ABSTRACT

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Interest in pasture-based pork products has increased significantly in recent years. The market for natural pork products has led many to engage in this enterprise, but there has been a lack of information and knowledge about how to properly manage these operations in an environmentally conservative manner. A study was conducted to evaluate overall N and P deposition, ground cover, compaction, and topography changes as impacted by rotational shade, water, and feed structures in a pastured-pig operation over two 12-week pig occupations. Shade and waterer structures were rotated weekly for 12 weeks within a rotational (mobile) scheme and data compared to a stationary structure system, and to a managed hay operation with no pigs. Soil samples were acquired from subplots and analyzed for distribution of inorganic nitrogen (N) concentrations among main plot treatments, including nitrate (NO_3^-) and ammonium (NH_4^+), and soil test phosphorus (STP) values. A phosphorus loss assessment was also undertaken to evaluate changes associated with pig occupation of pasture plots. Topography changes were documented by mapping with LIDAR technology qualitatively. Soil inorganic N concentrations were higher in exterior subplot positions than in interior positions. This pattern was not maintained after a second pig group occupied the plots. Soil test phosphorus was unaffected by either pig occupation, and no changes were detected in the phosphorus loss assessment. Ground cover percentages were higher in control (hay) treatments than for pig treatments, however no difference was found between mobile and stationary structure treatments in either pig occupation. Soil compaction, as measured by soil bulk density, was found to be higher under

permanent shade structure locations as compared to mobile and control treatments. Mobile and control compaction levels were not different for the second occupation, utilizing a more intensive sampling scheme, suggesting a benefit to the rotation of infrastructure. The weekly rotation of infrastructure performed during both occupations was both labor intensive and time consuming. The observed lack of improvement in nutrient distribution to a rotational infrastructure may limit its utility in pastured hog systems. However, there are some options available that would allow the production of pasture-raised pigs while minimizing associated nutrient loading and pasture degradation.

Optimizing Nutrient Management and Vegetative
Ground Cover on Pastured-Pig Operations

by
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BIOGRAPHY

I was raised in a small community near Dublin, NC where I attended elementary school. I graduated from Tar Heel High School in 1990 and attended Bladen Community College for 1 year. Subsequently, I attended North Carolina State University from 1991 to 1994 and received my BS in Conservation, focusing on soil science. In 1995 I took a position as an Environmental Health Specialist with the Wayne County (NC) Health Department and performed soil evaluations and designed septic systems for on-site waste water disposal. In 1996, I was chosen to serve as a Soil Conservationist with the USDA-Natural Resources Conservation Service in Wayne County where I served two years. I was then selected as the District Conservationist for Lenoir County, NC in 1998 where I served for three years. I was able to obtain the District Conservationist position back home in Bladen County in 2001 where I served for 7 years. In 2008, I returned to NCSU to obtain my MS in Soil Science.

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OPTIMIZING NUTRIENT MANAGEMENT AND VEGETATIVE GROUND COVER ON PASTURE-RAISED PIG OPERATIONS

North Carolina ranks second nationally in total swine production with 9.3 million pigs in the state currently (USDA-NASS, 2010)**.** While most swine are raised in confinement operations, recently there has been an increase in hogs produced in alternative systems, where animals are allowed more movement and interaction in both indoor and outdoor environments. These systems have been developed to meet consumer niche demand resulting from animal welfare and environmental preferences (Vibart, 2008). Pasture-raised pigs (PRP) is one of these alternative systems, defined as raising pigs outdoors on pasture and commonly using portable housing and electric fencing to facilitate rotation of pasture sites (Kennedy, 1998). There are now an estimated 100 PRP producers in North Carolina (N.C. Choices, personal communication) and many in other states. Former small-scale independent hog producers, as well as limited resource farmers, are attracted to PRP production as an agricultural enterprise because capital outlay and costs for buildings and equipment are relatively low, energy costs and water requirements may be lower than indoor production systems, and the market sale price per pound is typically 40 to 60% higher than conventionally raised hogs (Whole Foods Market; Smithfield Foods; Larson et al., 1996).

National growth of the alternative meat industry, and PRP in particular, has been significant. U.S. sales of natural meat, such as outdoor-raised pork, were projected to increase 93% from 2007 to 2012, yet high market growth rates have led to supply shortages with producers unable to meet burgeoning demand from retailers (Mintel Group Report, 2007). While U.S. retail sales of red meat were projected to grow at an annual average rate of 0.8% from 2007 to 2012, sales in the natural and organic segment, representing approximately 2% of total red meat sales, were forecast to increase at an annual rate of 11.3% in the same time period (Mintel, Red Meat – US - December 2007), likely driving the development of many PRP operations. Locally, North Carolina has witnessed a dramatic jump in the number of meat-handlers obtaining licenses to process local livestock, from 136 to 350 between 2007 and July 2010, a 257% increase (NC Choices, personal communication, 2010).

While economic incentives resulting from PRP attract many new growers to the production model, the industry is encountering growing pains related to possible environmental risks. Most of these concerns relate to misuse of the soil resource and nutrient management when swine are raised in a pasture or paddock. This literature review outlines types of alternative swine operations with emphasis on PRP systems, and summarizes the body of literature describing environmental issues associated with this alternative practice in North Carolina and beyond.

Conventional Swine Production Systems

Conventionally, farmers throughout the U.S. have maximized pork production through the construction of pig confinement houses. Confinement houses, which are high-density housing structures for swine, were introduced in the U.S. in the late 1960's and contain features to provide pigs with shelter, feed, water, and waste collection (Iowa State University, 1992). Facilities commonly have concrete slatted floors with a flush system that allows the wastes to be washed out of the houses into an anaerobic waste treatment lagoon. Typically, the lagoon effluent, containing many nutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium, zinc, copper, and boron, is applied to a growing crop at agronomic rates to supply the nitrogen and other nutrient needs of the target crop (NCSU Extension, 2000). The target crop is then removed from the farm, taking with it many of the nutrients applied in the lagoon effluent.

