lantana camara* 'New Gold' measured over the course of 28 days in a simulated landscape in 2012.

Treatment[Z]	Foliar Nutrient[Y]				
	Ca[X]	Mg	Mn	P	K
Control	1.18a[W]	0.75a	108.67a	0.42a	2.44a
100:0 SP:PLA	1.18a	0.72a	117.78a	0.50a	2.42a
75:25 SP:PLA	1.17a	0.72a	112.12a	0.48a	2.30a
50:50 SP:PLA	1.18a	0.72a	108.37a	0.49a	2.46a
25:75 SP:PLA	1.19a	0.72a	99.63a	0.47a	2.22a
0:100 SP:PLA	1.20a	0.74a	107.66a	0.50a	2.22a
	NS[V]	*NS*	*NS*	*NS*	*NS*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Samples composed of recently matured leaves.
[X]Macronutrients reported as percentage of dry matter. Mn reported in $mg \cdot kg^{-1}$ dry matter.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[V]P-value derived from analysis of variance; NS = not significant.

Table 3.8. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources during greenhouse production on flower number of *Lantana camara* 'New Gold' grown in a simulated landscape for 49 days in 2012.

Treatment[Z]	Shoot Dry Weight (g)
Control	421.8a[Y]
100:0 SP:PLA	571.0a
75:25 SP:PLA	569.5a
50:50 SP:PLA	571.3a
25:75 SP:PLA	524.7a
0:100 SP:PLA	521.8a
	NS[X]

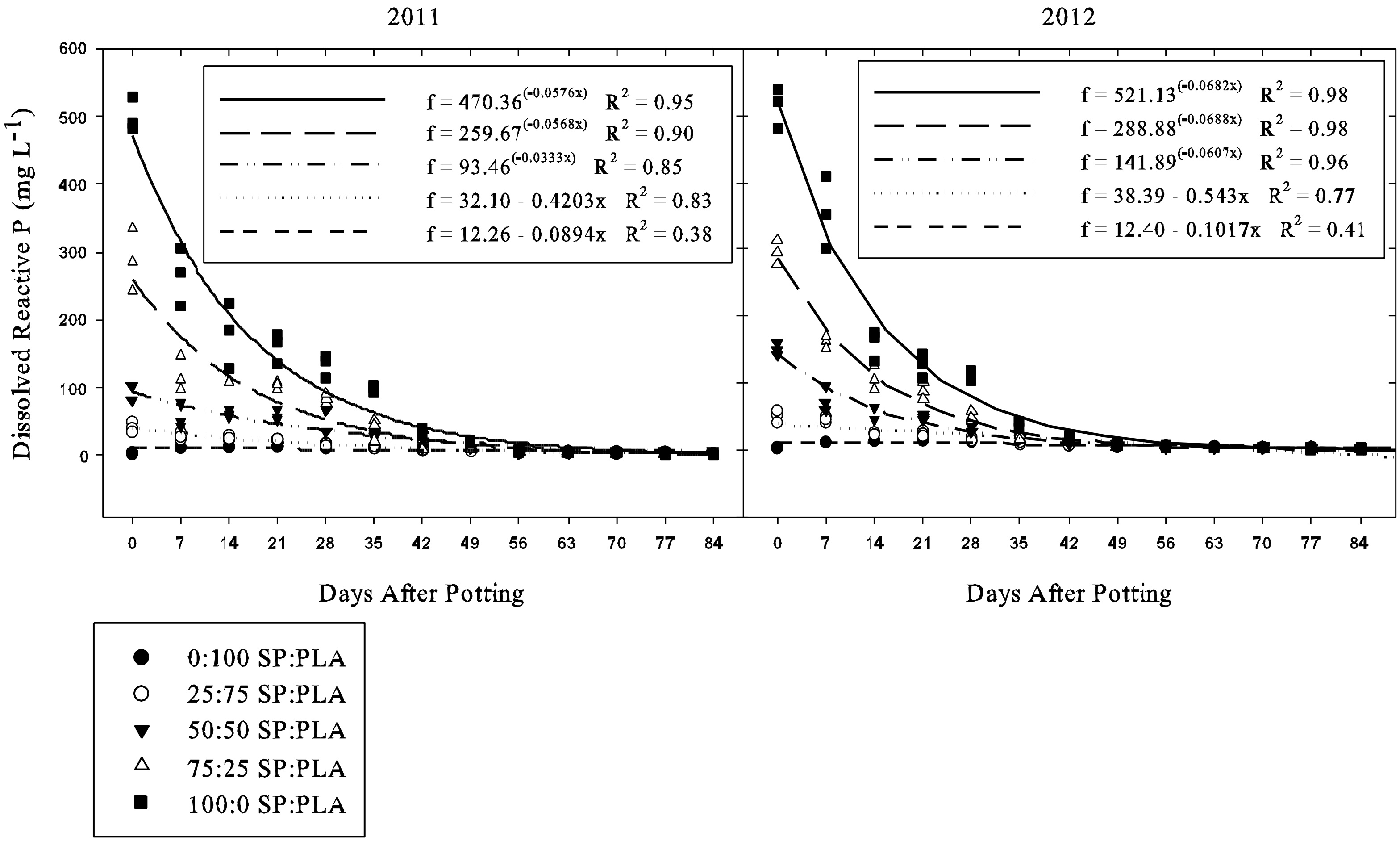
[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

[X]P-value derived from analysis of variance; NS = not significant.

25% gradations (in the order of 75:25, 50:50, and 25:75 SP:PLA), reduced cumulative DRP losses 45, 71, and 87% and 44, 69, and 85%, in 2011 and 2012, respectively, compared to 100% SP-fertilized lantana. All fertilizer treatments containing SP exhibited high initial DRP losses of 498, 290, 96, and 40 mg DRP L^{-1} and 513, 296, 150, and 51 mg DRP L^{-1} at 0 DAP in 2011 and 2012, respectively, with subsequent DRP losses declining over time. On the other hand, PLA, as a single P source, resulted in generally static DRP losses, reaching maxima of 14 mg DRP L^{-1} in both years. Reductions in initial DRP losses were disproportionate to the percentage of PLA applied and were greater than expected.

Figure 3.1. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on dissolved reactive phosphorus concentrations in leachate from *Lantana camara*. 'New Gold' over an 84 day experimental period.



Substrate leachate-pH and EC

Phosphorus source, as single sources and in combination, affected substrate leachate-pH (Table 3.9). Although leachate-pH generally remained within recommended range of 5.4 to 6.8 for soilless substrates (Fonteno et al., 1996), as the percentage of PLA increased, substrate leachate-pH increased at each measurement date to maxima of 6.98 and 7.05 in 2011 and 2012, respectively. All P sources and combination increased leachate-EC compared to controls for the first 21 to 28 DAP, but did not exceed recommended substrate leachate-EC range of 0.5 to 3.0 mS cm^{-1} throughout the experiment (Table 3.10). Overall, no pattern of leachate-EC and P source or combination was found.

Experiment II

Effluent-TP was increased by P application, regardless of source, at each measurement date (Table 3.11). Similar to leachate-DRP, cumulative effluent-TP was reduced 69%, from 348.52±15.86 to 106.51±7.89 mg P $container^{-1}$ through PLA application (Table 3.12). For the experiment, 77% of applied P, from SP alone, was collected in effluent, compared with only 24% from PLA. By 14 DAP, 76% of cumulative TP was collected from SP, compared to only 25% from PLA (Table 3.11). In fact 76, 92, 98, and 99% of cumulative TP was collected from the 100% SP treatment by 14, 28, 42, and 56 DAP, respectively. On the other hand, similar to leachate-DRP, TP was released from PLA more slowly and over a more extended time period as 25, 48, 72, 86, and 95% of cumulative effluent-TP was collected from PLA by 14, 28, 42, 56, and 70 DAP. In addition, 91% of applied P, from SP, was accounted for, compared to only 40% from PLA (Table 3.12).

Table 3.9. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on substrate leachate-pH from *Lantana camara* 'New Gold' over an 84 day experimental period.

Treatment[Z]	Substrate leachate-pH												
	2011												
	0 DAP[Y]	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	70 DAP	77 DAP	84 DAP
Control	4.97c[X]	6.41a	6.20b	6.47b	6.59ab	6.36bc	6.09b	6.22b	6.39bc	6.48cd	6.54bcd	6.54b	6.47bc
100:0 SP:PLA	4.36d	5.02d	5.17e	5.08e	5.14d	5.27e	5.42c	5.55d	6.15c	6.20d	6.31d	6.34c	6.39bc
75:25 SP:PLA	4.59d	5.66c	5.44d	5.71d	5.88c	5.92d	6.15b	5.93c	6.40bc	6.24d	6.40cd	6.35c	6.30c
50:50 SP:PLA	5.02c	6.01b	5.76c	6.08c	6.25bc	6.16cd	6.21b	6.26b	6.57abc	6.55bc	6.59abc	6.53b	6.36bc
25:75 SP:PLA	5.61b	6.23ab	6.14b	6.05c	6.64ab	6.56ab	6.51ab	6.59a	6.68ab	6.85ab	6.71ab	6.69a	6.54ab
0:100 SP:PLA	6.10a	6.47a	6.56a	6.69a	6.92a	6.85a	6.77a	6.68a	6.98a	6.89a	6.78a	6.79a	6.74a
	<0.0001[W]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0012*	*<0.0001*	*0.0002*	*<0.0001*	*0.0003*
	2012												
Control	4.92c	6.27ab	6.36ab	6.39b	6.51b	6.32c	6.12c	6.11cd	6.22cd	6.23cd	6.18c	6.11d	-
100:0 SP:PLA	4.43d	4.69d	4.89e	4.96d	5.09e	5.18e	5.67d	5.82d	6.11d	6.18d	6.24c	6.21cd	-
75:25 SP:PLA	4.42d	5.50c	5.55d	5.40c	5.69d	5.51d	6.07c	6.04cd	6.26cd	6.20d	6.19c	6.20d	-
50:50 SP:PLA	5.01c	6.14b	5.91c	6.19b	6.11c	6.37bc	6.31b	6.33bc	6.42bc	6.34c	6.29c	6.37bc	-
25:75 SP:PLA	5.58b	6.26ab	6.15bc	6.12b	6.56b	6.59b	6.48b	6.51b	6.64ab	6.59b	6.51b	6.48b	-
0:100 SP:PLA	6.06a	6.54a	6.58a	6.79a	6.93a	7.05a	6.86a	6.85a	6.76a	6.82a	6.83a	6.70a	-
	<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	-

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Days after potting.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05). P values are listed at the bottom of each column.

[W]Values in columns followed by different letters were significant according to Tukey’s Honest Significance Difference Test (α = 0.05).

Table 3.10. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on substrate leachate-EC from *Lantana camara* 'New Gold' over an 84 day experimental period.

Treatment[Z]	Substrate leachate-EC												
	2011												
	0 DAP[Y]	7 DAP	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	70 DAP	77 DAP	84 DAP
Control	1.03c[X]	1.18d	1.38c	1.26c	1.28a	1.66ab	1.51a	0.54a	0.46a	0.39a	0.35b	0.34b	0.38b
100:0 SP:PLA	2.39b	2.40b	2.16ab	1.91ab	1.66a	1.73ab	1.36a	0.68a	0.55a	0.81a	0.77a	0.72a	0.64a
75:25 SP:PLA	2.52b	1.96c	2.12b	1.76b	1.38a	1.58b	1.13a	0.69a	0.64a	0.88a	0.65a	0.75a	0.64a
50:50 SP:PLA	2.49b	2.19bc	2.44a	2.06a	1.40a	1.82a	1.42a	0.63a	0.61a	0.81a	0.72a	0.71a	0.65a
25:75 SP:PLA	2.72b	2.42bc	2.18ab	1.89ab	1.43a	1.81a	1.45a	0.67a	0.67a	0.73a	0.66a	0.64a	0.63a
0:100 SP:PLA	3.33a	3.21a	2.45a	1.86b	1.63a	1.79a	1.33a	0.66a	0.69a	0.57a	0.67a	0.69a	0.63a
	<0.0001[W]	*<0.0001*	*<0.0001*	*<0.0001*	*NS*	*0.0091*	*NS*	*NS*	NS	*0.0487*	*0.0001*	*<0.0001*	*0.004*
	2012												
Control	1.04c	1.14d	1.30c	1.24b	1.18c	1.40c	1.08a	0.87a	0.62b	0.72b	0.60b	0.67a	-
100:0 SP:PLA	2.58b	2.79b	2.51ab	2.08a	2.02a	1.65bc	1.35a	1.07a	1.03a	0.98a	0.91a	0.73a	-
75:25 SP:PLA	2.34b	2.16c	2.05b	1.82a	1.95ab	1.59bc	1.31a	0.89a	1.19a	1.00a	0.94a	0.85a	-
50:50 SP:PLA	2.37b	2.52bc	2.66a	2.18a	1.84ab	1.65bc	1.32a	0.96a	1.07a	1.00a	1.00a	0.80a	-
25:75 SP:PLA	2.72b	2.82b	2.35ab	1.93a	1.71b	1.81ab	1.28a	0.81a	1.05a	0.92a	0.90a	0.78a	-
0:100 SP:PLA	3.22a	3.27a	2.49ab	2.07a	1.93ab	1.95a	1.16a	0.87a	1.18a	1.02a	0.93a	0.83a	-
	<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0007*	*NS*	*NS*	*0.0003*	*0.0001*	*0.0037*	*NS*	-

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Days after potting.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05). P values are listed at the bottom of each column.

[W]Values in columns followed by different letters were significant according to Tukey’s Honest Significance Difference Test (α = 0.05).

Table 3.11. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on total phosphorus in effluent from *Lantana camara* 'New Gold' grown in a closed system over an 84 day experimental period in 2012.

Treatment[Z]	Effluent-Total P (mg P L^{-1})						
	14 DAP[Y]	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Total
Control	0.70f[X]	0.35c	0.56c	0.84d	0.52d	0.84e	3.82e
100:0 SP:PLA	265.26a	55.22a	19.59ab	3.85bc	3.49bc	1.12de	348.52a
75:25 SP:PLA	186.55b	54.85a	11.47b	2.79c	2.14c	1.77bc	259.57b
50:50 SP:PLA	117.43c	33.47b	12.19b	4.97b	3.44bc	1.47cd	172.99c
25:75 SP:PLA	68.69d	25.14b	11.56b	4.16bc	4.56b	2.15b	116.27d
0:100 SP:PLA	26.62e	25.02b	25.05a	15.38a	8.80a	5.64a	106.51d
	<0.0001[W]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Days after potting.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

[W]P-value derived from analysis of variance; NS = not significant.

Table 3.12. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on phosphorus fate and partitioning from *Lantana camara* ‘New Gold’ grown in a closed system for 84 days in 2012.

	Recovered Phosphorus[Z]					
Treatment[Y]	Shoot-P (mg)	Root-P (mg)	Total Plant Tissue-P (mg)	Effluent-P (mg)	Total Recovered-P (mg)	Percent Recovered-P
Control	4.70b[X]	1.97c	6.67c	3.82	10.49	-
100:0 SP:PLA	54.59a	5.84b	60.42b	348.52a	408.94a	90.88a
75:25 SP:PLA	63.18a	8.89a	72.07ab	259.57b	331.63b	73.70b
50:50 SP:PLA	73.84a	9.10a	82.94a	172.99c	255.93c	56.87c
25:75 SP:PLA	58.19a	7.72ab	65.91ab	116.27d	182.18d	40.48d
0:100 SP:PLA	65.48a	8.84a	74.32ab	106.51d	180.82d	40.18d
	<0.0001[W]	*<0.0001*	*<0.0485*	*<0.0001*	*<0.0001*	*<0.0001*

[Z]Recovered phosphorus expressed as amounts (mg); Total Recovered-P (mg) = (Effluent-P + Plant Tissue-P); Percent Recovered-P = [Total Recovered-P (mg) / Applied-P (450 mg·container^{-1})] *100.

[Y]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[X]Values in column followed by different letters are significant according to Tukey's Studentized Range Test (α = 0.05).

[W]P-value derived from analysis of variance; NS = not significant.

Application of 50:50 SP:PLA led to the highest amount of recovered P in plant tissues (Table 3.12). Other P treatments were similar with the exception of 100:0 SP:PLA, which led to slightly lower tissue P accumulation.

Phosphorus application increased growth index throughout the experiment similar to growth in experiment I (Table 3.13). Application of P, regardless of source, increased shoot biomass (Table 3.14) while flower numbers were increased with either P source throughout the experiment (Table 3.15).

Experiment III

Combustion temperature affected water-mediated P dissolution from poultry litter (Figure 3.2). As combustion temperature was increased from 500 to 750 to1000 °C, cumulative P dissolution decreased from 1062 to 369 to 0.75 mg DRP L^{-1} for a 96 hour period. Commercially produced PLA had P dissolution rates in deionized water similar to poultry litter combusted at 1000 °C.

Discussion

Poultry litter ash has been reported as a suitable P source for greenhouse crop production that has liming capability to reduce micronutrient toxicities associated with acidic soils and soilless substrates (Wells et al., 2013). However, the most positive attribute of PLA as a P-fertilizer for greenhouse crop production may be reduction of potential P losses. In the current experiment, lantana fertilized with 100% PLA exhibited reductions in DRP and TP losses of 92% and 69%, respectively compared to lantana fertilized with 100% SP. Reductions in initial DRP losses were disproportionate to the percentage of PLA applied and were greater than expected. For example, replacement of the SP fraction of the P fertilizer with 25, 50, and 75%

Table 3.13. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on growth index of *Lantana camara* ' New Gold' grown in a closed system over an 84 day experimental period in 2012.

Treatment[Z]	Growth Index[Y]						
	14 DAP[X]	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Average
Control	8.67c[W]	14.97b	19.14c	22.58b	28.33b	31.00b	20.78b
100:0 SP:PLA	18.36a	31.19a	37.75ab	41.78a	48.350a	53.06a	38.44a
75:25 SP:PLA	19.19a	30.22a	38.47a	47.03a	50.97a	53.44a	39.89a
50:50 SP:PLA	17.89ab	29.75a	34.86ab	42.22a	48.58a	54.83a	38.02a
25:75 SP:PLA	13.86b	25.47a	31.61ab	41.56a	48.97a	54.61a	36.01a
0:100 SP:PLA	13.89b	24.00a	28.53b	43.92a	49.08a	53.61a	35.50a
	<0.0001[V]	*<0.0001*	*0.0001*	*0.0003*	*0.0007*	*0.0005*	*0.0006*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.

[Y]Growth index was measured in cm as: [(Height + Widest Width + Perpendicular Width) / 3].

[X]Days after potting.

[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

[V]P-value derived from analysis of variance; NS = not significant.

Table 3.14. Effects of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on biomass accumulation of *Lantana camara* 'New Gold' grown in a closed system over an 84 day experimental period in 2012. .

Treatment[Z]	Dry Weight[Y]		
	Shoot	Root	Shoot:Root
Control	9.68b[X]	6.77b	1.44b
100:0 SP:PLA	32.56a	8.88ab	3.75a
75:25 SP:PLA	32.59a	10.19a	3.22a
50:50 SP:PLA	38.04a	10.21a	3.75a
25:75 SP:PLA	27.74a	8.15ab	3.41a
0:100 SP:PLA	32.14a	8.75ab	3.70a
	<0.0001[W]	*0.0282*	*0.0027*

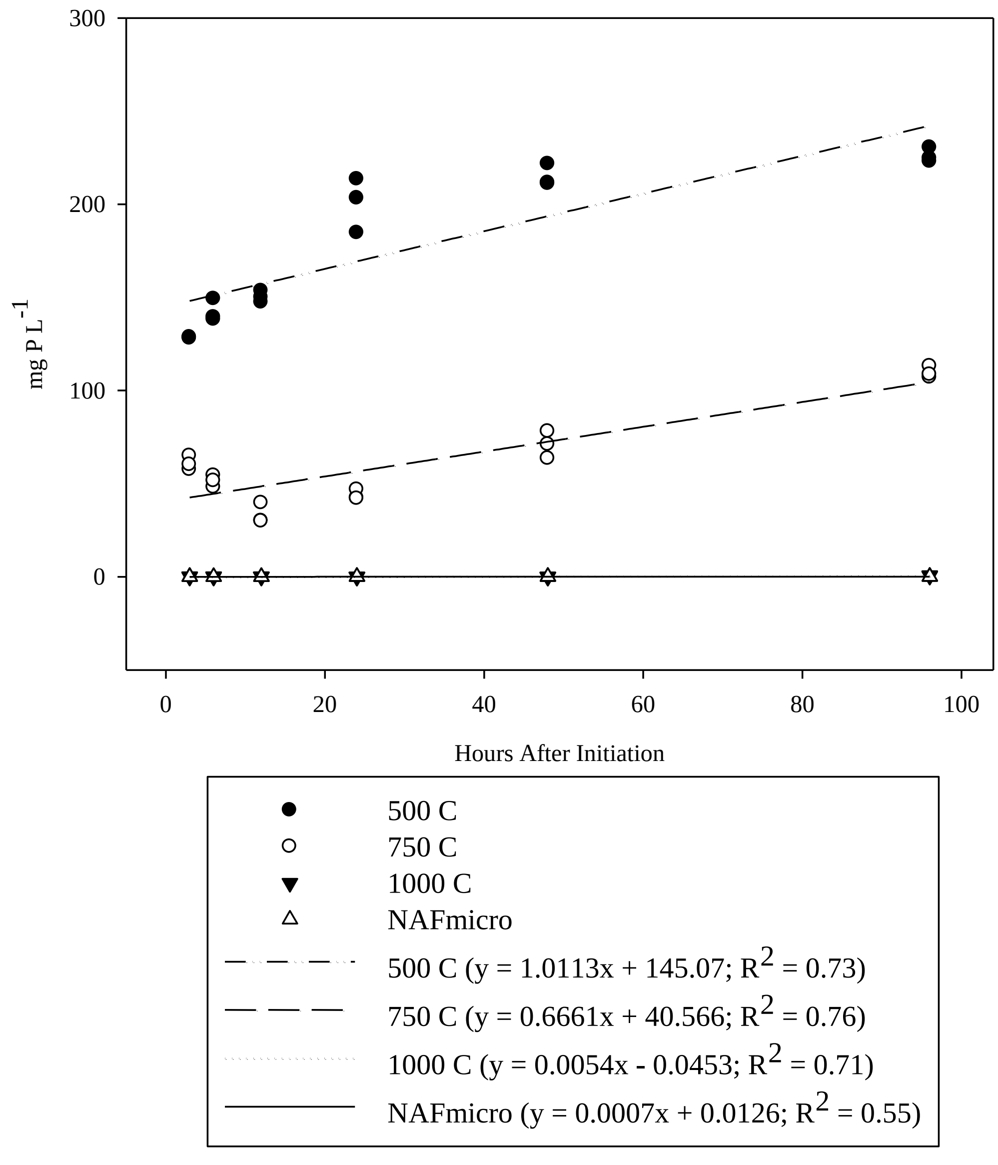
[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[W]P-value derived from analysis of variance; NS = not significant.

Table 3.15. Effect of superphosphate, poultry litter ash, and combinations thereof as phosphorus sources on flower counts of *Lantana camara* 'New Gold' grown in a closed system over an 84 day experimental period in 2012.

Treatment[Z]	Flower Count[Y]						
	14 DAP[X]	28 DAP	42 DAP	56 DAP	70 DAP	84 DAP	Total
Control	4.00b[W]	10.66c	11.67c	6.00c	7.33d	10.67b	50.33d
100:0 SP:PLA	41.00a	71.66ab	126.00b	103.67ab	113.33c	140.00a	595.67c
75:25 SP:PLA	41.33a	89.68ab	160.67a	112.00ab	142.67ab	180.00a	726.33a
50:50 SP:PLA	27.00a	90.33a	145.33ab	102.00ab	121.00bc	153.00a	638.67bc
25:75 SP:PLA	30.67a	72.33ab	143.33ab	92.67b	115.00c	138.33a	592.33c
0:100 SP:PLA	38.67a	67.67b	156.33a	120.00a	148.33a	172.33a	703.33ab
	0.0001[V]	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

[Z]Treatments were: Control = no exogenous P applied; SP = superphosphate; PLA = poultry litter ash.
[Y]Flower buds showing color at the time of data collection.
[X]Days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[V]P-value derived from analysis of variance; NS = not significant.

Figure 3.2. Combustion temperature affects dissolution kinetics of poultry litter phosphorus.



PLA resulted in average initial DRP loss reductions of 45, 70, and 86%, respectively. Use of readily available nutrients early in crop production should be questioned (Altland and Buamscha, 2008) from an environmental, as well as, production standpoint. To amplify on the work of Altland and Buamscha (2008), since plant roots are not fully developed to exploit the entire substrate, high concentrations of soluble nutrients early in the production cycle are most likely unnecessary.

Even though all experimental units received the same volume of water daily, DRP losses decreased each subsequent week for all SP-containing fertilizer treatments but remained stable at 13 mg DRP L^{-1} for 100% PLA the first five weeks after potting (WAP). These differences in DRP losses suggest PLA-P solubility, a factor known to affect P leaching losses, is not dependent on water usage during crop production. According to Raviv and Lieth (2008), solution P concentrations for most greenhouse crops should fall between 5 and 60 mg P L^{-1} while a lower and narrower range of 5 to 10 mg P L^{-1} is recommended for container-grown crops when employing CRFs (Yeager et al., 2007). However, over-application of P is often the result of target N fertilization rates used to determine application of complete, water-soluble fertilizers commonly applied to greenhouse crops (Smith et al., 2004). Monocalcium phosphate, which is water-soluble, is the primary P-containing compound within SP (Prochnow et al., 2003). Although total P content is somewhat similar for SP and PLA, on average 93% of SP-P is present in water-soluble forms (Gowariker, 2009) while a miniscule fraction of PLA-P is considered water soluble (Codling, 2006) likely due to formation of water-insoluble di- and tri-calcium phosphates due to high temperatures during combustion (Van Wazer, 1958). Given the lack of P-sorption capacities of common substrate components (Khandan-Mirkohi and Schenk, 2008; Bilderback, 2001), P is lost from soilless substrates relatively quickly when applied in water-soluble forms. Yeager and Barrett (1984) reported up to 37% of P, applied as superphosphate

(SP), leached within one day post application with up to 76% P losses within 21 days after application. In a subsequent experiment, Yeager and Barrett (1986) reported 80% of applied P leached from a substrate composed of pine bark, peat moss, and sand within 21 days. Therefore, reductions in P losses through application of PLA during container production are a direct result of low water-solubility of PLA-P compared to SP-P.

While low water-solubility of PLA-P is important to achieve P-loss reductions during crop production cycles, it may be seen as too limiting a characteristic for application of PLA for some container crops. However, management of PLA processing conditions may manipulate PLA-P solubility. Codling (2006) reported solubility of P-containing compounds within poultry litter is altered through combustion. Faridullah et al. (2013) combusted chicken and duck litters at differing temperatures and used various extractants, including deionized water, to characterize P solubilities from resultant ashes. Water solubility of P contained within chicken and duck litters was reduced through combustion, but did not differ based on temperatures ranging from 200 to 900 °C. Plant uptake of P was generally not affected by combustion temperature when ashes were applied to a sandy soil. Differences between those results and the current experiment's results may be explained by differences in methodology. In the current experiment, a more dynamic system was employed to characterize dissolution kinetics of P from PLA as opposed to simple extraction techniques. In either case, results of both experiments indicate that water solublility is a poor indicator of plant-available P, further pointing to the need to reduce applications of water-soluble P fertilizers to substrates with low P-sorption capacities.

Although information on PLA-P speciation is not available in the literature, it is presumed that most PLA-P is present as calcium phosphates (Bachmann and Eichler-Lobermann, 2010). While monocalcium phosphate, the primary form of SP-P, has been reported to be water-soluble (Prochnow et al., 2003), high temperatures during poultry litter combustion would likely lead to the formation of water insoluble di- and tricalcium phosphates (Van Wazer, 1958). It is likely that combustion temperature of poultry litter during commercial energy production far exceeds 1000 ˚C (Habetz and Echols, 2006). Therefore, low water solubility of P contained within commercially available PLA, which was applied in greenhouse experiments, is affected by high combustion temperatures. Although, P dissolution from PLA combusted at 1000 ˚C or above was very low in water, plant P uptake was not reduced in Experiments I and II, as previously described. Due to the energy-expensive nature of P uptake in plants (Mills and Jones, 1996), water solubility of P from applied sources may not be a prerequisite for adequate P uptake, especially from soilless substrates.

Given the positive environmental attributes of PLA as a P fertilizer source in container crop production, it is important to evaluate the effect of PLA on plant growth and quality. In these series of experiments growth differences in lantana were inconsistent between years most likely an artifact of environmental conditions. In 2011, lantana fertilized with 100% PLA reduced growth indices 33, 21, and 24% at 42, 56, and 70 DAP, respectively, compared to those fertilized with 100% SP in 2011. These reductions in growth were accompanied with reduced shoot and root biomasses of 41 and 28% for PLA-fertilized lantana compared 100% SP. As the portion of SP increased, as a percentage of P applied, lantana growth and biomass slightly increased. However, in 2012, the differences in growth indices, shoot biomass, and root biomass were not consistently evident between P fertilization treatments. Shoot:root biomass, which commonly indicates P-deficiency in crops (Mengel and Kirkby, 1987), did not differ between P-fertilization treatments in 2011 or 2012; nor did flowering of lantana differ between P-fertilization treatments from 42 to 84 DAP.

Differences in lantana response to P-fertilization treatments in 2011 and 2012 may be the result of environmental conditions. During 2011 lantana was grown at an average temperature of

23.7 °C with shorter light durations compared to 28.4 °C and longer light periods in 2012. Temperature has been shown to affect vigor and rooting of containerized plants (Mathers et al., 2007). Delayed rooting would limit root system interaction with a low soluble P source such as PLA. The interaction of roots with PLA may be an important mechanism for releasing P in plant available forms (Hinsinger, 2001). In a multi-year experiment comparing P fertilizer source and placement on P availability to eucalyptus in an acidic Brazilian oxisol, Dias et al. (2000) reported eucalyptus root systems increased P dissolution rates of low soluble rock phosphates for increased plant uptake. Rhizospheric chemical conditions differ significantly from the surrounding bulk soil or substrate environment due to processes involving ion release, gaseous flux, and exudation of organic ligands. Release of these chemicals around the root alters pH to affect P solubility, thus availability (Hinsinger, 2001).

Other factors such as the availability of Mn can be directly affected by substrate pH (Fonteno et al., 1996; Mills and Jones, 1996; Reed, 1996; Handreck and Black, 2010). Handreck and Black (2010) reported Mn availability in organic potting substrates, unlike mineral soils, is highest between a pH range of 4.0 and 5.0 and declines at pHs above 5.5. Average substrate pH of lantanas fertilized with 100% PLA increased from 5.52 to 6.69 and 5.46 to 6.73 in 2011 and 2012, respectively, compared with those fertilized with 100% SP. Furthermore, 100% SP-fertilized plants experienced larger fluctuations in substrate pH during the course of the experiment than did 100% PLA-fertilized plants in both years indicating incorporation of PLA buffers against large changes in substrate pH during container production cycles. The increase in substrate pH, due to fertilization with PLA, lowered Mn availability and reduced potential for toxicity. Although plant Mn toxicities occur in organic soils and soilless substrates, toxicity levels have been shown to be affected by applications of Fe (Handreck, 1997), K (Alam et al., 2005), Ca (Alam et al., 2006), or Mg (le Bot et al. 1990). In this experiment, Iron, K, Ca, and

Mg were in adequate concentrations with each P source and most likely ameliorated possible Mn toxicities since symptoms were not observed for either P source. In previous research, PLA has been reported to act as a pH adjusting amendment that would not require the same application rates of lime as more acid-forming P sources (Faridullah et al., 2009; Wells et al., 2013).

Post-production lantana were established in a landscape to evaluate the effect of production P-fertility on landscape performance of lantana. Over the seven week observation period, regardless of P source or combination, lantana supplied with adequate P nutrition during production resulted in fastest growth, highest biomass, and increased flowering. However, control plants that received no P fertilization during greenhouse production were able to accumulate adequate P within the landscape to increase growth, but lagged compared to plants that had received P fertilization during greenhouse containerized production. This indicates P management during production can affect lantana growth and establishment within the landscape simply through increasing initial plant size, thereby improving photosynthetic potential.

Conclusions

Mitigation of P losses from containerized plant production sites poses a challenge to responsible growers in the nursery and greenhouse industry. Recycled P, in the form of low water-soluble biomass ash such as PLA, has potential to recycle P and limit P environmental impact. Use of PLA in lantana production reduced DRP and TP losses of 92% and 69%, respectively compared to lantana fertilized with 100% SP. Availability of PLA-P is influenced by root interaction and as a result may not be suitable for all crops and substrate combinations. However, PLA-P solubility can be manipulated during processing by altering combustion temperatures. This would render PLA fertilizer products capable of meeting various crop P requirements and timings.

Application of PLA as a P fertilizer amendment limited lantana growth in some cases, but differences were small, especially in the second year of the experiment. Once installed in the landscape, however, no differences in lantana growth and establishment were observed based on greenhouse production P source. Therefore, from an environmental standpoint, the benefit of great reductions in P losses from container production achieved through PLA application exceeded the slight decreases in plant vigor observed during crop production.