While confinement systems maximize pork production, as well as consolidate wastes in a central location for treatment, they raise concerns about animal welfare as well as welfare of laborers working in these environments (Donham et al., 2007; Schiffman et al., 2005). In particular, humans have been shown to be adversely affected by the air quality inside of pig confinement housing structures. It has been shown that swine workers with respiratory symptoms are at higher risks for airway injury due to their exposure to environmental conditions within a pig confinement house (Schwartz et al., 1992).

Quality of animal life may also be an issue where pigs in confinement have been shown to express stress-related behaviors such as tail biting, aggressiveness, bar chewing, and frequent getting up and lying down, attributed to lack of sufficient space or stimuli (Scipioni et al., 2009). Pig injuries, including skin abrasions, sole bruising, and joint and claw swelling, are associated with flooring systems in confinement buildings and are a cause for concern (Kilbride et al., 2009). Minimization of these behaviors is challenging when pigs are in a confined environment. Pigs in confinement had higher incidences of abscesses (7.4%) pleuritis, and respiratory inflammation, than organically reared pigs (1.8%) (Hansson et al., 2000). Farrowing crates, commonly used in confinement, have been shown to increase piglet savaging by gilts (young female breeding pig), suggesting the limitations on normal behavior imposed by the farrowing crates may be a contributing factor (Jarvis et al., 2004). However, Kavanagh (1995) has shown decreased piglet mortality with farrowing crates than with farrowing nests without crates.

There are also numerous environmental hazards associated with confinement swine operations. Commercial confinement operations commonly collect pig wastes in an anaerobic lagoon where both chemical precipitation and biological anaerobic stabilization occurs (Lovanh et al., 2009). Objectionable odors, harmful atmospheric emissions, volatile organic compounds, nutrient loading on waste application sites, and high labor costs are just a few of the concerns associated with this type of waste treatment (Loughrin et al., 2006; Lovanh et al., 2009; Sistani and McLaughlin, 2006; Welty et al., 1986). Risk of major environmental impact from a waste lagoon rupture is high (Torre et al., 2004), whether it be from a lack of proper management or a flaw in lagoon construction.

<u>Alternative Indoor Swine Production Systems: Hoop Houses</u>

Apart from PRP operations, hoop houses are another low-cost alternative to conventional slotted-floor barns, providing a covered structure with an earthen or concrete flooring system and utilizing hay, straw, or corn-stover bedding within the houses (VanDerPol and Honeyman, 2003). These houses are stocked at an average density of 1 pig $m^{2\ -1}$ (Patton et al., 2004) as compared to confinement operations with an average stocking density of 1.5 pig $m^{2\ -1}$ (Funk et al., 2007). They allow pigs to express natural behaviors such as rooting and lounging, confining animals for only a short period of time during farrowing. The hay, straw, or corn stover bedding serves as an absorptive material for waste which is later composted and land applied at agronomic rates to a growing crop (Tishmack, 2003). Research has shown that swine raised in deep straw are at least as cost-effective as those grown in confinement because of the higher premium price of the pork at market (VanDerPol and Honeyman, 2003).

<u>Alternative Outdoor Swine Production Systems: Pasture-Raised Pigs</u>

Pasture-raised pig systems are an approach for raising pigs outdoors that utilizes portable housing and pasture as and as a source of nutrients, offering a producer low start-up and production costs (Kennedy, 1998). Pasture-raised pigs are often marketed as antibiotic and growth-hormone free, raised humanely, and in an environmentally friendly manner, bringing to farmers the impressive premium price in the alternative food marketplace (Honeyman et al., 2006). An unpublished economic analysis performed in 1996 suggested that the return on investment in this business, excluding the cost of land, is about 15.5% per litter (Larson et al., 1996).

There are flexibilities inherent in PRP's including pasture placement due to the use of portable fencing, freedom to relocate feed and water structures, and ease of adjustment of pen sizes to better manage the herd (Larson et al., 1996). Anecdotal information suggests that pasture-raised pig operations may also offer a reduction in labor requirements and fuel expenditures related to waste handling associated with commercial operations, although no studies have been identified quantifying these factors.

Animal Behavior and Pasture-Raised Pig Operations

Pasture-raised pig operations can have significant effects on pig health and well-being. Since they are not confined in houses, pastured pigs enjoy more freedom to explore their environment and to express their natural behaviors, resulting in less stressed animals than those confined in commercial operations (Edwards, 2005). Evidence of improved health benefits are associated with PRP's, such as improved immunity against bacteria as compared to pigs reared in confinement (Rudine et al., 2007).

Pigs raised on pasture spend more than half of their time foraging and exploring (Stolba and Gush, 1989) and use rooting as a means to search for and locate food (Edge et al., 2005). Although this rooting behavior has been shown to loosen up the soil and improve soil pore volumes similar to tillage (Quintern and Sundrum, 2006), rooting can also be highly destructive to pastures (Stolba and Gush, 1989). Animal lounging behavior can also create deep *wallows*, locally-depressed areas used by pigs for reducing their body temperature (Heitman et al., 1959). Wallowing behavior is expressed within a wide air temperature range from -4 to 24^{o}C (Olsen et al., 2001) and increases as ambient temperatures rise (Huynh et al., 2005; Heitman et al., 1959). As North Carolina daytime high temperatures in the summer have been documented to exceed 32^{o}C for over 90 days in a single year (NC State Climate Office, 2010), it is likely that pig rooting and wallowing behaviors also increase and contribute to irregular pasture topography.

Environmental Risks of Pasture-Raised Pig Operations

Pasture raised pork operations have their own unique set of environmental hazards. Research reports documenting these risks are few in number, however those that exist have shown excessive nutrient loading and losses.