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CHAPTER 4: POULTRY LITTER ASH PLACEMENT AFFECTS PHOSPHORUS DISSOLUTION IN A HORTICULTURAL SUBSTRATE

Introduction

Poultry litter is a biomass source consisting mostly of bird manure and bedding materials (Robinson and Sharpley, 1996) and is a waste product from poultry production that is in great abundance in several areas of the United States. It contains higher amounts of phosphorus (P) than ruminant manures since fowls lack the ability to extract organically-bound P from feeds (Sommers and Sutton, 1980). Poultry litter has been used as a fertilizer source for many agricultural commodities but its usage has been limited due to associated transportation costs (Bernhart et al., 2010) and environmental concerns for surface and ground water impairment (Sharpley et al., 1994; Sharpley et al., 1998). Repeated land applications of poultry litter based on desired nitrogen application rates has led to P accumulation in soils of poultry producing regions (Maguire and Mullins, 2008) and accelerated eutrophication of adjacent water bodies (White et al., 2010).

Processes to concentrate nutrients in poultry litter in order to reduce transportation costs and alleviate environmental concerns have included compaction (Bernhart et al. 2010), pelletization (McMullen, 2005), composting (Brodie et al., 2000), P removal (Szogi et al. 2008), gasification (Priyadarsan et al. 2004), and combustion (Codling et al., 2002; Shiemenz and Eicler-Lobermann, 2010). However, combusting poultry litter may be the most efficient means to concentrate P and reduce environmental concerns associated with raw poultry litter application. The combustion process is more complicated for poultry litter than for traditional fuel sources due to inconsistency of litter composition, moisture content, and relatively high ash content (Jia and Anthony, 2011). Over time combustion has become feasible due to technological advances in incinerator configurations (Habetz and Echols, 2006). For example, Fibrominn is a power plant located in Benson, Minnesota that is currently producing 55 MW of energy per year through the co-combustion of poultry litter and wood; with poultry litter constituting more that 60% of the furnace feedstock. The resultant ash is utilized as a nutrient-rich fertilizer for agronomic crops. The majority of the ash content from the furnace feedstock is generated from the poultry litter (IPEP, 2006; Jia and Anthony, 2011) since wood has a low ash content (Misra et al., 1993).

Few experiments have investigated the potential of poultry litter ash (PLA) as a fertilizer amendment. In a laboratory experiment, Codling (2006) reported that PLA contained high concentrations of P, but that most PLA-P was water-insoluble. However, PLA was a successful P source for wheat (*Triticum aestivum* L) in a previous experiment (Codling et al., 2002). Faridullah et al. (2009) reported chicken and duck litter ashes to be suitable nutrient sources for Japanese mustard spinach (*Brassica rapa* L.) grown on a sandy soil. Bachmann and Eichler-Lobermann, (2010) reported that PLA supplied adequate amounts of P to buckwheat (*Fagopyrum escultentum* Lifago), oil radish (*Raphnus sativus oleiformis* Adagio), phacelia (*Phacelia tanacetifolia* Lisette), and ryegrass (*Lolium multiflorum westerwoldicum* Gordo) while also enriching soil-P pools. In recent experiments, PLA has been used to grow verbena (*Verberna canadensis* Britton 'Homestead Purple') and lantana (*Lantana camara* L. 'New Gold') while reducing leachate-DRP and effluent-TP losses 92 and 69%, respectively (Wells et al., 2013).

While PLA application reduces P losses from a soilless substrate compared with a water-soluble P source when incorporated within the substrate, no studies have characterized the effect PLA placement has on plant growth and P leaching losses. In a related experiment, Warren et al. (1997), reported reductions of more than 80% of leachate-TP when controlled release fertilizers (CRFs) were surface applied to a soilless substrate, as opposed to incorporated within the substrate. In 2001, Warren et al. (2001) concluded increases in P-leaching, due to increased P solubility, was a result of either more uniform dispersal of or increased moisture surrounding incorporated fertilizer prills compared with those that were surface-applied. Therefore, the objective of this experiment was to characterize effects PLA application rate and placement have on plant growth, quality, and leachate-P losses during greenhouse crop production.

Materials and Methods

Experiment setup

Forty *Lantana camara* L. 'New Gold' and *Verbena canadensis* Britton 'Homestead Purple' plants growing in 105-cell trays were selected for uniform quality and size prior to the initiation of experiments on 6 September 2011 and 29 February 2012. For each species, two plants were transplanted into 20 1.6-L containers for a total of 40 containers. Substrate was composed of amended pine bark, screened to <0.38 cm, and peat moss (4:1; v:v). Pre-plant incorporated amendments, common to all treatments, consisted of 0.89 kg m^{-3} of micronutrient package (Micromax, Scotts Company, Marysville, OH), 0.25 kg K m^{-3} (0N-0P-35.7K), and 1.5 kg pulverized dolomitic limestone m^{-3}. Phosphorus treatment source was PLA (10% P) screened to <2.0 mm to remove large agglomerations and extraneous material, either pre-plant incorporated or post-plant topdressed uniformly on the substrate surface, at either 140 or 280 g P m^{-3}. Poultry litter ash used in this experiment was the product of commercial energy production via combustion of poultry litter and was obtained courtesy of North American Fertilizer, LLC. Containers were arranged in a 2 (P rate) x 2 (PLA placement) factorial in a completely randomized design with five single container replications. Treatments were: 1) pre-plant incorporated PLA at 280 g P m^{-3} 2) pre-plant incorporated PLA at 140 g P m^{-3} 3) post-plant topdressed PLA at 280 g P m^{-3} 4) post-plant topdressed PLA at 140 g P m^{-3}. All plants were maintained under greenhouse conditions at 24.1 °C and 28.2 °C in 2011 and 2012, respectively, with no supplemental irradiance, for 42 and 70 d for verbena and lantana, respectively. During the experiment, plants were supplied with 350 ml water d^{-1} including 120 ml aliquots $container^{-1}$ N at 250 mg NH_4NO_3 L^{-1}.

Plant response

Growth was measured bi-weekly using a growth index [(height + widest width + perpendicular width) / 3]. Flowers were quantified on a bi-weekly basis in 2012 by counting flower buds showing color. At the end of each experimental period, shoots and roots were harvested, separated with roots washed to remove substrate, dried at 60 °C for 72 hours, and biomass recorded. Leaf samples of 0.5 g, composed of the most recently matured leaves, were milled to <0.5 mm (Thomas Wiley® Mini-Mill; Thomas Scientific, Swedesboro, NJ) and digested in concentrated nitric acid at an average temperature of 120 °C. Samples were then diluted to 20 ml with deionized water, vortexed, and filtered before being analyzed for elemental Al, B, Ca, Cu, Fe, Mg, Mn, Mo, P, K, Na, S, and Zn using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Spectro ArCos; SPECTRO Analytical Instruments, Kleve, Germany; Louisiana State University Soil Testing and Plant Analysis Laboratory, Baton Rouge, LA).

Leachate collection and P analyses

Leachate from three replicates per treatment of *Lantana camara* L. 'New Gold' was collected weekly following the Virginia Tech extraction method (Wright, 1986). Leachate samples were cooled to room temperature (21 ºC) and leachate-pH and EC measured (Orion Star A215 solution analyzer, Thermo Scientific Inc., Beverly, MA). In the laboratory, a 15 ml aliquot of leachate was filtered through a 0.45 µm disposable nylon filter (22 mm diameter, Whatman™; GE Healthcare UK Limited, Buckinghamshire) in preparation for dissolved reactive phosphorus (DRP) analysis using the molybdate colorimetric method developed by Murphy and Riley (1962) and modified by Pote and Daniel (2000). Dissolved reactive P was quantified at 880 nm using a spectrophotometer (Spectronic 20, Bausch and Lomb, Rochester, NY).

Statistical analysis

Verbena and lantana were arranged in completely randomized designs with five replicates on raised benches in a greenhouse. Growth index, flower count, plant dry weight, leachate-pH and EC, and tissue nutrient concentration were analyzed using the mixed procedure in SAS/STAT® statistical software (SAS Institute Inc., 2011). Where appropriate, means for each measurement at each collection interval were separated using Tukey's Honest Significant Difference Test at a significance level of 0.05. All data were analyzed using SAS/STAT® statistical software (SAS Institute Inc., 2011).

Results

Plant response

Verbena

In general, growth index of verbena was not affected by P rate in 2011 (Table 4.1). Over the 42-day experiment, average growth index increased 19% from 17.30 to 20.65 for verbena fertilized with incorporated PLA compared with PLA applied as a topdressing. While individual factors did not generally affect growth index of verbena in 2012, an interesting interaction occurred in which increasing PLA application rate increased growth index of verbena fertilized with incorporated PLA from 29.53 to 41.03 at 28 days after potting (DAP) and from 35.33 to 47.33 at 42 DAP, but did not affect growth of verbena fertilized with PLA as a topdressing. In 2011, shoot biomass was slightly increased, from 15.45 to 16.85 g when PLA application rate was decreased from 280 to 140 g P m^{-3} (Table 4.2). An identical increase in biomass was observed when PLA was incorporated into the substrate, as opposed to applied as a topdressing.

Interestingly, root biomass followed the same trends almost exactly (Table 4.2). An interaction was observed in which verbena root biomass increased 74% from 2.86 to 4.99 g when PLA application rate decreased from 280 to 140 g P m^{-3} and PLA was applied as a topdressing, but was unaffected by PLA application rate when PLA was incorporated into the substrate. In 2012, verbena flowering was not affected by PLA application rate but was increased for the experiment 26% from 42.17 to 53.33 when PLA was incorporated instead of topdressed (Table 4.3).

Tissue nutrient accumulation

While effects of PLA application rate and placement were inconsistent for some nutrients, foliar Mn and P concentrations were affected by PLA placement in both years (Table 4.4). Foliar Mn decreased 65% from 208.09±14.01 to 73.25±13.92 mg Mn kg^{-1} in 2011 and 40% from 118.61±9.17 to 71.32±22.87 mg Mn kg^{-1} in 2012 when PLA was incorporated into the substrate instead of applied as a topdressing. In contrast, foliar P concentrations increased from 0.23±0.05 to 0.29±0.05% P in 2011 and 0.23±0.03 to 0.32±0.02% P in 2012. A similar response was observed for verbena roots in 2011 in which root Mn concentration decreased 85% from 209±82.46 to 30.44±11.25 mg Mn kg^{-1} and root P concentration increased 67% from 0.15±0.05 to 0.25±0.07% when PLA was incorporated into the substrate instead of applied as a topdressing (Table 4.5).

Lantana

Increasing PLA application rate from 140 to 280 g P m^{-3} reduced lantana growth index from 15.7 to 11.95 at 28 DAP and from 17.43 to 13.35 at 42 DAP in 2011, but generally did not elicit the same response in 2012 (Table 4.6). Although PLA placement did not affect growth index of lantana in 2011, lantana fertilized with PLA incorporated into the substrate had higher

Table 4.1. Effects of poultry litter ash rate and placement on growth index of *Verbena canadensis* 'Homestead Purple' over a 42 day experimental period.

Rate (g m^{-3})	Placement	Growth Index 2011			
		14 DAP	28 DAP	42 DAP	Average
140	-	14.78a	16.80a	27.70a	19.76a
280	-	13.13b	14.84a	26.58a	18.18a
		0.0483	*NS*	*NS*	*NS*
-	Topdressed	12.41b	13.93b	25.55a	17.30b
-	Incorporated	15.50a	17.71a	28.73a	20.65a
		0.0011	*0.0013*	*NS*	*0.019*
140	Topdressed	13.65ab	15.63ab	27.10a	18.79a
280	Topdressed	11.17b	12.23b	24.00a	15.80a
140	Incorporated	15.92a	17.97a	28.30a	20.73a
280	Incorporated	15.08a	17.45a	29.17a	20.57a
		NS	*NS*	*NS*	*NS*

Rate (g m^{-3})	Placement	Growth Index 2012			
		14 DAP	28 DAP	42 DAP	Average
140	-	17.93a	33.00a	38.35b	29.76a
280	-	18.46a	35.94a	44.76a	33.06a
		NS	*NS*	*0.0012*	*NS*
-	Topdressed	14.15b	33.67a	41.78a	29.87a
-	Incorporated	22.24a	35.28a	41.33a	32.95a
		0.0007	*NS*	*NS*	*NS*
140	Topdressed	14.61bc	36.47ab	41.36b	30.81a
280	Topdressed	13.69c	30.86b	42.19ab	28.92a
140	Incorporated	21.25ab	29.53b	35.33c	28.70a
280	Incorporated	23.22a	41.03a	47.33a	37.19a
		NS	*0.0006*	*0.0027*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Growth index was measured in cm as: [(Height + widest width + perpendicular width) / 3].
[X]Days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[V]P-value derived from analysis of variance; NS = not significant.

Table 4.2. Effects of poultry litter ash rate and placement on biomass accumulation of *Verbena canadensis* 'Homestead Purple' over a 42 day experimental period.

Rate ($g\ m^{-3}$)	Placement[Z]	2011 Shoot[Y]	2011 Root	2011 Shoot:Root
140	-	16.85a[X]	5.27a	3.23b
280	-	15.45b	3.91b	4.14a
		0.005[W]	*0.0002*	*<0.0001*
-	Topdressed	15.45b	3.92b	4.11a
-	Incorporated	16.85a	5.26a	3.25b
		0.005	*0.0002*	*<0.0001*
140	Topdressed	16.30ab	4.99a	3.28b
280	Topdressed	14.60b	2.86b	4.95a
140	Incorporated	17.40a	5.56a	3.18b
280	Incorporated	16.30ab	4.96a	3.32b
		NS	*0.0067*	*<0.0001*

Rate ($g\ m^{-3}$)	Placement	2012 Shoot	2012 Root	2012 Shoot:Root
140	-	24.10a	10.43a	2.32b
280	-	25.17a	8.92b	2.82a
		NS	*0.0122*	*0.0088*
-	Topdressed	23.53b	9.38a	2.54a
-	Incorporated	25.74a	9.98a	2.60a
		0.0022	*NS*	*NS*
140	Topdressed	24.02b	10.33a	2.34a
280	Topdressed	23.04b	8.43a	2.74a
140	Incorporated	24.18b	10.53a	2.30a
280	Incorporated	27.30a	9.42a	2.90a
		0.0038	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

Table 4.3. Effects of poultry litter ash rate and placement on flower counts of Verbena canadensis 'Homestead Purple' over a 42 day experimental period in 2012.

Rate	Placement[Z]	Flower Counts[Y]			
($g\ m^{-3}$)		14 DAP[X]	28 DAP	42 DAP	Total
140	-	9.17a[W]	16.33a	20.83a	46.33a
280	-	8.17a	17.33a	23.67a	49.17a
		NS[V]	*NS*	*NS*	*NS*
-	Topdressed	7.50b	15.33a	19.33b	42.17b
-	Incorporated	9.83a	18.33a	25.17a	53.33a
		0.0068	NS	0.0212	0.0026
140	Topdressed	9.33a	14.67a	19.33a	43.33b
280	Topdressed	5.67b	16.00a	19.33a	41.00b
140	Incorporated	9.00a	18.00a	22.33a	49.33ab
280	Incorporated	10.67a	18.67a	28.00a	57.33a
		0.0033	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[Y]Flower buds showing color.

[X]Days after potting.

[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).

[V]P-value derived from analysis of variance; NS = not significant.

growth indices than those fertilized with PLA applied as a topdressing at every measurement date in 2012. Another trend was observed in 2012 in which lantana growth index was decreased at the higher PLA application rate when PLA was applied as a topdressing instead of incorporated into the substrate.

Shoot biomass of lantana was not affected by P rate in 2011 or 2012 (Table 4.7). However, shoot biomass of lantana fertilized with PLA incorporated into the substrate increased 32% from 8.18 to 10.78 g in 2011 and 16% from 23.50 to 27.23 g in 2012 compared those

Table 4.4. Effects of poultry litter ash rate and placement on foliar nutrient concentrations of *Verbena canadensis* 'Homestead Purple' grown in an experiment lasting 42 days.

Rate	Placement[Z]	2011				
(g m^{-3})		Ca[Y]	Mg	Mn	P	K
140	-	1.41a[X]	0.68a	149.27a	0.23b	1.97b
280	-	1.12b	0.63b	132.07b	0.29a	2.66a
		0.0084[W]	*0.0103*	*0.0285*	*0.0192*	*0.0025*
-	Topdressed	1.10b	0.66a	208.09a	0.23b	2.71a
-	Incorporated	1.42a	0.65a	73.25b	0.29a	1.92b
		0.0054	*NS*	*<0.0001*	*0.0093*	*0.0012*
140	Topdressed	1.18b	0.66ab	214.38a	0.20b	2.35ab
280	Topdressed	1.04b	0.64ab	201.80a	0.25ab	3.07a
140	Incorporated	1.63a	0.71a	84.17b	0.26ab	1.59c
280	Incorporated	1.20b	0.62b	62.34b	0.32a	2.25bc
		NS	*NS*	*NS*	*NS*	*NS*
		2012				
		Ca	Mg	Mn	P	K
140	-	0.74a	0.45a	102.58a	0.27a	1.67a
280	-	0.67a	0.45a	87.34a	0.29a	1.85a
		NS	*NS*	*NS*	*NS*	*NS*
-	Topdressed	0.83a	0.41a	118.61a	0.23b	1.76a
-	Incorporated	0.58a	0.49a	71.32b	0.32a	1.76a
		NS	NS	0.0003	0.0001	NS
140	Topdressed	0.67a	0.39a	117.57a	0.21b	1.50b
280	Topdressed	0.50a	0.43a	119.65a	0.25b	2.03a
140	Incorporated	0.82a	0.52a	87.59ab	0.32a	1.84ab
280	Incorporated	0.84a	0.46a	55.04b	0.33a	1.67ab
		NS	*NS*	*NS*	*NS*	*0.0022*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Macronutrients reported as percentage of dry matter. Mn reported in mg·kg^{-1} dry matter.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[W]P-value derived from analysis of variance; NS = not significant.