Pigs are not ruminants, but when pastured, forage consumption can contribute up to 5% of their nutrient requirements (Edwards, 2003). Concentrated feed represents a large nutrient import into the pasture environment. Spillage of feed adjacent to feeding units has been documented and implicated as a source of soil nutrient loading in numerous studies (Guilloux et al., 1998; Quintern and Sundrum, 2006). Quintern and Sundrum (2006) suggest that reducing concentrated feed rations in order to increase utilization of existing grass fodder may be a means to reduce the amount of nitrogen loss originating from the feed source. When sow feed rations are reduced to 80%, animals express increased rooting and grazing behavior than those given full rations (Andresen and Redbo, 1999). Pigs express a higher degree of exploratory behavior following introduction to new pasture areas, suggesting that the progressive introduction of new areas to graze may be a positive strategy for better waste and nutrient distribution (Andersson and Skakkebaek, 1999; Quintern and Sundrum, 2006).

Waste and nutrient distribution tends to be uneven in PRP's, driven by habitual animal behaviors that modify the waste distribution in relation to outdoor pen infrastructure. Quintern and Sundrum (2006) found ammonium (NH_4-N) concentrations can be as high as 429 ppm (parts per million or mg L^{-1}) where swine urine is deposited adjacent to rest areas, but less than 10 ppm throughout the paddocks including huts and shelters. They found fecal

N to be distributed 5-15 m from pasture infrastructure such as feeders, waterers, and shade, suggesting that pigs tend to defecate away from these areas in their paddocks, (Quintern and Sundrum, 2006). Pigs in a semi-natural environment, containing grassed, riparian, and wooded zones, have also been found to defecate between 5 and 15 meters away from their lounging area (commonly adjacent to pig huts), predominantly in uphill areas (Stolba and Gush, 1989; Watson et al., 2003).

Salomon et al. (2007), utilizing two existing organic swine fattening operations found some benefit to rotating the open pen infrastructure, such as feeders, waterers, and shade, in order to redistribute wastes. They found that swine defecation behavior in a rotational system occurred within 1 to 15 meters of their lounging area, and that the pigs avoided defecating near their hut (shelter structure), drinking, and feeding facilities.

Swine feeding behavior can vary depending on stocking rates of swine on a pasture. When fattening pigs are rotated weekly to new plots, rooting and lounging increase at higher stocking densities (1000 pigs ha^{-1}), while comsumption of forage vegetation occurs more frequently at low stocking densities (500 pigs ha^{-1}) (Andresen and Redbo, 1999), suggesting that pigs will eat more frequently when the forage supply is higher due to reduced competition.

Stocking rate, length of time pigs reside in the pen and vegetation type are primary determinants of vegetation cover in PRP systems. In a study using gestating gilts in Texas, authors demonstrated that at a stocking rate of 17.5 gilts ha^{-1} (7 gilts ac^{-1}), the percentage of vegetation cover ('Spar' old-world bluestem [*Bothriochloa ischaemum* L. Keng]), on the study sites remained nearly 80% for the first 120 days of their study and above 80% for the next 30 days, indicating that the pig presence and natural activities were not having a negative impact on vegetative recovery (Rachuonyo and McGlone, 2006). In a recent 39-day unpublished study performed at the Center for Environmental Farming Systems in Goldsboro, NC, it was demonstrated that in a tall fescue (*Schedonorus P. Beauv*.) pasture with a stocking rate of 37 (15 pigs ac^{-1}), each weighing 113 kg (250 lb), a 75% vegetative cover could be maintained (Jim Green, personal communication). In a follow-up study utilizing bermudgrass groundcover grazed by 36 kg (80 lb) feeder to finish (fattening) pigs, 90% ground cover was maintained at 37 pigs ha^{-1} (15 pigs ac^{-1}), 85% ground cover at 74 pigs ha^{-1} (30 pigs ac^{-1}), and 75% ground cover at 111 pigs ha^{-1} (45 pigs ac^{-1}) (Green, 2008, unpublished data).

While a majority of studies addressing nutrient and vegetation losses on pasture are from ruminant studies, such studies can serve as a model to understand the importance of vegetative ground cover management to prevent nutrient losses. It is well understood that high total N losses are associated with bare ground areas under cattle (Butler et al., 2007) and sheep (Lilley and Moore, 2009). Butler et al. (2007) suggest thresholds of 45% basal vegetative ground cover and 70% canopy vegetative cover be maintained and suggested N losses may be minimized if it is provided. There is concern about the preservation of ground cover in PRP operations, however no standards exist to guide land managers to an optimal vegetation type or rate of vegetation cover. Studies have shown that maintaining vegetative cover throughout the stocking period, during fall and winter months, as well as rotating swine to alternate locations annually, may be important in minimizing nitrate losses (Blombäck et al., 2003; Williams et al., 2000).

Although NO_3-N losses from agricultural systems have received abundant attention in the literature, phosphorous (P) loss from these systems can also contribute to environmental damage. Phosphorus is often the most limiting nutrient and can cause eutrophication of water bodies (Carpenter et al., 1998a; Smith et al., 2006). There has been little research on the effects of PRP operations on soil test phosphorus (STP). However, research has shown that when surface soil P levels are elevated, whether from fertilizer or manure, P loss through surface runoff increases (Burkitt et al., 2010; McDowell and Sharpley, 2001; Pote et al., 1999; Romkens and Nelson, 1974). Soil P is typically held tightly to soil particles, but can leach when soil P concentrations are high and soil is sandy (Hansen et al., 2002; Johnson et al., 2005). Phosphorus has been shown to accumulate in high traffic areas in pastures where ground cover is minimal (Butler et al., 2006). Loss of soil and attached P due to erosional forces can occur in these bare soil areas or in compacted areas in pastures (Batey, 2009; Hansen et al., 2002). When applied P is greater than crop requirements, STP concentrations increase there is greater risk of P loss via erosion or by becoming soluble and leaching to ground water (Hansen et al., 2002), thus contributing to eutrophication (Carpenter et al., 1998b).

Regional Issues: Pasture-Raised Pigs in North Carolina

Initial observations in North Carolina indicate very little preventative planning to minimize damaging environmental effects of PRP operations. Often, limited resource farmers have entered into this enterprise with minimal land or financial capital available to support more intensive animal operations. These farmers may utilize unproductive land for the rearing of swine and may incorporate wooded areas to provide a source of shade for their pigs. Many of these utilized areas are perennial, seasonal, or intermittent streams at risk of nutrient loading and subsequent eutrophication processes that may result from direct deposition of pig wastes (Carpenter et al., 1998a).

Pasture-raised pig operations in North Carolina are typically on small tracts of land and often have little or no rotation of animals to new pasture sites due to lack of available land. Some farmers have additional acreage available, but do not want to sacrifice productive cropland for this enterprise, as this would limit their income on other portions of their farms. State regulations require that swine farms with a sufficient number of animals to be defined as feedlots, obtain a permit that requires the farmer to follow specific waste management guidelines (NC DENR Environmental Management Commission, 2001). These regulations have been designed for confinement operations, but little guidance on proper management is available for PRP operations, which risk overstocking and poor use of existing resources. Observations in North Carolina have suggested that overuse of small acreage has led to the degradation of farm resources including soil and water quality, tree survival, and aesthetics.

Rotation of pigs to new pasture areas on the farm is currently the recommended practice for North Carolina PRP. The United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) recommends this system such that pigs are moved to another pasture or field once the grass in the current pasture is reduced to 75% surface coverage (Tech. Note, 2008). This allows the pastures time to recover from the foraging pressure. Also, in order to harvest nutrients deposited in a rotational pasture-based system, is also recommended to periodically (depending on stocking rate and site condition), plant the existing former pasturing areas to a nutrient-utilizing crop will take up some of the nutrients deposited. The crop and sequestered nutrients would then subsequently be removed from the farm (Tech. Note, 2008). Ideal times for this relocation may align with seasonality associated with the planting a nutrient-scavenging crop on the current site and the availability of a forage crop elsewhere on the farm.

Pasture-raised pig stocking rates in North Carolina appear to be higher than those used in Europe, where most of the published nutrient studies have originated and range from 4.7 pigs ha^{-1} (1.9 pigs ac^{-1}) (Salomon et al., 2007) to 10 fattening pigs ha^{-1} (4 pigs ac^{-1}) (Quintern and Sundrum, 2006). Typical PRP operations in eastern North Carolina for PRP operations range from 0.81to 3.24 ha (2-8 acres) in size, most being less than 1.21 ha (3 acres). In these systems, observed stocking rates are commonly the maximum allowed, by law, around 24 sows per farm and the resultant 225 pigs, equating to a total of just under 250 pigs threshold which requires a permit (West, E., USDA-NRCS, personal communication, 2009). For larger farms, defined as those having an average of 3.24 ha (8 acres), this stocking rate is close to the recommended rate of 37 pigs ha^{-1} used in the Green study, but for the smaller farms, the stocking rate is equivalent to around 205 pigs ha^{-1} (83 pigs ac^{-1}).

The PRP concept is not novel, but interest in these operations has increased, along with concerns about environmental problems associated with their uninformed management. The PRP production strategy has been shown to have potential pig welfare and health advantages over the traditional widely adopted confinement production strategy. However, they have been shown to be problematic due to high soil nutrient loading and losses to the environment. The overall goal of this study was to further the knowledge base supporting PRP production in such a way to facilitate conservation and preservation of proper ground cover, and utilization of nutrients at risk for loss to the environment through improved management practices, while allowing producers an expectation of reasonable profits. Specific objectives for this study were to determine the effects of a rotational infrastructure system within pig pastures on PRP operations on: 1) soil inorganic nitrogen and soil test phosphorus (STP) distribution and loading; 2) ground cover; 3) topography; and, 4) soil bulk density (BD).

EFFECTS OF ROTATIONAL INFRASTRUCTURE WITHIN PASTURE-RAISED PIG OPERATIONS ON SOIL NUTRIENT DISTRIBUTION AND BULK DENSITY, TOPOGRAPHY, AND GROUND COVER

Interest in niche pork (*Sus scrofa domestica*) markets has increased significantly in recent years, with the number of pigs produced estimated to be on the order of 500,000 to 750,000 pigs annually (Honeyman et al., 2006) **.** The market and premium price for natural pork products has led many farmers to engage in this enterprise, but there has been a lack of information and knowledge about how to properly manage these operations in an environmentally conservative manner. Pasture-raised pigs (PRP) is an alternative system for producing natural pork, defined as raising pigs outdoors on pasture, commonly using portable housing and electric fencing (Kennedy, 1998).

Nitrogen (N) inputs and subsequent losses are common in PRP operations due to importation of feed, high stocking rates, and pig behavior. In a Danish study using lactating sows on pasture, Eriksen et al. (2002) found that pig biomass only accounted for 44% of imported feed N while the remaining was lost through ammonia volatilization, denitrification, and nitrate (NO_3 -N) leaching, suggesting that pigs do not efficiently utilize feed N. Pig behavior, specifically their tendency to deposit wastes habitually in preferred excretory areas (Olsen et al., 2001; Stolba and Gush, 1989), has been shown to unevenly distribute N in paddocks (Eriksen, 2001), presenting a high risk for NO_3 -N and ammonia (NH_3 -N) losses (Watson et al., 1998). Studies have shown that excess NO_3 -N in groundwater can contribute to eutrophication of water courses (Carpenter et al. 1998), as well as risks to human health associated with N in drinking water (Powlson et al., 2008), both resulting from agricultural losses.