Table 4.5. Effects of poultry litter ash rate and placement on root nutrient concentrations of *Verbena canadensis* 'Homestead Purple' grown in an experiment lasting 42 days in 2011.

Rate	Placement[Z]					
($g\ m^{-3}$)		Ca[Y]	Mg	Mn	P	K
140	-	0.25a[X]	0.20a	103.43a	0.16b	1.42b
280	-	0.24a	0.19a	136.01a	0.24a	2.01a
		NS[W]	*NS*	*NS*	*0.0197*	*0.0117*
-	Topdressed	0.26a	0.20a	209.00a	0.15b	1.99a
-	Incorporated	0.23a	0.19a	30.44b	0.25a	1.44b
		NS	*NS*	*0.0007*	*0.0047*	*0.0161*
140	Topdressed	0.26a	0.20a	172.91ab	0.12b	1.74ab
280	Topdressed	0.27a	0.20a	245.07a	0.18ab	2.25a
140	Incorporated	0.24a	0.20a	33.94b	0.2ab	1.11b
280	Incorporated	0.22a	0.18a	26.95b	0.29a	1.78ab
		NS	*NS*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Macronutrients reported as percentage of dry matter. Mn reported in $mg{\cdot}kg^{-1}$ dry matter.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

fertilized with PLA applied as a topdressing. Root biomass of lantana decreased from 4.48 to 3.17 g in 2011 when PLA application rate decreased from 140 to 280 g P m^{-3} in 2011, but no differences in root biomass were evident between PLA application rates in 2012 (Table 4.7). However, in 2012 lantana root biomass increased slightly from 8.78 to 9.95 g when PLA was topdressed as opposed to incorporated. No consistent trend was observed for shoot:root biomass between years (Table 4.7).

Table 4.6. Effects of poultry litter ash rate and placement on growth index of *Lantana camara* 'New Gold' over a 70 day experimental period.

Rate	Placement[Z]	Growth Index[Y] 2011					
($g\ m^{-3}$)		14 DAP[X]	28 DAP	42 DAP	56 DAP	70 DAP	Average
140	-	13.65a[W]	15.70a	17.43a	32.10a	36.00a	22.98a
280	-	10.50a	11.95b	13.35b	26.70a	29.53a	18.41a
		NS[V]	*0.045*	*0.039*	*NS*	*NS*	*NS*
-	Topdressed	10.93a	12.50a	14.0a	26.93a	30.63a	19.00a
-	Incorporated	13.22a	15.15a	16.78a	31.87a	34.90a	22.38a
		NS	*NS*	*NS*	*NS*	*NS*	*NS*
140	Topdressed	12.93a	15.47a	17.27a	31.07a	34.47a	22.24a
280	Topdressed	8.93a	9.53a	10.73a	22.80a	26.80a	15.76a
140	Incorporated	14.37a	15.93a	17.60a	33.13a	37.53a	23.71a
280	Incorporated	12.07a	14.37a	15.97a	30.60a	32.27a	21.05a
		NS	*NS*	*NS*	*NS*	*NS*	NS

Rate	Placement	Growth Index 2012					
($g\ m^{-3}$)		14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	Average
140	-	10.82b	19.5b	31.53a	45.39a	50.53a	31.55a
280	-	12.35a	21.85a	30.61a	45.25a	49.89a	31.99a
		NS	*0.0295*	*NS*	*NS*	*NS*	*NS*
-	Topdressed	9.79b	18.74b	29.52b	42.68b	44.58b	29.06a
-	Incorporated	13.38a	22.61a	32.62a	47.96a	55.83a	34.48a
		0.0005	*0.0024*	*0.0333*	*0.03*	*0.0228*	*NS*
140	Topdressed	9.78b	19.86b	32.9a	44.92ab	47.50a	30.87a
280	Topdressed	9.81b	17.61b	26.75b	40.44b	41.67a	27.26a
140	Incorporated	11.86b	19.14b	30.78ab	45.86ab	53.56a	32.24a
280	Incorporated	14.89a	26.08a	34.46a	50.06a	58.11a	36.72a
		0.0444	*0.0008*	*0.0051*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Growth index was measured in cm as: [(Height + widest width + perpendicular width) / 3].
[X]Days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[V]P-value derived from analysis of variance; NS = not significant.

Flowering of lantana was typically not affected by P rate in 2012 (Table 4.8) However, lantana fertilized with PLA incorporated into the substrate had increased flower numbers at each measurement date starting at 14 DAP compared with those fertilized with PLA applied as a topdressing. Flower numbers of lantana were increased for the 70-d experimental period from 378 to 440 when PLA was incorporated into the substrate instead of applied as a topdressing.

Tissue nutrient accumulation

Similar to the results concerning verbena nutrient uptake, lantana foliar Mn and P concentrations were affected by PLA rate and placement (Table 4.9). As PLA application rate increased from 140 to 280 g P m^{-3} lantana foliar Mn concentrations decreased from 209.62±54.02 to 155.84±50.83 mg kg^{-1} in 2011 and from 188.3±56.82 to 137.25±39.24 mg kg^{-1} in 2012. Similarly, and more markedly, foliar Mn decreased from 230.49±31.12 to 34.97±28.16 mg kg^{-1} in 2011 and from 205.1±39.13 to 120.45±22.4 mg kg^{-1}in 2012 when lantana were fertilized with substrate-incorporated PLA instead of PLA applied as topdressing. Similar, yet opposite trends were observed for lantana foliar P concentrations. Lantana foliar P concentrations increased from 0.25±0.05 to 0.28±0.05% P in 2011 and from 0.26±0.05 to 0.32±0.08% P in 2012 as PLA application rate increased from 140 to 280 g P m^{-3}. Application method of PLA had a similar, but more marked effect on lantana foliar P concentrations. Incorporation of PLA into the substrate increased lantana foliar P concentrations from 0.22±0.02 to 0.32±0.02% P in 2011 and from 0.24±0.03 to 0.34±0.06% P in 2012 compared with PLA applied as a topdressing. Lantana root Mn and P concentrations followed similar trends compared to foliar results with root Mn decreasing 50% from 89.45±11.16 to 45.16±21.42 mg Mn kg^{-1} and root P increasing from 0.10±0.01 to 0.15±0.01% P in 2011 when PLA was incorporated into the substrate instead of applied as a topdressing (Table 4.10).

Table 4.7. Effects of poultry litter ash rate and placement on biomass accumulation of *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.

Rate ($g\ m^{-3}$)	Placement[Z]	2011 Shoot[Y]	2011 Root	2011 Shoot:Root
140	-	10.19a[X]	4.48a	3.21a
280	-	8.76a	3.17b	2.31b
		NS[W]	*0.0194*	*0.0092*
-	Topdressed	8.18b	3.40a	2.86a
-	Incorporated	10.78a	4.24a	2.66a
		0.0239	*NS*	*NS*
140	Topdressed	9.36a	4.00ab	2.45a
280	Topdressed	6.99a	2.79b	3.27a
140	Incorporated	11.03a	4.95a	2.17a
280	Incorporated	110.53a	3.54a	3.16a
		NS	*NS*	*NS*

Rate ($g\ m^{-3}$)	Placement	2012 Shoot	2012 Root	2012 Shoot:Root
140	-	25.99a	9.62a	2.59a
280	-	24.79a	9.11a	2.62a
		NS	*NS*	*NS*
-	Topdressed	23.50b	9.95a	2.31b
-	Incorporated	27.23aa	8.78b	2.90a
		0.0357	*0.0368*	*0.0004*
140	Topdressed	25.01a	10.21a	2.40bc
280	Topdressed	21.90a	9.70a	2.22c
140	Incorporated	26.88a	9.02a	2.78ab
280	Incorporated	27.57a	8.53a	3.02a
		NS	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Shoot and root dried biomasses were measured in grams while Shoot:Root ratio is unitless.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

Table 4.8. Effects of poultry litter ash rate and placement on flower counts of *Lantana camara* 'New Gold' over a 70 day experimental period in 2012.

Rate	Placement[Z]	Flower Counts[Y]					
($g\ m^{-3}$)		14 DAP[X]	28 DAP	42 DAP	56 DAP	70 DAP	Total
140	-	23.83a[W]	46.83a	131.33a	97.67a	106.83b	406.50a
280	-	26.00a	42.67a	131.33a	95.50a	115.67a	411.17a
		NS[V]	*NS*	*NS*	*NS*	*0.0237*	*NS*
-	Topdressed	23.83a	36.33b	122.17b	89.83b	105.50b	377.67b
-	Incorporated	26.00a	53.17a	140.50a	103.33a	117.00a	440.00a
		NS	<0.0001	0.002	0.0081	0.0067	0.0004
140	Topdressed	24.00a	42.67b	123.00ab	96.67ab	108.00b	394.33bc
280	Topdressed	23.67a	30.00c	121.33b	83.00b	103.00b	361.00c
140	Incorporated	23.67a	51.00ab	139.67ab	98.67ab	105.67b	418.67ab
280	Incorporated	28.33a	55.33a	141.33a	108.00a	128.33a	461.33a
		NS	*0.0064*	*NS*	*0.0176*	*0.0024*	*0.0069*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Flower buds showing color.
[X]Days after potting.
[W]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[V]P-value derived from analysis of variance; NS = not significant.

Substrate Leachate-pH and EC

Substrate leachate-pH measured from lantana was typically increased by increasing PLA application rate from 140 to 280 g P m-3 (Table 4.11). Similarly, incorporation of PLA into the substrate increased substrate leachate-pH compared with PLA applied as a topdressing. Leachate-EC was higher 7 to 42 DAP in 2011 and at every measurement date in 2012 for lantana fertilized at 280 g P m^{-3} than for those fertilized with 140 g P m^{-3} (Table 4.12). Applying PLA as a topdressing increased leachate-EC of lantana compared with incorporation of PLA into the substrate.

Table 4.9. Effects of poultry litter ash rate and placement on foliar nutrient concentrations of *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.

Rate (g m^{-3})	Placement[Z]	2011				
		Ca[Y]	Mg	Mn	P	K
140	-	0.74a[X]	0.41a	209.62a	0.25b	2.23a
280	-	0.78a	0.39a	155.84b	0.28a	2.29a
		NS[W]	*NS*	*<0.0001*	*0.0006*	*NS*
-	Topdressed	0.65b	0.41a	230.49a	0.22b	2.31a
-	Incorporated	0.86a	0.39a	134.97b	0.32a	2.21a
		0.0139	*NS*	*<0.0001*	*<0.0001*	*NS*
140	Topdressed	0.67a	0.42a	258.79a	0.20d	2.34a
280	Topdressed	0.63a	0.41a	202.20b	0.23c	2.28a
140	Incorporated	0.80a	0.41a	160.45c	0.30b	2.12a
280	Incorporated	0.92a	0.37a	109.48d	0.33a	2.31a
		NS	*NS*	*NS*	*NS*	*NS*
		2012				
		Ca	Mg	Mn	P	K
140	-	0.69a	0.30b	188.30a	0.26b	1.40a
280	-	0.71a	0.33a	137.25b	0.32a	1.44a
		NS	*0.0158*	*0.0003*	*0.0035*	*NS*
-	Topdressed	0.62b	0.27b	205.10a	0.24b	1.47a
-	Incorporated	0.78a	0.37a	120.45b	0.34a	1.37b
		<0.0001	<0.0001	<0.0001	0.0002	NS
140	Topdressed	0.66b	0.27c	237.90a	0.22b	1.48a
280	Topdressed	0.57c	0.27c	172.29b	0.26b	1.46a
140	Incorporated	0.71b	0.33b	138.70bc	0.29b	1.32a
280	Incorporated	0.85a	0.40a	102.20c	0.39a	1.41a
		<0.0001	*0.0188*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Macronutrients reported as percentage of dry matter. Mn reported in mg·kg^{-1} dry matter.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[W]P-value derived from analysis of variance; NS = not significant.

Leachate-Dissolved Reactive Phosphorus

In general, as P rate increased from 140 to 280 g P m^{-3} DRP leachate losses increased 30% from 5.51±3.16 to 7.14±3.94 mg P L^{-1} in 2011 and 18% from 5.65±3.46 to 6.69±3.84 mg P L^{-1} in 2012 (Tables 4.13 and 4.14). Leachate-DRP losses were not proportionate to PLA application rate increases. Interestingly, PLA placement method appeared to have a more pronounced effect on leachate-DRP in both years compared to P application rate. On average, leachate-DRP was increased 127% from 3.87±1.11 to 8.77±3.66 mg P L^{-1} in 2011and 141% from 3.62±0.98 to 8.72±3.59 mg P L^{-1} in 2012 for PLA incorporated within the substrate than applied as a topdressing.

Discussion

Placement of PLA affected P availablity in the substrate. Incorporation of PLA within the substrate increased average leachate-DRP 127 and 141% in 2011 and 2012, respectively, compared to topdressing applications. Given the nature of P uptake by plants, it is likely that root system-PLA interaction accelerated P dissolution and plant uptake. Phosphorus uptake was increased through root system interaction with low soluble rock phosphates in a multi-year experiment evaluating P source and placement on eucalyptus growth in an acidic soil (Dias et al., 2000). Processes including ion release, gaseous flux, and organic ligand exudation, can alter rhizospheric chemical conditions in order to enhance P solubility and uptake from soils (Hinsinger, 2001). While rhizospheric chemical parameters were not measured directly in this experiment, based on plant tissue analyses greater uptake was most likely a result of increased root and P interaction from PLA incorporated within the substrate. In addition to root-P interactions, organic acids within the substrate, not originating from plant roots, may have also affected P solubility (Bolan et al., 1994).

Table 4.10. Effects of poultry litter ash rate and placement on root nutrient concentrations of *Lantana camara* 'New Gold' grown in an experiment lasting 70 days in 2011.

Rate ($g\ m^{-3}$)	Placement[Z]	Ca[Y]	Mg	Mn	P	K
140	-	0.25a[X]	0.23a	79.34a	0.11b	0.21b
280	-	0.26a	0.25a	55.27b	0.13a	0.25a
		NS[W]	*NS*	*0.008*	*0.0015*	*0.0174*
-	Topdressed	0.23a	0.23a	89.45a	0.10b	0.22a
-	Incorporated	0.28a	0.25a	45.16b	0.15a	0.24a
		NS	*NS*	*0.0002*	*<0.0001*	*NS*
140	Topdressed	0.23a	0.24a	99.46a	0.09c	0.20a
280	Topdressed	0.23a	0.23a	79.45ab	0.10c	0.24a
140	Incorporated	0.28a	0.23a	59.23bc	0.13b	0.22a
280	Incorporated	0.29a	0.27a	31.10c	0.16a	0.26a
		NS	*NS*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Macronutrients reported as percentage of dry matter. Mn reported in $mg{\cdot}kg^{-1}$ dry matter.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

In either case, P concentrations in plant biomass were increased when PLA was incorporated into the substrate. In contrast, topdressed PLA remained at or near the substrate surface during the experiment and limited PLA-root interactions. Consequently, leachate-DRP and biomass P concentrations were reduced for PLA topdressing applications compared to incorporated PLA treatments. In a previous related experiment, tissue nutrient concentrations, including shoot and root P, were increased by incorporating controlled-release fertilizers (CRF) into the growing substrate, as opposed to surface application (Warren, et al. 2001). In fact, total plant P content was reduced >70%, regardless of CRF formulation, when the fertilizer was topdressed rather than incorporated. Leachate-TP was also increased up to 88% (Warren et al.,

Table 4.11. Effects of poultry litter ash rate and placement on substrate leachate-pH measured from *Lantana camara* 'New Gold' grown in an experiment lasting 70 days.

Rate	Placement[Z]	Substrate Leachate-pH									
		2011									
(g m^{-3})		7 DAP[Y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
140	-	6.01a[X]	6.02a	6.48a	6.74a	6.54b	6.26a	6.32b	6.44a	6.26b	6.34a
280	-	6.00a	6.06a	6.56a	6.81a	6.81a	6.39a	6.48a	6.45a	6.42a	6.44a
		NS[W]	*NS*	*NS*	*NS*	*0.0086*	*NS*	*0.0122*	*NS*	*0.0203*	*NS*
-	Topdressed	5.83b	5.71b	6.36b	6.68a	6.55b	6.26a	6.37a	6.37a	6.21b	6.26b
-	Incorporated	6.19a	6.37a	6.68a	6.88a	6.80a	6.39a	6.43a	6.2a	6.48a	6.53a
		0.0038	*0.0005*	*0.0019*	*NS*	*0.0128*	*NS*	*NS*	*NS*	*0.0013*	*0.0016*
140	Topdressed	6.05ab	5.78bc	6.38b	6.77ab	6.46b	6.19a	6.28b	6.50a	6.21b	6.29b
280	Topdressed	5.60c	5.63c	6.33b	6.58b	6.65ab	6.32a	6.45ab	6.23a	6.20b	6.22b
140	Incorporated	5.98bc	6.26ab	6.57ab	6.71ab	6.63ab	6.32a	6.36ab	6.39a	6.31b	6.39b
280	Incorporated	6.40a	6.48a	6.79a	7.05a	6.96a	6.47a	6.51a	6.66a	6.64a	6.66a
		0.0014	*NS*	*NS*	*0.0322*	*NS*	*NS*	*NS*	*0.0484*	*0.0154*	*0.0181*
		2012									
140	-	5.68a	6.02a	6.21b	6.32b	6.54b	6.58a	6.51b	6.42b	6.31b	6.29b
280	-	5.82a	6.00a	6.36a	6.50a	6.67a	6.77a	6.73a	6.60a	6.58a	6.50a
		NS	*NS*	*0.0063*	*0.0007*	*0.0265*	*NS*	*0.0002*	*0.0007*	*0.0003*	*0.0136*
-	Topdressed	5.59b	5.84b	6.12b	6.28b	6.41b	6.42b	6.57b	6.35b	6.25b	6.20b
-	Incorporated	5.92a	6.18a	6.46a	6.53a	6.80a	6.79a	6.66a	6.67a	6.58a	6.58a
		0.0054	*0.0004*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0002*	*0.024*	*<0.0001*	*<0.0001*	*0.0004*
140	Topdressed	5.75b	6.01b	6.09c	6.21c	6.32b	6.31c	6.35b	6.25c	6.08c	6.15b
280	Topdressed	5.42b	5.67c	6.15c	6.35bc	6.51b	6.53bc	6.80a	6.44b	6.42b	6.25b
140	Incorporated	5.62b	6.03b	6.33b	6.42b	6.77a	6.85a	6.67a	6.58b	6.55b	6.42b
280	Incorporated	6.22a	6.32a	6.58a	6.64a	6.82a	6.74ab	6.65a	6.77a	6.61a	6.74a
		0.0007	*0.0005*	*0.0454*	*NS*	*NS*	*0.0213*	*<0.0001*	*NS*	*0.0031*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.
[Y]Days after potting.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test ($\alpha = 0.05$).
[W]P-value derived from analysis of variance; NS = not significant.

Table 4.12. Effects of poultry litter ash rate and placement on substrate leachate-EC measured in *Lantana camara* 'New Gold' grown in an experiment lasting 70 days .

Rate	Placement[Z]	Substrate Leachate-EC 2011									
(g m^{-3})		7 DAP[Y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	Average
140	-	2.00b[X]	1.97b	1.79b	1.56b	1.70a	1.83b	1.13a	0.75a	0.42a	1.46b
280	-	2.81a	2.54a	2.40a	2.22a	1.97a	2.15a	1.13a	0.89a	0.58a	1.85a
		0.0001[W]	*<0.0001*	*0.0001*	*0.0001*	*NS*	*0.0091*	*NS*	*NS*	*NS*	*0.0183*
-	Topdressed	2.60a	2.49a	2.37a	2.20a	2.18a	2.37a	1.19a	0.83a	0.48a	1.86a
-	Incorporated	2.21b	2.02b	1.82b	1.58b	1.49b	1.61b	1.06a	0.81a	0.52a	1.46b
		0.0091	*0.0001*	*0.0002*	*0.0002*	*0.014*	*<0.0001*	*NS*	*NS*	*NS*	*0.0172*
140	Topdressed	2.18bc	2.14b	1.97bc	1.73b	2.03ab	2.20a	1.25a	0.79a	0.46a	1.63ab
280	Topdressed	3.02a	2.84a	2.78a	2.67a	2.32a	2.53a	1.12a	0.87a	0.57a	2.08a
140	Incorporated	1.81c	1.80c	1.62c	1.39b	1.36c	1.46b	0.99a	0.71a	0.38a	1.29b
280	Incorporated	2.60ab	2.23b	2.02b	1.77b	1.62bc	1.76b	1.14a	0.91a	0.59a	1.63ab
		NS	*NS*	*0.0456*	*0.0169*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
		2012									
140	-	1.94b	1.88b	1.87b	1.57b	1.21b	1.20b	0.98b	0.83b	0.57b	1.34b
280	-	2.55a	2.33a	2.35a	2.18a	1.59a	1.45a	1.27a	1.3a	0.76a	1.72a
		<0.0001	*0.0008*	*<0.0001*	*<0.0001*	*0.0005*	*0.0036*	*0.012*	*0.0063*	*0.0062*	*0.008*
-	Topdressed	2.34a	2.30a	2.35a	2.07a	1.62a	1.63a	1.39a	1.14a	0.78a	1.73a
-	Incorporated	2.15b	1.92b	1.87b	1.68b	1.18b	1.01b	0.86b	0.71b	0.55b	1.33b
		0.0186	*0.0022*	*<0.0001*	*0.0004*	*0.0002*	*<0.0001*	*<0.0001*	*<0.0001*	*0.002*	*0.0059*
140	Topdressed	2.14b	2.18a	2.15b	1.74b	1.44b	1.51a	1.20b	1.08ab	0.69a	1.57ab
280	Topdressed	2.53a	2.42a	2.56a	2.41a	1.79a	1.74a	1.58a	1.20a	0.87a	1.90a
140	Incorporated	1.74c	1.59b	1.59c	1.41c	0.98c	0.88b	0.75c	0.57c	0.44b	1.11b
280	Incorporated	2.56a	2.25a	2.15b	1.95b	1.38b	1.15b	0.96bc	0.86b	0.65ab	1.55ab
		0.0077	*0.0421*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting .
[Y]Days after potting.
[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).
[W]P-value derived from analysis of variance; NS = not significant.

Table 4.13. Effect of poultry litter ash rate and placement on leachate dissolved reactive phosphorus measured from *Lantana camara* 'New Gold'over the course of a 70 day experiment in 2011.

Rate	Placement[Z]	Dissolved Reactive Phosphorus ($mg \cdot L^{-1}$)										
($g\ m^{-3}$)		7 DAP[Y]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	56 DAP	63 DAP	70 DAP	Average
140	-	7.73a[X]	8.38a	7.33b	6.06b	5.86b	4.58b	5.23b	3.23b	3.44a	3.20a	5.51b
280	-	8.03a	9.03a	9.11a	8.38a	8.69a	8.16a	7.21a	5.36a	4.16a	3.24a	7.14a
		NS[W]	*NS*	*0.0005*	*0.0093*	*<0.0001*	*0.0003*	*0.0075*	*0.0021*	*NS*	*NS*	*0.0083*
-	Topdressed	3.07b	4.60b	4.48b	3.97b	4.93b	3.89b	4.56b	3.03b	3.19b	3.01a	3.87b
-	Incorporated	12.70a	12.82a	11.96a	10.47a	9.63a	8.85a	7.88a	5.56a	4.41a	3.44a	8.77a
		<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0003*	*0.0007*	*0.0083*	*NS*	*<0.0001*
140	Topdressed	3.06b	4.49b	4.38c	3.60c	3.96d	2.76c	3.90c	2.77b	3.02b	2.76a	3.47c
280	Topdressed	3.08b	4.70b	4.59c	4.34c	5.89c	5.02bc	5.21bc	3.28b	3.37b	3.26a	4.28c
140	Incorporated	12.42a	12.27a	10.29b	8.52b	7.76b	6.40b	6.56b	3.68b	3.87ab	3.66a	7.54b
280	Incorporated	12.98a	13.37a	13.62a	12.42a	11.49a	11.29a	9.21a	7.44a	4.95a	3.22a	10.00a
		NS	*NS*	*0.001*	*0.0495*	*0.0117*	*NS*	*NS*	*0.0092*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[Y]Days after potting.

[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

[W]P-value derived from analysis of variance; NS = not significant.

Table 4.14. Effect of poultry litter ash rate and placement on leachate dissolved reactive phosphorus measured from *Lantana camara* 'New Gold' over the course of a 70 day experiment in 2012.

Rate	Placement[Z]	Dissolved Reactive Phosphorus (mg·L^{-1})						
(g m^{-3})		7 DAP[Y]	14 DAP	28 DAP	42 DAP	56 DAP	70 DAP	Average
140	-	6.80b[X]	8.43b	7.40b	4.88b	3.81b	2.56b	5.65a
280	-	7.32a	9.45a	8.58a	6.55a	4.64a	3.60a	6.69a
		0.0103[W]	*0.0352*	*0.0146*	*0.029*	*0.0295*	*0.0143*	*NS*
-	Topdressed	3.19b	4.87b	4.46b	3.64b	3.11b	2.43b	3.62b
-	Incorporated	10.93a	13.01a	11.52a	7.80a	5.34a	3.73a	8.72a
		<0.0001	*<0.0001*	*<0.0001*	*0.0002*	*0.0001*	*0.0047*	*<0.0001*
140	Topdressed	3.22c	4.32b	4.24c	3.44c	2.76c	2.00b	3.33b
280	Topdressed	3.15c	5.43b	4.69c	3.83bc	3.46bc	2.86ab	3.90b
140	Incorporated	10.37b	12.54a	10.56b	6.32b	4.86ab	3.11ab	7.96a
280	Incorporated	11.50a	13.47a	12.48a	9.27a	5.82a	4.35a	9.48a
		0.005	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

[Z]Topdressed = post-plant application spread evenly on substrate surface; Incorporated = mixed thoroughly into substrate prior to potting.

[Y]Days after potting.

[X]Values in columns followed by different letters were significant according to Tukey's Honest Significance Difference Test (α = 0.05).

[W]P-value derived from analysis of variance; NS = not significant.

2001) and 83% (Warren et al., 1997) when CRF was incorporated into the substrate. Researchers concluded increased P solubility resulting from CRF incorporation was due to uniform dispersal of fertilizer prills throughout the substrate and/or increased moisture content within the substrate. Broschat (2005) reported release rates of P from CRFs were slowed when CRFs were surface applied to substrates compared with incorporated, but were increased over incorporation rates when placed in water.

In this experiment, substrate leachate-DRP was affected by both P rate and PLA placement with PLA placement be the more substantial factor. Subsequently, both shoot and root P concentrations were affected to a greater extent by PLA placement than PLA application rate. For example, when PLA application rate was reduced from 280 to 140 g P m^{-3}, leachate-DRP concentrations were not reduced proportionally. In fact, during the first two weeks of the experiment, leachate-DRP concentration was not reduced by lowering PLA application rate in 2011 and was only slightly reduced in 2012. Losses of P from container production have previously been shown to be unaffected by P rate even when high-technology CRFs were used as P sources. In an experiment spanning 100 days, Tyler et al. (1996) reported cumulative effluent-DRP was reduced 57% by reducing leaching fraction by 50%, but was not affected by fertilizer application rate. Similarly, in an experiment focused on reducing P losses from containerized plants by amending substrates with calcined clay, Owen et al. (2008) reported cumulative effluent-DRP was unaffected by P application rate, but was dependent on irrigation rate and substrate amendment. Given the results of current and previous experiments, P dissolution rate in a soilless substrate may not be a function of P application rate but rather PLA-P solubility is controlled by root interaction.

In addition to influencing PLA-P dissolution, PLA application rate and placement also affected substrate pH and EC and thus nutrient uptake. Since solution pH strongly affects Mn solubility in soilless substrates (Handreck and Black, 2010), the effect of PLA placement on substrate leachate-pH led to decreased foliar and root Mn concentrations in verbena and lantana grown in substrates amended with PLA. In general, substrate leachate-pH was within the range at which inorganic P is most available to plants (Schachtman et al., 1998). This indicates P plant uptake was not likely limited due to substrate pH effects on P solubility. Leachate-DRP concentrations were within the recommended range of 5 to 60 mg P L^{-1} (Raviv and Lieth, 2008) for greenhouse crops throughout the experiment for PLA that was incorporated within the substrate.

Substrate EC is a measurement of the concentration of salts in the substrate solution and is highly affected by fertilizer application rate (Fain et al., 2008). In this experiment substrate EC was, as expected, affected by PLA application rate. However, PLA application method also greatly affected substrate EC. Topdressing PLA increased substrate EC compared to PLA incorporation into the substrate. Increased EC leaching from topdressed PLA treatments were unexpected but may be the result of increased interaction of PLA with irrigation water. Direct contact with irrigation water would have increased solubility of ancillary salts that could have limited substrate and root interaction for higher EC measurements compared to incorporated PLA treatments.

During a 47-week experiment evaluating nutrient release patterns from commonly-used CRFs incorporated in a substrate composed of peat moss, pine bark, and sand (5:4:1, v:v:v) used to fill fallow containers, Merhaut et al. (2006) reported that TP concentrations ranged from 15 to 60 mg P L^{-1} for the first 10 weeks, but averaged below 10 mg L^{-1} for the final 27 weeks. According to the authors, nutrient release would have been expected to accelerate if plants were grown in the substrate. They concluded commonly-used water soluble fertilizers, including CRFs, may supply excessive nutrients early in the growing cycle of a plant leading to shortages of nutrients in the later weeks of the production cycle. Although, pre-plant incorporation of water-soluble P fertilizers within the growing substrate is a common practice for containerized plant production, this practice should be questioned given the high nutrient leaching losses (Altland and Buamscha, 2008). Use of PLA as a P source may reduce unnecessary P losses from containerized plant production with little to no deleterious effects to plant growth and quality; and may provide growers with an alternative to costly, high-technology fertilizers.

Conclusions

Application of PLA as a topdressing did not reduce plant growth parameters in every case, but did reduce flowering and plant P uptake compared with application of PLA as a substrate amendment. Reductions in plant P uptake when PLA was applied as a topdressing were most likely the result of limited interaction between plant roots and PLA. It is believed the interaction of plant roots is one of the primary mechanisms for P release form PLA. Reductions in leachate-DRP of 5.0 mg P L^{-1} achieved through PLA topdressing are minimal when considering reductions in leachate-DRP when comparing PLA incorporated within the substrate to water-soluble P sources. Therefore, topdressing is not recommended as the primary application method of PLA due to decreased plant growth and quality. For greenhouse crop container production PLA should be pre-plant incorporated within the substrate at a rate of at least 140 g P (as total P) m^{-3} but not exceeding 280 g P m^{-3}.

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APPENDIX: TESTS OF FIXED EFFECTS FOR REPORTED DATA

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 14 days after potting

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	3.00	0.1213
Prate	1	16	1.13	0.3197
Limerate*Prate	1	16	5.91	0.0412
Psource	1	16	0.66	0.4403
Limerate*Psource	1	16	0.19	0.6762
Prate*Psource	1	16	0.65	0.4431
Limerate*Prate*Psource	1	16	0.43	0.5293

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 28 days after potting

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	2.07	0.1883
Prate	1	16	3.16	0.1132
Limerate*Prate	1	16	2.69	0.1395
Psource	1	16	0.07	0.8000
Limerate*Psource	1	16	0.00	0.9964
Prate*Psource	1	16	0.62	0.4546
Limerate*Prate*Psource	1	16	0.40	0.5465

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 42 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	5.44	0.0480
Prate	1	16	0.00	0.9581
Limerate*Prate	1	16	0.00	0.9461
Psource	1	16	0.19	0.6705
Limerate*Psource	1	16	0.01	0.9223
Prate*Psource	1	16	1.84	0.2122
Limerate*Prate*Psource	1	16	0.59	0.4651

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 14 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	1.50	0.2562
Prate	1	16	1.78	0.2186
Limerate*Prate	1	16	2.09	0.1859
Psource	1	16	0.02	0.8921
Limerate*Psource	1	16	0.00	0.9783
Prate*Psource	1	16	1.50	0.2562
Limerate*Prate*Psource	1	16	0.07	0.7935

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 28 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.09	0.7678
Prate	1	16	4.13	0.0765
Limerate*Prate	1	16	0.51	0.4941
Psource	1	16	0.04	0.8463
Limerate*Psource	1	16	0.13	0.7295
Prate*Psource	1	16	0.16	0.6994
Limerate*Prate*Psource	1	16	0.07	0.7989

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 42 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	10.07	0.0131
Prate	1	16	3.05	0.1188
Limerate*Prate	1	16	2.37	0.1619
Psource	1	16	0.01	0.9290
Limerate*Psource	1	16	0.01	0.9234
Prate*Psource	1	16	0.12	0.7358
Limerate*Prate*Psource	1	16	0.00	0.9915

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 56 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	23.47	0.0013
Prate	1	16	6.98	0.0296
Limerate*Prate	1	16	0.69	0.4313
Psource	1	16	0.37	0.5612
Limerate*Psource	1	16	0.90	0.3694
Prate*Psource	1	16	0.07	0.8004
Limerate*Prate*Psource	1	16	1.10	0.3239