Although NO_3 -N losses from agricultural systems have received abundant attention in the literature, phosphorous (P) loss from these systems can also contribute to environmental damage. Phosphorus is often the most limiting nutrient and causes eutrophication of water bodies (Carpenter et al., 1998b; Smith et al., 2006). There has been little research on the effects of PRP operations on changes in soil test phosphorus (STP). However, when surface soil P levels are elevated, whether from applications of fertilizer or manure, P loss through surface runoff is known to increase (Burkitt et al., 2010; McDowell and Sharpley, 2001; Pote et al., 1999; Romkens and Nelson, 1974). Soil P is typically held tightly to soil particles, but can leach when soil P concentrations are high and soil is sandy (Hansen et al., 2002; Johnson et al., 2005). Phosphorus has been shown to accumulate in high traffic areas in pastures where ground cover is minimal (Butler et al., 2006). Loss of soil and attached P due to erosion can occur in these bare soil areas or compacted areas in pastures (Batey, 2009; Hansen et al., 2002). When applied P is greater than crop requirements, STP concentrations increase and may become soluble and at risk for leaching to ground water (Hansen et al., 2002) and contribute to eutrophication (Carpenter et al., 1998a).

One approach being utilized to evaluate and minimize P loss has been to perform a P loss assessment as a means to estimate the prospective P loss pathways in agricultural soils. The Phosphorus Loss Assessment Tool (PLAT) is a tool developed in North Carolina to meet the NRCS 590 Nutrient management standard (NRCS, 2008), which requires a P loss assessment on any field to which P-containing animal wastes are applied. The North Carolina PLAT utilizes field-collected data in conjunction with STP to generate a rating that has nutrient management application management impacts. The NC PLAT tool considers four loss pathways: erosion, runoff, leaching, and applied P runoff. Results serve as both qualitative and quantitative estimates of potential P loss on farm fields/pastures (Osmond et al., 2008).

The presence of vegetative ground cover is important to limiting P mobility and to plant uptake of P and inorganic nitrogen (i.e., soil mineral N, $N_{min)}$. There is concern in PRP operations about the preservation of ground cover, however no standards exist to guide land managers to an optimal vegetation type or rate of vegetative cover. Studies have shown that maintaining vegetative cover throughout the stocking period during fall and winter months, as well as rotating swine to alternate locations annually, may be important in minimizing NO_3 -N losses (Blombäck et al., 2003; Williams et al., 2000).

In a study on a cow pasture system in Raleigh, NC, Butler et al. (2007) found that, like P, the highest total N loss was associated with areas of compacted bare ground, and suggested that if 45% basal vegetative ground cover and 70% canopy ground cover is provided, N loss may be minimized. In a pastured sheep operation, ground cover could be sustained at or above 70% if livestock were moved off the pasture at an 80-90% ground cover threshold, but at a loss of overall operational profitability (Lilley and Moore, 2009).

Soil compaction can be a serious problem in pastured animal operations (Greenwood and McKenzie, 2001). In a review of compaction studies (Drewry et al., 2008), pastures impacted by animal treading showed decreased yields, increased soil bulk density (BD), and reduced soil drainage (Mulholland and Fullen, 1991). It has been found that compaction from grazing animals is often limited to the upper portion of the soil (Greenwood and

McKenzie, 2001). Willatt and Pullar (1984) found that with increased stocking densities of sheep, soil BD increased and water infiltration decreased on grazed pastures. Soil compaction in topsoil on sloped sites can lead to soil erosion (Batey, 2009) and loss of nutrients attached to soil particles (Hansen et al., 2002). Some areas within pastures perceived as compacted due to the lack of ground cover have become denuded as a result of overgrazing, rooting, wallowing, and tissue damage from pig traffic (Drewry et al., 2008), rather than compaction.

Topography changes are inevitable in pasture operations. Mulholland and Fullen (1991) suggested that hoof damage from cattle can lead to soil structural and hydrological changes in pastures. Pigs, similarly, create topographical changes in pastures, expressed through rooting (Stolba and Gush, 1989), lounging behavior, and creation of wallows, which are locally depressed areas used by pigs for reducing their body temperature (Heitman et al., 1959). Wallows are often filled with water and are a favored place for pigs to lie and coat themselves with mud, protecting their skin from sunburn. There has been limited research on topography of pastured-pig operations, which may provide valuable insight into how to minimize soil disturbance in these operations.

Understanding overall pig behavior provides us opportunity to attempt to change pig excretory behavior such that a more even distribution of wastes and nutrients can occur. Studies have shown that pigs tend to urinate closer to their lounging areas and defecate farther away, but avoid their feeding areas (Olsen et al., 2001; Stolba and Gush, 1989; Watson et al., 1998). Implementation of a rotational shade, water, and feed infrastructure scheme (Quintern and Sundrum, 2006) may change the urination and defecation patterns within PRP operations, leading to better distribution of nutrients, less land disturbance, and less degradation of vegetative ground cover. The objectives of this study were to determine the effects of a rotational infrastructure system within a pasture-raised pig operation on: 1) soil N and STP distribution and loading; 2) ground cover; 3) topographical changes; and, 4) soil BD. We hypothesized that rotation of shade, water, and feed infrastructure would: 1) facilitate improved distribution of N and STP; 2) create a more even distribution of wallows within plots; and 3) reduce soil BD within plots.

Materials and methods

Site description. The study took place at Cherry Farm Research Station in Goldsboro, NC in the coastal plain region within the Neuse River floodplain, where highly variable soil types are common. Soil mapping units included Wickham Series (Fine-loamy, mixed, thermic, Typic Hapludult), Wahee Series (Fine, mixed, thermic, Aeric Endoaquult), Altavista Series (Fine-loamy, mixed, thermic, Aquic Hapludult), State Series (Fine-loamy, mixed, thermic, Typic Hapludult), and Dogue Series (Fine, mixed, thermic, Aquic Hapludult) (NRCS, 2010). Soil surface horizons ranged from sand to sandy loam. Subsurface horizons ranged from sandy clay loam to gravelly clay. The site had previously been utilized for production of corn, soybeans, and rye cover crop. An existing drainage ditch adjacent to this site facilitates crop production on lower landscape positions.

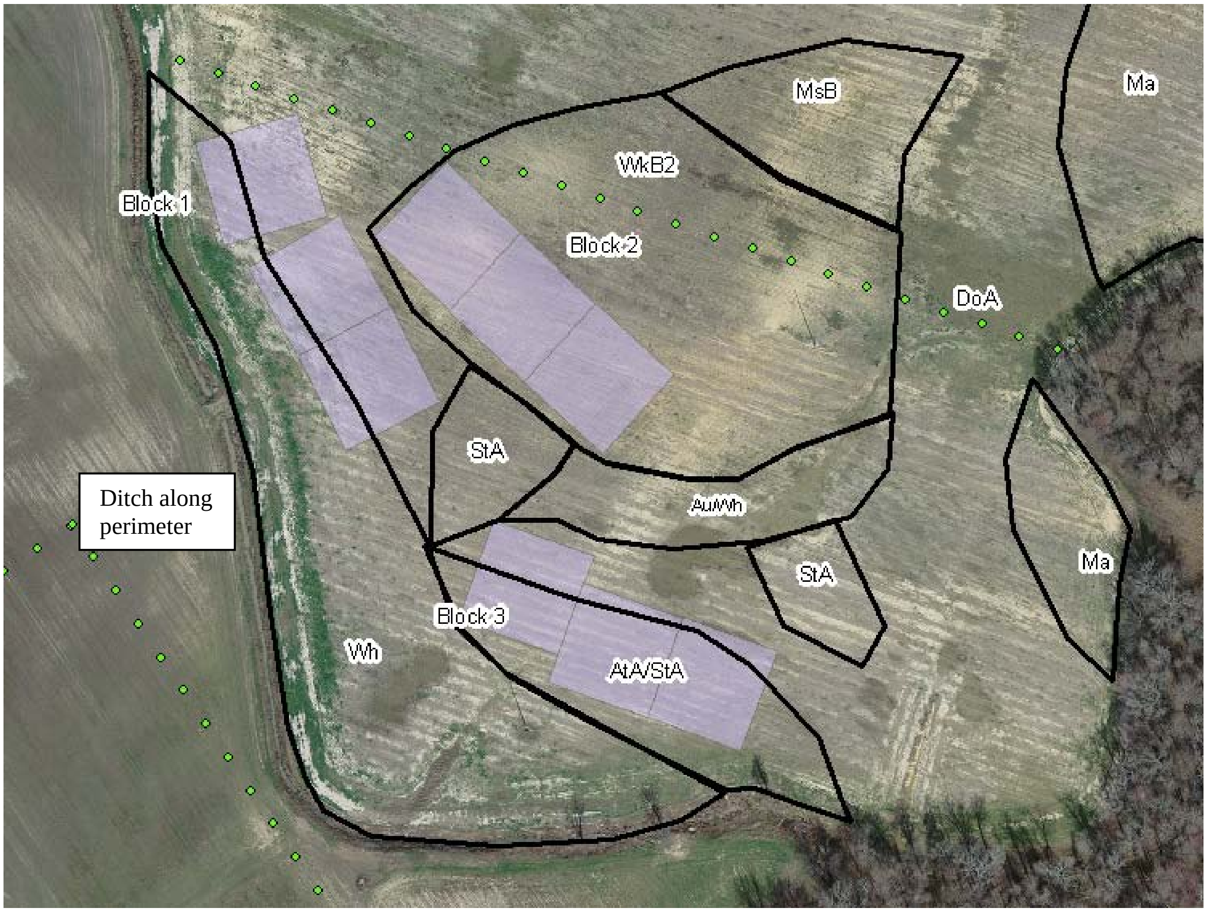

Figure1
Soil map overlay of study area displaying block locations. Series labels defined: AtA (Altavista), Au (Augusta), DoA (Dogue), Ma (Masda), StA (State), Wh (Wasda), WkB2 (Wickham, 2-6%).

Swine variety and stocking rate. Two separate pig occupations were conducted for this study: Experiment 1 (Exp 1) – Summer, 2009 (July 23 – October 15); and Experiment 2 (Exp 2) – Spring, 2010 (March 23 – June 15). Duroc pigs were stocked at 74 pigs ha^{-1} (30 pigs ac^{-1}) and were raised as feeder-to-finish pigs (topping operation) for Exp 1 and 2. Initial mean weight at stocking for Exp 1 was 31.9 kg pig^{-1}. For Exp 2, Duroc-Yorkshire cross were stocked at an identical rate to Exp 1 with an initial mean weight at stocking of 26 kg pig^{-1}. Nitrogen and phosphorus inputs from each pig occupation were 235 kg N ha^{-1} and 40 kg P ha^{-1}, respectively. Nitrogen and P input from pigs per treatment were extrapolated using pig excretion N and P concentrations in mass per animal per day and multiplied by stocking rate and length of pig occupation (ASAE, 2005).

Experimental block and plot establishment. A randomized complete block design including three blocks and three treatments of plot size 1619 m^2 (40.2 m X 40.2 m) (0.16 ha) was established. Blocks were positioned based on existing soil field mapping units. Treatments included mobile versus stationary shade-waterer structures, and a control with no pigs managed as a hay system. Treatment plots were divided into 16 square subplots of 101 m^2 in size.

Stationary treatment. Stationary treatment plots were established by positioning a square shade structure (16 m^2), constructed of 2.54 cm polyvinyl chloride (PVC) pipe and shade cloth, with attached nipple waterer. The shade/waterer structure for the stationary treatment remained in place throughout this study. Feed structures were placed centrally along the lower plot perimeter and remained stationary throughout both experiments (Figure 2).