Appendix Table 2.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 70 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	5.53	0.0465
Prate	1	16	3.53	0.0970
Limerate*Prate	1	16	0.64	0.4459
Psource	1	16	0.22	0.6488
Limerate*Psource	1	16	0.02	0.8786
Prate*Psource	1	16	0.04	0.8387
Limerate*Prate*Psource	1	16	0.02	0.8987

Appendix Table 2.2. Type 3 Tests of Fixed Effects for shoot dry weight of *Verbena canadensis* 'Homestead Purple'				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	32	64.75	<.0001
Prate	1	32	34.49	<.0001
Limerate*Prate	1	32	1.96	0.1713
Psource	1	32	10.98	0.0023
Limerate*Psource	1	32	5.83	0.0217
Prate*Psource	1	32	1.12	0.2985
Limerate*Prate*Psource	1	32	32.06	<.0001

Appendix Table 2.2. Type 3 Tests of Fixed Effects for shoot dry weight of *Lantana camara* 'New Gold'				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	32	0.42	0.5198
Prate	1	32	3.14	0.0861
Limerate*Prate	1	32	0.16	0.6877
Psource	1	32	1.02	0.3204
Limerate*Psource	1	32	10.44	0.0029
Prate*Psource	1	32	3.31	0.0780
Limerate*Prate*Psource	1	32	2.16	0.1511

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 14 days after potting

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.11	0.7401
Prate	1	16	38.29	<.0001
Limerate*Prate	1	16	0.32	0.5815
Psource	1	16	0.62	0.4425
Limerate*Psource	1	16	5.58	0.0311
Prate*Psource	1	16	1.03	0.3263
Limerate*Prate*Psource	1	16	1.53	0.2337

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 28 days after potting

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	1.03	0.3251
Prate	1	16	36.15	<.0001
Limerate*Prate	1	16	0.01	0.9387
Psource	1	16	6.64	0.0203
Limerate*Psource	1	16	1.03	0.3251
Prate*Psource	1	16	0.30	0.5922
Limerate*Prate*Psource	1	16	0.74	0.4031

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 42 days after potting

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	1.05	0.3208
Prate	1	16	4.53	0.0492
Limerate*Prate	1	16	0.75	0.3988
Psource	1	16	0.75	0.3988
Limerate*Psource	1	16	1.05	0.3208
Prate*Psource	1	16	3.88	0.0664
Limerate*Prate*Psource	1	16	1.80	0.1990

Appendix Table 2.3. Type 3 Tests of Fixed Effects for total flower count of *Verbena canadensis* 'Homestead Purple'

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	2.24	0.1542
Prate	1	16	67.24	<.0001
Limerate*Prate	1	16	0.60	0.4505
Psource	1	16	3.64	0.0745
Limerate*Psource	1	16	5.87	0.0276
Prate*Psource	1	16	1.41	0.2529
Limerate*Prate*Psource	1	16	0.07	0.7998

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 14 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	11.71	0.0035
Prate	1	16	3.80	0.0690
Limerate*Prate	1	16	1.58	0.2271
Psource	1	16	0.68	0.4226
Limerate*Psource	1	16	11.71	0.0035
Prate*Psource	1	16	0.02	0.8982
Limerate*Prate*Psource	1	16	0.42	0.5251

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 28 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	4.46	0.0507
Prate	1	16	38.02	<.0001
Limerate*Prate	1	16	3.34	0.0864
Psource	1	16	0.55	0.4687
Limerate*Psource	1	16	6.03	0.0259
Prate*Psource	1	16	0.21	0.6540
Limerate*Prate*Psource	1	16	0.33	0.5760

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* ‘New Gold’ at 42 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	86.14	<.0001
Prate	1	16	167.42	<.0001
Limerate*Prate	1	16	0.86	0.3671
Psource	1	16	0.00	0.9571
Limerate*Psource	1	16	2.51	0.1329
Prate*Psource	1	16	0.97	0.3404
Limerate*Prate*Psource	1	16	2.01	0.1750

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* ‘New Gold’ at 56 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	2.15	0.1622
Prate	1	16	5.05	0.0391
Limerate*Prate	1	16	0.28	0.6051
Psource	1	16	2.76	0.1163
Limerate*Psource	1	16	1.82	0.1964
Prate*Psource	1	16	1.92	0.1844
Limerate*Prate*Psource	1	16	0.11	0.7441

Appendix Table 2.3. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 70 days after potting				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.09	0.7705
Prate	1	16	15.56	0.0012
Limerate*Prate	1	16	0.96	0.3426
Psource	1	16	0.48	0.4987
Limerate*Psource	1	16	1.18	0.2928
Prate*Psource	1	16	1.65	0.2169
Limerate*Prate*Psource	1	16	0.00	0.9569

Appendix Table 2.3. Type 3 Tests of Fixed Effects for total flower count of *Lantana camara* 'New Gold'				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	19.41	0.0004
Prate	1	16	80.15	<.0001
Limerate*Prate	1	16	0.80	0.3835
Psource	1	16	0.60	0.4482
Limerate*Psource	1	16	8.38	0.0105
Prate*Psource	1	16	3.24	0.0908
Limerate*Prate*Psource	1	16	0.11	0.7433

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 0 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	138.73	<.0001
Prate	1	16	16.73	0.0009
Limerate*Prate	1	16	1.90	0.1866
Psource	1	16	2238.25	<.0001
Limerate*Psource	1	16	20.11	0.0004
Prate*Psource	1	16	20.11	0.0004
Limerate*Prate*Psource	1	16	0.16	0.6986

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 7 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	191.85	<.0001
Prate	1	16	1.58	0.2274
Limerate*Prate	1	16	0.05	0.8314
Psource	1	16	1762.81	<.0001
Limerate*Psource	1	16	16.55	0.0009
Prate*Psource	1	16	35.16	<.0001
Limerate*Prate*Psource	1	16	2.85	0.1108

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 14 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	268.25	<.0001
Prate	1	16	8.30	0.0109
Limerate*Prate	1	16	8.94	0.0087
Psource	1	16	2495.73	<.0001
Limerate*Psource	1	16	47.42	<.0001
Prate*Psource	1	16	72.79	<.0001
Limerate*Prate*Psource	1	16	24.11	0.0002

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 21 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	71.15	<.0001
Prate	1	16	9.47	0.0072
Limerate*Prate	1	16	10.64	0.0049
Psource	1	16	667.49	<.0001
Limerate*Psource	1	16	0.25	0.6211
Prate*Psource	1	16	21.55	0.0003
Limerate*Prate*Psource	1	16	2.37	0.1435

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 28 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	254.07	<.0001
Prate	1	16	3.34	0.0862
Limerate*Prate	1	16	10.46	0.0052
Psource	1	16	1937.85	<.0001
Limerate*Psource	1	16	0.27	0.6131
Prate*Psource	1	16	17.80	0.0007
Limerate*Prate*Psource	1	16	7.39	0.0152

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 35 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	393.53	<.0001
Prate	1	16	0.49	0.4919
Limerate*Prate	1	16	19.02	0.0005
Psource	1	16	2602.51	<.0001
Limerate*Psource	1	16	0.06	0.8033
Prate*Psource	1	16	87.80	<.0001
Limerate*Prate*Psource	1	16	1.20	0.2887

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 42 days after potting.

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	138.40	<.0001
Prate	1	16	0.31	0.5865
Limerate*Prate	1	16	4.69	0.0457
Psource	1	16	649.27	<.0001
Limerate*Psource	1	16	5.84	0.0279
Prate*Psource	1	16	19.88	0.0004
Limerate*Prate*Psource	1	16	0.07	0.7917

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 49 days after potting.

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	364.10	<.0001
Prate	1	16	43.54	<.0001
Limerate*Prate	1	16	3.62	0.0753
Psource	1	16	977.65	<.0001
Limerate*Psource	1	16	25.53	0.0001
Prate*Psource	1	16	70.25	<.0001
Limerate*Prate*Psource	1	16	0.35	0.5605

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 56 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	478.29	<.0001
Prate	1	16	14.87	0.0014
Limerate*Prate	1	16	2.88	0.1092
Psource	1	16	775.84	<.0001
Limerate*Psource	1	16	11.72	0.0035
Prate*Psource	1	16	24.05	0.0002
Limerate*Prate*Psource	1	16	15.35	0.0012

Appendix Table 2.4. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' at 63 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	155.60	<.0001
Prate	1	16	0.00	0.9806
Limerate*Prate	1	16	10.47	0.0052
Psource	1	16	515.29	<.0001
Limerate*Psource	1	16	2.74	0.1174
Prate*Psource	1	16	17.43	0.0007
Limerate*Prate*Psource	1	16	15.82	0.0011

Appendix Table 2.4. Type 3 Tests of Fixed Effects for average substrate leachate-pH measured from *Lantana camara* 'New Gold'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	94.98	<.0001
Prate	1	16	2.64	0.1240
Limerate*Prate	1	16	1.11	0.3081
Psource	1	16	593.18	<.0001
Limerate*Psource	1	16	3.35	0.0860
Prate*Psource	1	16	15.07	0.0013
Limerate*Prate*Psource	1	16	0.21	0.6561

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 0 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	1.07	0.3153
Prate	1	16	187.23	<.0001
Limerate*Prate	1	16	0.17	0.6839
Psource	1	16	449.38	<.0001
Limerate*Psource	1	16	0.13	0.7215
Prate*Psource	1	16	1.18	0.2925
Limerate*Prate*Psource	1	16	0.00	0.9593

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 7 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	2.53	0.1314
Prate	1	16	286.99	<.0001
Limerate*Prate	1	16	0.07	0.8009
Psource	1	16	95.28	<.0001
Limerate*Psource	1	16	0.07	0.8009
Prate*Psource	1	16	0.70	0.4146
Limerate*Prate*Psource	1	16	2.21	0.1564

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 14 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	5.38	0.0340
Prate	1	16	377.24	<.0001
Limerate*Prate	1	16	0.08	0.7874
Psource	1	16	14.17	0.0017
Limerate*Psource	1	16	0.18	0.6774
Prate*Psource	1	16	1.88	0.1892
Limerate*Prate*Psource	1	16	1.04	0.3219

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 21 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.21	0.6504
Prate	1	16	144.17	<.0001
Limerate*Prate	1	16	0.03	0.8558
Psource	1	16	4.78	0.0440
Limerate*Psource	1	16	0.00	0.9758
Prate*Psource	1	16	16.02	0.0010
Limerate*Prate*Psource	1	16	0.00	0.9517

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 28 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	1.34	0.2638
Prate	1	16	192.54	<.0001
Limerate*Prate	1	16	1.45	0.2462
Psource	1	16	0.01	0.9110
Limerate*Psource	1	16	0.38	0.5484
Prate*Psource	1	16	76.45	<.0001
Limerate*Prate*Psource	1	16	3.73	0.0715

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate Leachate-EC measured from *Lantana camara* ‘New Gold’ at 35 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.00	0.9799
Prate	1	16	129.68	<.0001
Limerate*Prate	1	16	0.41	0.5314
Psource	1	16	0.02	0.8998
Limerate*Psource	1	16	3.12	0.0965
Prate*Psource	1	16	24.39	0.0001
Limerate*Prate*Psource	1	16	0.08	0.7819

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* ‘New Gold’ at 42 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.40	0.5340
Prate	1	16	29.20	<.0001
Limerate*Prate	1	16	0.01	0.9288
Psource	1	16	0.53	0.4780
Limerate*Psource	1	16	2.53	0.1316
Prate*Psource	1	16	5.58	0.0312
Limerate*Prate*Psource	1	16	1.50	0.2379

Appendix Table 2.5. Type 3 Tests of Fixed Effects for Substrate Leachate-EC measured from *Lantana camara* 'New Gold' at 49 Days After Potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.05	0.8276
Prate	1	16	123.53	<.0001
Limerate*Prate	1	16	0.05	0.8276
Psource	1	16	11.03	0.0043
Limerate*Psource	1	16	8.28	0.0109
Prate*Psource	1	16	11.63	0.0036
Limerate*Prate*Psource	1	16	8.80	0.0091

Appendix Table 2.5. Type 3 Tests of Fixed Effects for Substrate leachate-EC measured from *Lantana camara* 'New Gold' at 56 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	9.21	0.0079
Prate	1	16	140.04	<.0001
Limerate*Prate	1	16	8.60	0.0097
Psource	1	16	4.09	0.0601
Limerate*Psource	1	16	18.05	0.0006
Prate*Psource	1	16	12.53	0.0027
Limerate*Prate*Psource	1	16	1.73	0.2071

Appendix Table 2.5. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' at 63 days after potting.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	5.85	0.0278
Prate	1	16	12.08	0.0031
Limerate*Prate	1	16	0.09	0.7636
Psource	1	16	8.20	0.0112
Limerate*Psource	1	16	1.86	0.1919
Prate*Psource	1	16	0.09	0.7636
Limerate*Prate*Psource	1	16	0.09	0.7636

Appendix Table 2.5. Type 3 Tests of Fixed Effects for average substrate leachate-EC measured from *Lantana camara* 'New Gold'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.00	0.9675
Prate	1	16	14.55	0.0015
Limerate*Prate	1	16	0.00	1.0000
Psource	1	16	0.96	0.3409
Limerate*Psource	1	16	0.05	0.8330
Prate*Psource	1	16	0.76	0.3973
Limerate*Prate*Psource	1	16	0.02	0.8790

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Ca concentration of *Verbena canadensis* 'Homestead Purple'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.04	0.8523
Prate	1	16	0.30	0.5936
Limerate*Prate	1	16	0.24	0.6333
Psource	1	16	9.47	0.0072
Limerate*Psource	1	16	4.38	0.0526
Prate*Psource	1	16	0.16	0.6960
Limerate*Prate*Psource	1	16	0.93	0.3481

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Mg concentration of *Verbena canadensis* 'Homestead Purple'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.49	0.4958
Prate	1	16	1.48	0.2416
Limerate*Prate	1	16	0.00	0.9869
Psource	1	16	0.92	0.3523
Limerate*Psource	1	16	1.23	0.2830
Prate*Psource	1	16	1.66	0.2164
Limerate*Prate*Psource	1	16	3.63	0.0750

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Mn concentration of *Verbena canadensis* ‘Homestead Purple’.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	9.86	0.0063
Prate	1	16	36.85	<.0001
Limerate*Prate	1	16	1.72	0.2077
Psource	1	16	214.07	<.0001
Limerate*Psource	1	16	0.00	0.9628
Prate*Psource	1	16	3.30	0.0879
Limerate*Prate*Psource	1	16	27.89	<.0001

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar P concentration of *Verbena canadensis* ‘Homestead Purple’.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.01	0.9220
Prate	1	16	14.82	0.0014
Limerate*Prate	1	16	9.98	0.0061
Psource	1	16	34.25	<.0001
Limerate*Psource	1	16	0.00	0.9459
Prate*Psource	1	16	1.27	0.2770
Limerate*Prate*Psource	1	16	0.87	0.3650

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar K concentration of *Verbena canadensis* 'Homestead Purple'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.46	0.5071
Prate	1	16	0.35	0.5638
Limerate*Prate	1	16	2.79	0.1146
Psource	1	16	0.03	0.8609
Limerate*Psource	1	16	19.09	0.0005
Prate*Psource	1	16	1.18	0.2938
Limerate*Prate*Psource	1	16	0.63	0.4403

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Ca concentration of *Lantana camara* 'New Gold'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	24.88	0.0001
Prate	1	16	13.45	0.0021
Limerate*Prate	1	16	5.56	0.0315
Psource	1	16	182.49	<.0001
Limerate*Psource	1	16	7.13	0.0167
Prate*Psource	1	16	10.47	0.0052
Limerate*Prate*Psource	1	16	2.81	0.1134

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Mg concentration of *Lantana camara* 'New Gold'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	53.25	<.0001
Prate	1	16	206.53	<.0001
Limerate*Prate	1	16	3.25	0.0902
Psource	1	16	95.98	<.0001
Limerate*Psource	1	16	3.74	0.0709
Prate*Psource	1	16	2.74	0.1172
Limerate*Prate*Psource	1	16	18.11	0.0006

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar Mn concentration of *Lantana camara* 'New Gold'.				
Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	9.28	0.0077
Prate	1	16	13.00	0.0024
Limerate*Prate	1	16	3.21	0.0921
Psource	1	16	443.33	<.0001
Limerate*Psource	1	16	0.01	0.9115
Prate*Psource	1	16	0.53	0.4765
Limerate*Prate*Psource	1	16	12.14	0.0031

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar P concentration of *Lantana camara* 'New Gold'.

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.20	0.6599
Prate	1	16	20.85	0.0003
Limerate*Prate	1	16	1.95	0.1813
Psource	1	16	77.97	<.0001
Limerate*Psource	1	16	0.03	0.8666
Prate*Psource	1	16	1.40	0.2534
Limerate*Prate*Psource	1	16	4.91	0.0416

Appendix Table 2.6. Type 3 Tests of Fixed Effects for foliar K concentration of *Lantana camara* 'New Gold'.

Effect	Num DF	Den DF	F Value	Pr > F
Limerate	1	16	0.27	0.6080
Prate	1	16	2.03	0.1732
Limerate*Prate	1	16	0.12	0.7328
Psource	1	16	4.00	0.0627
Limerate*Psource	1	16	5.03	0.0395
Prate*Psource	1	16	0.03	0.8617
Limerate*Prate*Psource	1	16	2.95	0.1051

Appendix Table 3.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' in 2011.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	24	1.62	0.1953
Treatment (PLA:SP)	28	5	24	10.86	<.0001
Treatment (PLA:SP)	42	5	24	36.45	<.0001
Treatment (PLA:SP)	56	5	24	35.64	<.0001
Treatment (PLA:SP)	70	5	24	36.92	<.0001
Treatment (PLA:SP)	Average	5	24	22.94	<.0001

Appendix Table 3.1. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	24	31.26	<.0001
Treatment (PLA:SP)	28	5	24	12.36	0.0002
Treatment (PLA:SP)	42	5	24	15.45	<.0001
Treatment (PLA:SP)	56	5	24	13.53	0.0001
Treatment (PLA:SP)	70	5	24	22.88	<.0001
Treatment (PLA:SP)	Average	5	24	14.22	0.0001

Appendix Table 3.2. Type 3 Tests of Fixed Effects for biomass of *Lantana camara* ‘New Gold’ in 2011.

Effect	Biomass	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Shoot	5	24	119.65	<.0001
Treatment (PLA:SP)	Root	5	24	35.52	<.0001
Treatment (PLA:SP)	Shoot:Root	5	24	25.95	<.0001

Appendix Table 3.2. Type 3 Tests of Fixed Effects for biomass of *Lantana camara* ‘New Gold’ in 2012.

Effect	Biomass	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Shoot	5	24	17.58	<.0001
Treatment (PLA:SP)	Root	5	24	3.75	0.0282
Treatment (PLA:SP)	Shoot:Root	5	24	7.08	0.0027

Appendix Table 3.3. Type 3 Tests of Fixed Effects for flower numbers of *Lantana camara* ‘New Gold’ in 2012.

Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	24	23.75	<.0001
Treatment (PLA:SP)	28	5	24	35.28	<.0001
Treatment (PLA:SP)	42	5	24	168.19	<.0001
Treatment (PLA:SP)	56	5	24	48.28	<.0001
Treatment (PLA:SP)	70	5	24	24.48	<.0001
Treatment (PLA:SP)	Total	5	24	227.55	<.0001

Appendix Table 3.4. Type 3 Tests of Fixed Effects for foliar nutrient concentrations of *Lantana camara* 'New Gold' in 2011.					
Effect	Nutrient	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Ca	5	12	0.98	0.4690
Treatment (PLA:SP)	Mg	5	12	5.66	0.0066
Treatment (PLA:SP)	Mn	5	12	32.38	<.0001
Treatment (PLA:SP)	P	5	12	216.66	<.0001
Treatment (PLA:SP)	K	5	12	11.28	0.0003

Appendix Table 3.4. Type 3 Tests of Fixed Effects for root nutrient concentrations of *Lantana camara* 'New Gold' in 2011.					
Effect	Nutrient	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Ca	5	12	38.57	<.0001
Treatment (PLA:SP)	Mg	5	12	4.90	0.0113
Treatment (PLA:SP)	Mn	5	12	13.93	0.0001
Treatment (PLA:SP)	P	5	12	61.61	<.0001
Treatment (PLA:SP)	K	5	12	24.01	<.0001

Appendix Table 3.5. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' planted in a simulated landscape in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	24	15.65	<.0001
Treatment (PLA:SP)	7	5	24	7.28	0.0003
Treatment (PLA:SP)	14	5	24	4.89	0.0032
Treatment (PLA:SP)	21	5	24	3.27	0.0215
Treatment (PLA:SP)	28	5	24	4.45	0.0052
Treatment (PLA:SP)	35	5	24	2.57	0.0534
Treatment (PLA:SP)	42	5	24	2.47	0.0613
Treatment (PLA:SP)	49	5	24	2.64	0.0490

Appendix Table 3.6. Type 3 Tests of Fixed Effects for flower counts of *Lantana camara* 'New Gold' planted in a simulated landscape in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	24	3.45	0.0172
Treatment (PLA:SP)	7	5	24	9.18	<.0001
Treatment (PLA:SP)	14	5	24	0.92	0.4868
Treatment (PLA:SP)	21	5	24	1.45	0.2419
Treatment (PLA:SP)	28	5	24	2.26	0.0813

Appendix Table 3.7. Type 3 Tests of Fixed Effects for foliar nutrient concentrations of *Lantana camara* 'New Gold' grown in a simulated landscape in 2012.					
Effect	Nutrient	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Ca	5	12	1.50	0.2603
Treatment (PLA:SP)	Mg	5	12	0.11	0.9873
Treatment (PLA:SP)	Mn	5	12	1.59	0.2366
Treatment (PLA:SP)	P	5	12	2.75	0.0702
Treatment (PLA:SP)	K	5	12	0.47	0.7897

Appendix Table 3.8. Type 3 Tests of Fixed Effects for shoot biomass of *Lantana camara* 'New Gold' grown in a simulated landscape in 2012.					
Effect	Biomass	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Shoot	5	24	1.32	0.2876

Appendix Table 3.9. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* 'New Gold' in 2011.

Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	18	75.47	<.0001
Treatment (PLA:SP)	7	5	17	75.37	<.0001
Treatment (PLA:SP)	14	5	17	135.84	<.0001
Treatment (PLA:SP)	21	5	12	223.51	<.0001
Treatment (PLA:SP)	28	5	12	49.41	<.0001
Treatment (PLA:SP)	35	5	12	61.45	<.0001
Treatment (PLA:SP)	42	5	12	20.17	<.0001
Treatment (PLA:SP)	49	5	12	70.70	<.0001
Treatment (PLA:SP)	56	5	12	8.53	0.0012
Treatment (PLA:SP)	63	5	12	21.04	<.0001
Treatment (PLA:SP)	70	5	12	12.91	0.0002
Treatment (PLA:SP)	77	5	12	46.27	<.0001

Appendix Table 3.9. Type 3 Tests of Fixed Effects for substrate leachate-pH measured from *Lantana camara* ‘New Gold’ in 2012.

Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	12	89.38	<.0001
Treatment (PLA:SP)	7	5	12	116.18	<.0001
Treatment (PLA:SP)	14	5	12	109.62	<.0001
Treatment (PLA:SP)	21	5	12	107.64	<.0001
Treatment (PLA:SP)	28	5	12	96.60	<.0001
Treatment (PLA:SP)	35	5	12	211.44	<.0001
Treatment (PLA:SP)	42	5	12	111.91	<.0001
Treatment (PLA:SP)	49	5	12	27.56	<.0001
Treatment (PLA:SP)	56	5	12	28.24	<.0001
Treatment (PLA:SP)	63	5	12	108.94	<.0001
Treatment (PLA:SP)	70	5	12	49.98	<.0001
Treatment (PLA:SP)	77	5	12	42.85	<.0001

Appendix Table 3.10. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' in 2011.

Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	18	67.66	<.0001
Treatment (PLA:SP)	7	5	17	114.31	<.0001
Treatment (PLA:SP)	14	5	17	25.52	<.0001
Treatment (PLA:SP)	21	5	12	47.43	<.0001
Treatment (PLA:SP)	28	5	12	2.36	0.1034
Treatment (PLA:SP)	35	5	12	5.20	0.0091
Treatment (PLA:SP)	42	5	11	0.92	0.5028
Treatment (PLA:SP)	49	5	12	0.91	0.5070
Treatment (PLA:SP)	56	5	12	1.51	0.2581
Treatment (PLA:SP)	63	5	12	3.13	0.0487
Treatment (PLA:SP)	70	5	12	14.15	0.0001
Treatment (PLA:SP)	77	5	12	16.54	<.0001

Appendix Table 3.10. Type 3 Tests of Fixed Effects for substrate leachate-EC measured from *Lantana camara* 'New Gold' in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	0	5	12	82.02	<.0001
Treatment (PLA:SP)	7	5	12	97.59	<.0001
Treatment (PLA:SP)	14	5	12	15.42	<.0001
Treatment (PLA:SP)	21	5	12	18.34	<.0001
Treatment (PLA:SP)	28	5	12	25.17	<.0001
Treatment (PLA:SP)	35	5	12	9.51	0.0007
Treatment (PLA:SP)	42	5	12	1.37	0.3013
Treatment (PLA:SP)	49	5	12	2.34	0.1052
Treatment (PLA:SP)	56	5	12	11.37	0.0003
Treatment (PLA:SP)	63	5	12	14.14	0.0001
Treatment (PLA:SP)	70	5	12	6.54	0.0037
Treatment (PLA:SP)	77	5	12	2.30	0.1102

Appendix Table 3.11. Type 3 Tests of Fixed Effects for effluent-TP measured from *Lantana camara* 'New Gold' grown in a closed system in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	12	60.22	<.0001
Treatment (PLA:SP)	28	5	12	46.11	<.0001
Treatment (PLA:SP)	42	5	12	22.95	<.0001
Treatment (PLA:SP)	56	5	12	26.56	<.0001
Treatment (PLA:SP)	70	5	12	121.37	<.0001
Treatment (PLA:SP)	84	5	12	128.24	<.0001
Treatment (PLA:SP)	Total	4	10	235.75	<.0001

Appendix Table 3.12. Type 3 Tests of Fixed Effects for phosphorus fate and partitioning measured from *Lantana camara* 'New Gold' grown in a closed system in 2012.					
Effect	Partition	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Shoot-P	5	12	37.00	<.0001
Treatment (PLA:SP)	Root-P	5	12	25.31	<.0001
Treatment (PLA:SP)	Total Plant-P	4	10	3.52	0.0485
Treatment (PLA:SP)	Effluent-P	4	10	235.75	<.0001
Treatment (PLA:SP)	Total Recovered-P	4	10	123.55	<.0001
Treatment (PLA:SP)	Percent Recovered-P	4	10	123.55	<.0001

Appendix Table 3.13. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' grown in a closed system in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	12	19.53	<.0001
Treatment (PLA:SP)	28	5	12	14.73	<.0001
Treatment (PLA:SP)	42	5	12	13.58	0.0001
Treatment (PLA:SP)	56	5	12	11.68	0.0003
Treatment (PLA:SP)	70	5	12	9.55	0.0007
Treatment (PLA:SP)	84	5	12	10.59	0.0005
Treatment (PLA:SP)	Average	5	12	10.09	0.0006

Appendix Table 3.14. Type 3 Tests of Fixed Effects for biomass of *Lantana camara* 'New Gold' grown in a closed system in 2012.					
Effect	Biomass	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	Shoot	5	12	17.58	<.0001
Treatment (PLA:SP)	Root	5	12	3.75	0.0282
Treatment (PLA:SP)	Shoot:Root	5	12	7.08	0.0027

Appendix Table 3.15. Type 3 Tests of Fixed Effects for flower numbers of *Lantana camara* 'New Gold' grown in a closed system in 2012.					
Effect	Days After Planting	Num DF	Den DF	F Value	Pr > F
Treatment (PLA:SP)	14	5	12	13.81	0.0001
Treatment (PLA:SP)	28	5	12	38.07	<.0001
Treatment (PLA:SP)	42	5	12	122.73	<.0001
Treatment (PLA:SP)	56	5	12	82.77	<.0001
Treatment (PLA:SP)	70	5	12	107.75	<.0001
Treatment (PLA:SP)	84	5	12	28.76	<.0001
Treatment (PLA:SP)	Total	5	12	192.00	<.0001

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 14 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	4.57	0.0483
Placement	1	16	15.88	0.0011
Rate*Placement	1	16	1.13	0.3034

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 28 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	4.10	0.0599
Placement	1	16	15.23	0.0013
Rate*Placement	1	16	2.22	0.1556

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 42 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.41	0.5311
Placement	1	16	3.33	0.0867
Rate*Placement	1	16	1.29	0.2723

Appendix Table 4.1. Type 3 Tests of Fixed Effects for average growth index of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	1.51	0.2369
Placement	1	16	6.81	0.0190
Rate*Placement	1	16	1.22	0.2862

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 14 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.12	0.7359
Placement	1	16	28.61	0.0007
Rate*Placement	1	16	0.91	0.3672

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	3.50	0.0983
Placement	1	16	1.05	0.3359
Rate*Placement	1	16	29.55	0.0006

Appendix Table 4.1. Type 3 Tests of Fixed Effects for growth index of *Verbena canadensis* 'Homestead Purple' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	24.12	0.0012
Placement	1	16	0.12	0.7425
Rate*Placement	1	16	18.26	0.0027

Appendix Table 4.1. Type 3 Tests of Fixed Effects for average growth index of *Verbena canadensis* 'Homestead Purple' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	1.66	0.2335
Placement	1	16	1.45	0.2625
Rate*Placement	1	16	4.12	0.0768

Appendix Table 4.2. Type 3 Tests of Fixed Effects for shoot dry weight of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	10.81	0.0050
Placement	1	16	10.81	0.0050
Rate*Placement	1	16	0.50	0.4918

Appendix Table 4.2. Type 3 Tests of Fixed Effects for root dry weight of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	41.43	0.0002
Placement	1	16	40.02	0.0002
Rate*Placement	1	16	13.17	0.0067

Appendix Table 4.2. Type 3 Tests of Fixed Effects for shoot:root dry weight of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	598.81	<.0001
Placement	1	16	537.86	<.0001
Rate*Placement	1	16	424.07	<.0001

Appendix Table 4.2. Type 3 Tests of Fixed Effects for shoot dry weight of *Verbena canadensis* 'Homestead Purple' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	3.14	0.0953
Placement	1	16	13.30	0.0022
Rate*Placement	1	16	11.42	0.0038

Appendix Table 4.2. Type 3 Tests of Fixed Effects for root dry weight of *Verbena canadensis* 'Homestead Purple' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	10.39	0.0122
Placement	1	16	1.62	0.2393
Rate*Placement	1	16	0.70	0.4270

Appendix Table 4.2. Type 3 Tests of Fixed Effects for shoot:root dry weight of *Verbena canadensis* 'Homestead Purple' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	11.84	0.0088
Placement	1	16	0.17	0.6871
Rate*Placement	1	16	0.45	0.5194

Appendix Table 4.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 14 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	2.40	0.1599
Placement	1	8	13.07	0.0068
Rate*Placement	1	8	17.07	0.0033

Appendix Table 4.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.29	0.6061
Placement	1	8	2.59	0.1461
Rate*Placement	1	8	0.03	0.8625

Appendix Table 4.3. Type 3 Tests of Fixed Effects for flower count of *Verbena canadensis* 'Homestead Purple' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	1.93	0.2026
Placement	1	8	8.17	0.0212
Rate*Placement	1	8	1.93	0.2026

Appendix Table 4.3. Type 3 Tests of Fixed Effects for total flower count of *Verbena canadensis* 'Homestead Purple' in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	1.19	0.3072
Placement	1	8	18.47	0.0026
Rate*Placement	1	8	3.95	0.0819

Appendix Table 4.3. Type 3 Tests of Fixed Effects for total flower count of *Verbena canadensis* 'Homestead Purple' in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	1.19	0.3072
Placement	1	8	18.47	0.0026
Rate*Placement	1	8	3.95	0.0819

Appendix Table 4.4. Type 3 Tests of Fixed Effects foliar Ca concentration of *Verbena canadensis* 'Homestead Purple' in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	12.08	0.0084
Placement	1	8	14.29	0.0054
Rate*Placement	1	8	3.29	0.1073

Appendix Table 4.4. Type 3 Tests of Fixed Effects foliar Mg concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	11.12	0.0103
Placement	1	8	0.87	0.3794
Rate*Placement	1	8	4.12	0.0768

Appendix Table 4.4. Type 3 Tests of Fixed Effects foliar Mn concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	7.12	0.0285
Placement	1	8	437.39	<.0001
Rate*Placement	1	8	0.52	0.4933

Appendix Table 4.4. Type 3 Tests of Fixed Effects foliar P concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	8.55	0.0192
Placement	1	8	11.58	0.0093
Rate*Placement	1	8	0.01	0.9343

Appendix Table 4.4. Type 3 Tests of Fixed Effects foliar K concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	18.71	0.0025
Placement	1	8	24.15	0.0012
Rate*Placement	1	8	0.04	0.8545

Appendix Table 4.5. Type 3 Tests of Fixed Effects root Ca concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.04	0.8522
Placement	1	8	1.33	0.2828
Rate*Placement	1	8	0.30	0.6009

Appendix Table 4.5. Type 3 Tests of Fixed Effects root Mg concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.61	0.4576
Placement	1	8	0.46	0.5180
Rate*Placement	1	8	2.18	0.1779

Appendix Table 4.5. Type 3 Tests of Fixed Effects root Mn concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.95	0.3577
Placement	1	8	28.60	0.0007
Rate*Placement	1	8	1.41	0.2698

Appendix Table 4.5. Type 3 Tests of Fixed Effects root P concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	8.44	0.0197
Placement	1	8	14.98	0.0047
Rate*Placement	1	8	0.26	0.6222