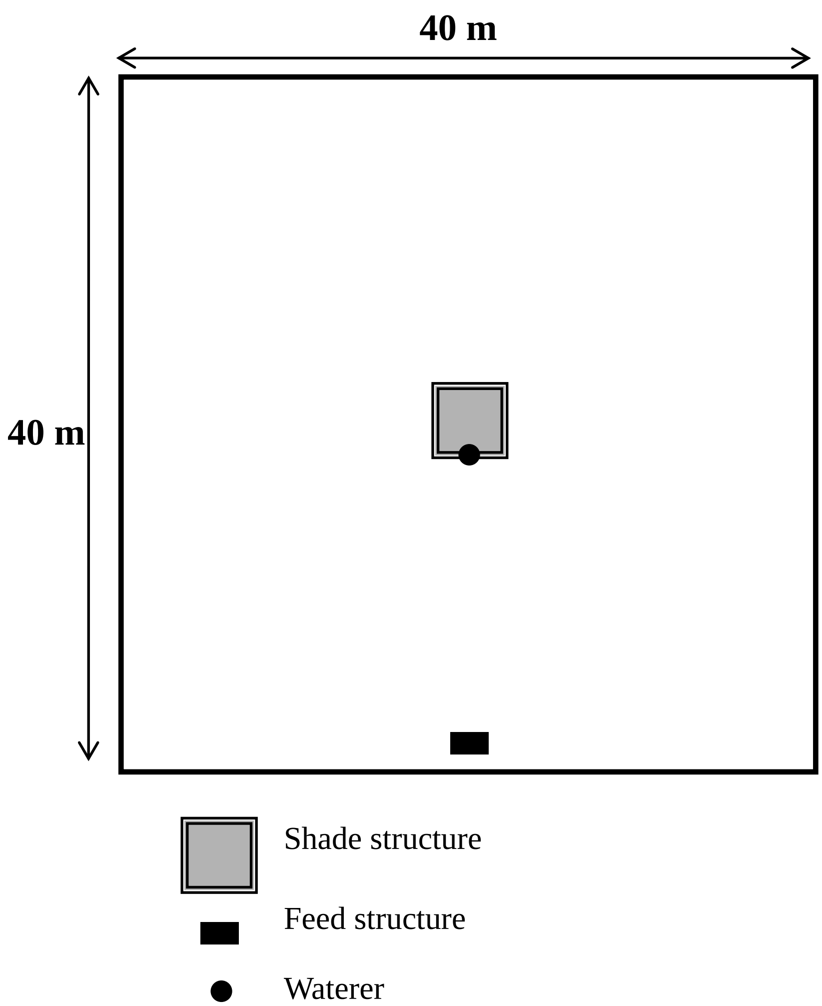

Figure 2
Stationary treatment plot. Shade structure located centrally within plot while feed structure is oriented centrally along lower plot boundary.

Mobile treatment. A Latin Square blocking scheme was developed in order to maintain distribution of shade structure rotation by age class and pig weight gain of the pigs as they grew (Figure 3.) Letters A, B, C, and D were assigned as follows: Weeks 1-4 =A; Weeks 5-8 =B; Weeks 9-12 = C; No Shade Structure = D. The Latin Square rotation scheme was developed using the statistical program SAS, version 9.1.3 (SAS, Inc., Cary, NC) to assign letters to subplots to ensure each row and column contained all assigned week groups above, and each block was randomized separately.

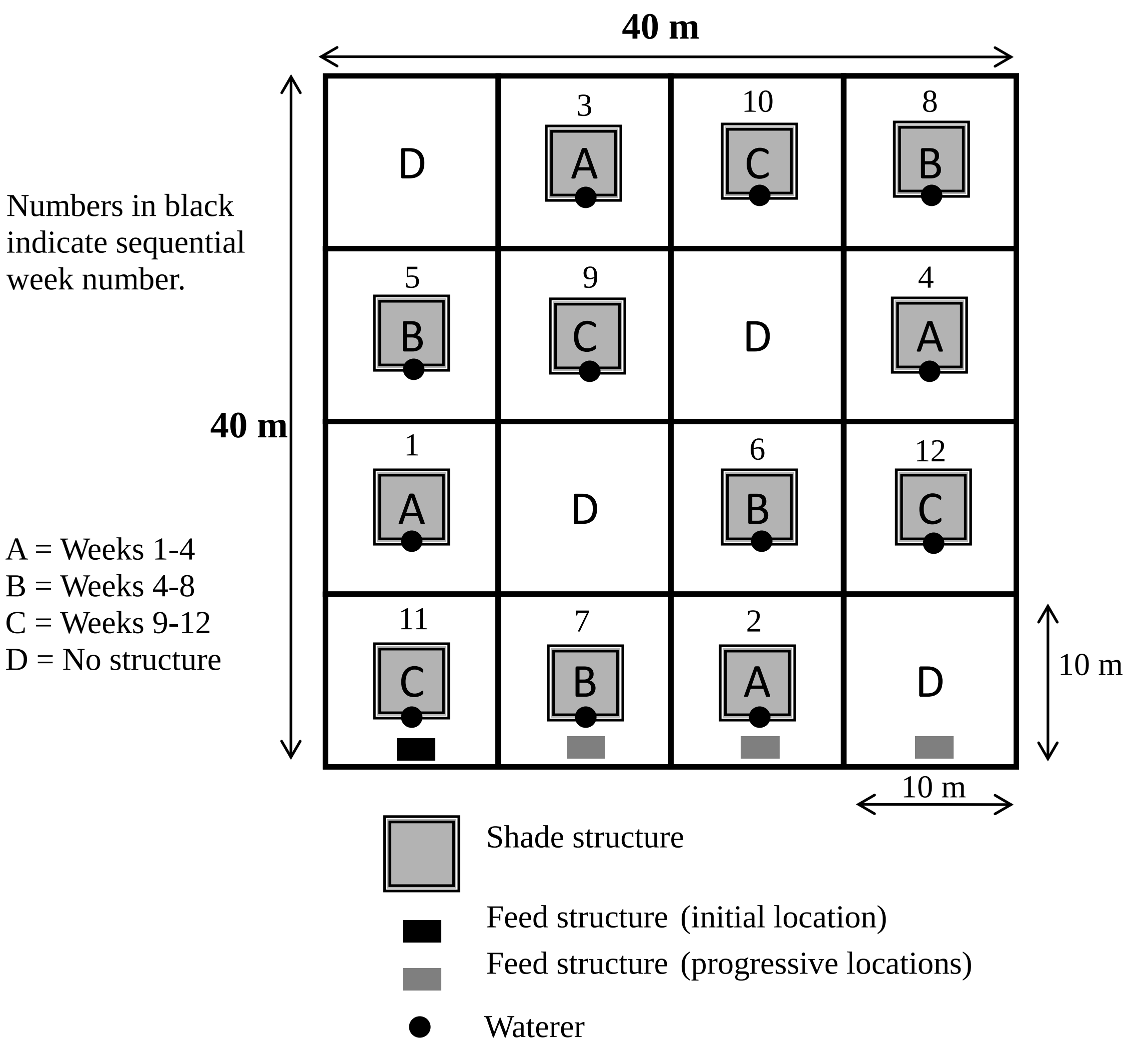

Figure 3
An example of the Latin square rotation scheme for mobile treatment. Feed structure remains at each location indicated for 3 weeks and then progressively moved to adjacent locations. The Latin square was randomized separately for each block.