Appendix Table 4.5. Type 3 Tests of Fixed Effects root K concentration of *Verbena canadensis* 'Homestead Purple' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	10.56	0.0117
Placement	1	8	9.23	0.0161
Rate*Placement	1	8	0.19	0.6766

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 14 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	4.23	0.0563
Placement	1	16	2.22	0.1553
Rate*Placement	1	16	0.31	0.5864

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 28 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	4.73	0.0450
Placement	1	16	2.36	0.1438
Rate*Placement	1	16	1.60	0.2235

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 42 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	5.06	0.0390
Placement	1	16	2.35	0.1448
Rate*Placement	1	16	1.82	0.1960

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 56 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	2.84	0.1113
Placement	1	16	2.37	0.1431
Rate*Placement	1	16	0.80	0.3842

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 70 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	3.17	0.0942
Placement	1	16	1.38	0.2576
Rate*Placement	1	16	0.11	0.7456

Appendix Table 4.6. Type 3 Tests of Fixed Effects for average growth index of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	4.49	0.0502
Placement	1	16	2.46	0.1365
Rate*Placement	1	16	0.78	0.3892

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 14 days after potting in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	5.89	0.0415
Placement	1	16	32.38	0.0005
Rate*Placement	1	16	5.67	0.0444

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 28 days after potting in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	7.00	0.0295
Placement	1	16	19.06	0.0024
Rate*Placement	1	16	26.83	0.0008

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 42 days after potting in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.59	0.4645
Placement	1	16	6.59	0.0333
Rate*Placement	1	16	14.57	0.0051

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 56 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.00	0.9464
Placement	1	16	6.94	0.0300
Rate*Placement	1	16	4.68	0.0625

Appendix Table 4.6. Type 3 Tests of Fixed Effects for growth index of *Lantana camara* 'New Gold' at 70 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.03	0.8772
Placement	1	16	7.90	0.0228
Rate*Placement	1	16	1.68	0.2306

Appendix Table 4.6. Type 3 Tests of Fixed Effects for average growth index of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.02	0.8813
Placement	1	16	3.70	0.0905
Rate*Placement	1	16	2.07	0.1885

Appendix Table 4.7. Type 3 Tests of Fixed Effects for shoot dry weight of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	1.92	0.1863
Placement	1	16	6.31	0.0239
Rate*Placement	1	16	0.82	0.3791

Appendix Table 4.7. Type 3 Tests of Fixed Effects for root dry weight of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	8.50	0.0194
Placement	1	16	3.55	0.0962
Rate*Placement	1	16	0.05	0.8239

Appendix Table 4.7. Type 3 Tests of Fixed Effects for shoot:root dry weight of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	11.66	0.0092
Placement	1	16	0.56	0.4769
Rate*Placement	1	16	0.09	0.7686

Appendix Table 4.7. Type 3 Tests of Fixed Effects for shoot dry weight of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.60	0.4502
Placement	1	16	5.26	0.0357
Rate*Placement	1	16	1.44	0.2481

Appendix Table 4.7. Type 3 Tests of Fixed Effects for root dry weight of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	1.14	0.3177
Placement	1	16	6.26	0.0368
Rate*Placement	1	16	0.00	0.9918

Appendix Table 4.7. Type 3 Tests of Fixed Effects for shoot:root dry weight of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	16	0.11	0.7445
Placement	1	16	32.96	0.0004
Rate*Placement	1	16	4.26	0.0728

Appendix Table 4.8. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 14 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.61	0.4565
Placement	1	8	0.61	0.4565
Rate*Placement	1	8	0.82	0.3930

Appendix Table 4.8. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	3.22	0.1104
Placement	1	8	52.58	<.0001
Rate*Placement	1	8	13.41	0.0064

Appendix Table 4.8. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.00	1.0000
Placement	1	8	20.37	0.0020
Rate*Placement	1	8	0.17	0.6924

Appendix Table 4.8. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 56 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.32	0.5898
Placement	1	8	12.24	0.0081
Rate*Placement	1	8	8.88	0.0176

Appendix Table 4.8. Type 3 Tests of Fixed Effects for flower count of *Lantana camara* 'New Gold' at 70 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	7.76	0.0237
Placement	1	8	13.15	0.0067
Rate*Placement	1	8	19.03	0.0024

Appendix Table 4.8. Type 3 Tests of Fixed Effects for total flower count of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.20	0.6697
Placement	1	8	34.98	0.0004
Rate*Placement	1	8	13.00	0.0069

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Ca concentration of *Lantana camara* 'New Gold' in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.34	0.5770
Placement	1	8	9.82	0.0139
Rate*Placement	1	8	1.36	0.2763

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Mg concentration of *Lantana camara* 'New Gold' in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.26	0.6254
Placement	1	8	0.26	0.6267
Rate*Placement	1	8	0.08	0.7810

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Mn concentration of *Lantana camara* 'New Gold' in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	648.70	<.0001
Placement	1	8	2047.19	<.0001
Rate*Placement	1	8	1.77	0.2197

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar P concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	30.18	0.0006
Placement	1	8	293.73	<.0001
Rate*Placement	1	8	0.19	0.6781

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar K concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	1.19	0.3068
Placement	1	8	3.05	0.1189
Rate*Placement	1	8	5.33	0.0498

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Ca concentration of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	3.84	0.0858
Placement	1	8	141.75	<.0001
Rate*Placement	1	8	60.84	<.0001

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Mg concentration of *Lantana camara* ‘New Gold’ in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	9.30	0.0158
Placement	1	8	78.19	<.0001
Rate*Placement	1	8	8.63	0.0188

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar Mn concentration of *Lantana camara* ‘New Gold’ in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	36.56	0.0003
Placement	1	8	100.51	<.0001
Rate*Placement	1	8	2.97	0.1230

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar P concentration of *Lantana camara* ‘New Gold’ in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	16.64	0.0035
Placement	1	8	39.18	0.0002
Rate*Placement	1	8	3.80	0.0870

Appendix Table 4.9. Type 3 Tests of Fixed Effects foliar K concentration of *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.09	0.7742
Placement	1	8	0.69	0.4298
Rate*Placement	1	8	0.18	0.6789

Appendix Table 4.10. Type 3 Tests of Fixed Effects root Ca concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.01	0.9257
Placement	1	8	2.78	0.1339
Rate*Placement	1	8	0.06	0.8054

Appendix Table 4.10. Type 3 Tests of Fixed Effects root Mg concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.93	0.3624
Placement	1	8	1.28	0.2899
Rate*Placement	1	8	1.50	0.2562

Appendix Table 4.10. Type 3 Tests of Fixed Effects root Mn concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	12.30	0.0080
Placement	1	8	41.64	0.0002
Rate*Placement	1	8	0.35	0.5704

Appendix Table 4.10. Type 3 Tests of Fixed Effects root P concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	22.34	0.0015
Placement	1	8	143.40	<.0001
Rate*Placement	1	8	1.19	0.3079

Appendix Table 4.10. Type 3 Tests of Fixed Effects root K concentration of *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	8.93	0.0174
Placement	1	8	1.51	0.2542
Rate*Placement	1	8	0.08	0.7827

Appendix Table 4.11. Type 3 Tests of Fixed Effects of substrate leachate-pH measured from *Lantana camara* 'New Gold' at 7 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.02	0.8861
Placement	1	8	16.25	0.0038
Rate*Placement	1	8	22.76	0.0014

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 14 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.12	0.7403
Placement	1	8	32.39	0.0005
Rate*Placement	1	8	2.57	0.1479

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 21 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	1.39	0.2725
Placement	1	8	20.48	0.0019
Rate*Placement	1	8	3.74	0.0893

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 28 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.49	0.5019
Placement	1	8	3.80	0.0870
Rate*Placement	1	8	6.70	0.0322

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 35 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	11.93	0.0086
Placement	1	8	10.19	0.0128
Rate*Placement	1	8	0.93	0.3642

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 42 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	2.59	0.1463
Placement	1	8	2.23	0.1671
Rate*Placement	1	8	0.03	0.8658

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 49 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	10.37	0.0122
Placement	1	8	1.75	0.2226
Rate*Placement	1	8	0.06	0.8184

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 56 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.00	0.9665
Placement	1	8	1.88	0.2070
Rate*Placement	1	8	5.41	0.0484

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 63days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	8.33	0.0203
Placement	1	8	23.15	0.0013
Rate*Placement	1	8	9.41	0.0154

Appendix Table 4.11. Type 3 Tests of Fixed Effects on average substrate leachate-pH measured from *Lantana camara* 'New Gold' in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	3.06	0.1186
Placement	1	8	21.72	0.0016
Rate*Placement	1	8	8.76	0.0181

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 7 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	2.43	0.1574
Placement	1	8	14.27	0.0054
Rate*Placement	1	8	27.89	0.0007

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* ‘New Gold’ at 14 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.19	0.6717
Placement	1	8	34.05	0.0004
Rate*Placement	1	8	30.71	0.0005

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* ‘New Gold’ at 21 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	13.50	0.0063
Placement	1	8	68.01	<.0001
Rate*Placement	1	8	5.61	0.0454

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* ‘New Gold’ at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	28.47	0.0007
Placement	1	8	52.94	<.0001
Rate*Placement	1	8	1.36	0.2779

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 35 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	7.37	0.0265
Placement	1	8	72.53	<.0001
Rate*Placement	1	8	2.10	0.1850

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.91	0.3689
Placement	1	8	40.67	0.0002
Rate*Placement	1	8	8.16	0.0213

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 49 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	45.07	0.0002
Placement	1	8	7.77	0.0236
Rate*Placement	1	8	53.77	<.0001

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 56 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	28.90	0.0007
Placement	1	8	88.52	<.0001
Rate*Placement	1	8	0.00	1.0000

Appendix Table 4.11. Type 3 Tests of Fixed Effects on substrate leachate-pH measured from *Lantana camara* 'New Gold' at 63 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	35.36	0.0003
Placement	1	8	93.74	<.0001
Rate*Placement	1	8	17.45	0.0031

Appendix Table 4.11. Type 3 Tests of Fixed Effects on average substrate leachate-pH measured from *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	4.89	0.0580
Placement	1	8	24.46	0.0011
Rate*Placement	1	8	0.31	0.5902

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 7 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	48.55	0.0001
Placement	1	8	11.69	0.0091
Rate*Placement	1	8	0.06	0.8139

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 14 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	68.52	<.0001
Placement	1	8	47.86	0.0001
Rate*Placement	1	8	3.87	0.0848

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 21 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	49.79	0.0001
Placement	1	8	41.42	0.0002
Rate*Placement	1	8	5.59	0.0456

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 28 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	48.53	0.0001
Placement	1	8	42.79	0.0002
Rate*Placement	1	8	9.03	0.0169

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 35 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	3.63	0.0934
Placement	1	8	22.72	0.0014
Rate*Placement	1	8	0.02	0.9021

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 42 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	11.69	0.0091
Placement	1	8	68.16	<.0001
Rate*Placement	1	8	0.03	0.8602

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 49 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.01	0.9092
Placement	1	8	3.11	0.1156
Rate*Placement	1	8	3.81	0.0866

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 56 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	3.04	0.1192
Placement	1	8	0.06	0.8095
Rate*Placement	1	8	0.50	0.5001

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 63 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	4.54	0.0656
Placement	1	8	0.37	0.5614
Rate*Placement	1	8	0.18	0.6811

Appendix Table 4.12. Type 3 Tests of Fixed Effects on average substrate leachate-EC measured from *Lantana camara* ‘New Gold’ in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	8.73	0.0183
Placement	1	8	8.98	0.0172
Rate*Placement	1	8	0.19	0.6746

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* ‘New Gold’ at 7 days after potting in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	93.94	<.0001
Placement	1	8	8.67	0.0186
Rate*Placement	1	8	12.49	0.0077

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* ‘New Gold’ at 14 days after potting in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	27.69	0.0008
Placement	1	8	19.74	0.0022
Rate*Placement	1	8	5.84	0.0421

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 21 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	115.88	<.0001
Placement	1	8	127.43	<.0001
Rate*Placement	1	8	3.02	0.1203

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	81.24	<.0001
Placement	1	8	34.05	0.0004
Rate*Placement	1	8	0.94	0.3612

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 35 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	31.10	0.0005
Placement	1	8	40.48	0.0002
Rate*Placement	1	8	0.10	0.7576

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	16.50	0.0036
Placement	1	8	99.28	<.0001
Rate*Placement	1	8	0.07	0.7934

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 49 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	23.89	0.0012
Placement	1	8	76.26	<.0001
Rate*Placement	1	8	2.04	0.1911

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 56 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	13.50	0.0063
Placement	1	8	58.92	<.0001
Rate*Placement	1	8	2.14	0.1815

Appendix Table 4.12. Type 3 Tests of Fixed Effects on substrate leachate-EC measured from *Lantana camara* 'New Gold' at 63 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	13.58	0.0062
Placement	1	8	20.41	0.0020
Rate*Placement	1	8	0.08	0.7804

Appendix Table 4.12. Type 3 Tests of Fixed Effects on average substrate leachate-EC measured from *Lantana camara* 'New Gold' in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	12.29	0.0080
Placement	1	8	13.85	0.0059
Rate*Placement	1	8	0.24	0.6345

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 7 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.18	0.6854
Placement	1	8	189.52	<.0001
Rate*Placement	1	8	0.14	0.7137

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 14 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	2.26	0.1709
Placement	1	8	357.54	<.0001
Rate*Placement	1	8	1.03	0.3391

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 21 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	32.49	0.0005
Placement	1	8	575.08	<.0001
Rate*Placement	1	8	25.07	0.0010

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 28 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	11.57	0.0093
Placement	1	8	90.57	<.0001
Rate*Placement	1	8	5.35	0.0495

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 35 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	104.87	<.0001
Placement	1	8	289.13	<.0001
Rate*Placement	1	8	10.56	0.0117

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 42 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	37.73	0.0003
Placement	1	8	72.52	<.0001
Rate*Placement	1	8	5.09	0.0540

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 49 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	12.63	0.0075
Placement	1	8	35.47	0.0003
Rate*Placement	1	8	1.43	0.2653

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 56 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	20.08	0.0021
Placement	1	8	28.32	0.0007
Rate*Placement	1	8	11.66	0.0092

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 63 days after potting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	4.19	0.0747
Placement	1	8	12.10	0.0083
Rate*Placement	1	8	1.12	0.3204

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 70 days after planting in 2011.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	0.01	0.9372
Placement	1	8	1.08	0.3299
Rate*Placement	1	8	1.28	0.2900

Appendix Table 4.13. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* ‘New Gold’ at 70 days after planting in 2011.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	12.12	0.0083
Placement	1	8	109.22	<.0001
Rate*Placement	1	8	3.10	0.1163

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 7 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	11.11	0.0103
Placement	1	8	2403.46	<.0001
Rate*Placement	1	8	14.64	0.0050

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 14 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	6.40	0.0352
Placement	1	8	405.49	<.0001
Rate*Placement	1	8	0.05	0.8218

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 28 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	9.63	0.0146
Placement	1	8	343.36	<.0001
Rate*Placement	1	8	3.75	0.0887

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 42 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	7.06	0.0290
Placement	1	8	43.85	0.0002
Rate*Placement	1	8	4.13	0.0766

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 56 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	7.00	0.0295
Placement	1	8	50.10	0.0001
Rate*Placement	1	8	0.17	0.6923

Appendix Table 4.14. Type 3 Tests of Fixed Effects on substrate leachate-DRP measured from *Lantana camara* 'New Gold' at 70 days after potting in 2012.				
Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	9.71	0.0143
Placement	1	8	14.98	0.0047
Rate*Placement	1	8	0.31	0.5943

Appendix Table 4.14. Type 3 Tests of Fixed Effects on average substrate leachate-DRP measured from *Lantana camara* 'New Gold' at in 2012.

Effect	Num DF	Den DF	F Value	Pr > F
Rate	1	8	2.89	0.1275
Placement	1	8	68.80	<.0001
Rate*Placement	1	8	0.59	0.4638

VITA

Daniel Evan Wells was born in Opelika, Alabama in 1983 as the first-born son of Larry and Vickie Wells. His family moved to his hometown of Headland, Alabama in 1985, where he spent the rest of his childhood. His younger brother, Wesley Thomas Wells was born in April, 1989. He graduated from Headland High School in May, 2001. After attending George C. Wallace Community College on full academic scholarship, he enrolled at Auburn University in January, 2003, from which he received a Bachelor of Science in landscape horticulture in May, 2006. He enrolled in graduate school the following fall semester at Auburn University. He married Alexandrea Anne Williams on March 24, 2007 and received his Master of Science in container production horticulture in December, 2008. In August 2009, he enrolled at Louisiana State University and A & M College to pursue a Doctor of Philosophy in horticulture. His first son, Dane Alexander Wells, was born in September, 2010. The following year, his first daughter, Harper Evan Wells, was born in December. With the support of his family, he completed the requirements for his Doctor of Philosophy in March, 2013 and graduated in May, 2013.