Shade/waterer structures were placed centrally in each mobile treatment subplot and rotated weekly for the 12 week period among non-control subplots. Mobile treatment feed structures were initially placed as shown in Figure 3 for three weeks then subsequently moved linearly to adjacent subplots at three weeks intervals for both experiments.

Control. Control plots were established with summer and winter forages (see below) and maintained as a hay crop. Periodic cutting and removal of forage and subsequent application of N to stimulate regrowth were carried out to model characteristics of locally practiced hay management. Forage was cut either with a rotary mower or hay cutter, allowed to dry, baled in round bales, and removed from the plots.

Vegetation establishment and management. Prior to experiment initiation, the site was fallow for approximately 7 months with a sparse stand of volunteer cereal grain rye and ryegrass mixed with native weeds. The site was clipped and raked to remove above-ground biomass. For Exp 1, brown Mid-Rib (BMR) Hybrid Sudangrass (*Sorghum bicolor* L.*)*, a summer annual with low lignin content (Beck et al., 2007) was drilled to a depth of 1.27 cm (0.5 in.) on 19 cm (7.5 in.) rows with a 4.27 m (14 ft) Great Plains (Salina, Kansas) drill at a rate of 39.5 kg ha^{-1} (35.22 lbs ac^{-1}) (Table 1) in May 2009. Ammonium nitrate (NH_4NO_3) granular fertilizer was applied to all plots using a 1.82 m (6 ft) model 1006 Gandy (Owatonna, Minnesota) drop spreader at a rate of 54.1 kg ha^{-1} in mid-May.

Pigs were introduced to plots once vegetation reached approximately 120 cm height, 8 weeks after planting. For the Exp 1 control, 30% liquid N was applied to forage twice during the growing season following clipping and removal of forage – once in early August and again in mid-September 2009 at a rate of 56 kg N ha^{-1} (50 lb N ac^{-1}) and 33.6 kg N ha^{-1} (30 lb N ac^{-1}), respectively. Following Exp1 pig removal, all treatments were disked with a conventional disk, culti-packed, and planted with a combination of “Abruzzi” rye (*Secale* *cereale* L., a cool season annual), and Marshall ryegrass (*Lolium multiflorum* L.). Ryegrass was planted with a model SSP-10 Brillion (Brillion, Wisconsin) Pure Stand seeder at 28 kg ha^{-1} (25 lbs ac^{-1}) to a depth of 1.27 cm (0.5 inch) in approximately 15.24 cm (6 inch) rows. Rye was planted with a no-till drill at 67.2 kg ha^{-1} (60 lbs ac^{-1}) to a depth of 2.54 cm (0.5) inch on 19.05 cm (7.5 inch) rows at the beginning of November 2009 for utilization by pigs in Exp 2. Additional 30% liquid N was applied to the control plots at rate of 33.6 kg ha^{-1} (30 lb ac^{-1}) post-planting.

Due to cold and poor stand establishment, a booster application of 30% liquid N was applied in early March 2010 to all plots at a rate of 63.9 kg ha^{-1} (57 lb ac^{-1}). Pigs were introduced in late March 2010. Control plots received an additional liquid N application in mid-April at a rate of 44.8 kg ha^{-1} (40 lb ac^{-1}) following clipping and removal of forage.

Table 1
Schedule of field operations for experiments 1 and 2.

Treatment	Activity	Date
		Experiment 1
C M S	Soil sampling	May 20, 2009 (pre–Exp 1)
C M S	Hybrid sudangrass planted	May 20, 2009
C M S	Vegetation monitoring, weekly	July 23–Oct. 15, 2009
M S	Pigs introduced	July 23, 2009
M S	Plots mowed	July 24, 2009
C	Forage mowed and baled	July 31, 2009
C	Applied 22.7 kg N ac^{-1} (50 lb ac^{-1})	Aug. 4, 2009
C	Forage mowed and baled	Sept. 4, 2009
C	Applied 13.6 kg N ac^{-1} (30 lb ac^{-1})	Sept. 19, 2009
M S	Pigs removed	Oct. 15, 2009
M S	Plots mowed	Oct. 16, 2009 (post–Exp 1)
MS	Plots Leica-Scanned	Oct. 21-22, 2009
C M S	Soil sampling	Oct. 22-23, 2009
C M S	Bulk density evaluation	Oct. 22-23, 2009
C M S	Plots tilled	Nov. 1, 2009
C M S	Rye/ryegrass planted	Nov. 1, 2009
C	Applied 15.9 kg N ac^{-1} (35 lb ac^{-1})	Nov. 4, 2009
		Experiment 2
C M S	Soil sampling	Feb. 22-24, 2010 (pre-Exp 2)
C	Applied 25.8 kg N ac^{-1} (57 lb ac^{-1})	Mar. 9, 2010
M S	Applied 12.6 kg N ac^{-1} (27.8 lb ac^{-1})	Mar. 9, 2010
C M S	Vegetation monitoring	Mar. 19, 2010
M S	Pigs introduced	Mar. 23, 2010
C M S	Vegetation monitoring weekly	Mar. 30-Jun. 22, 2010
C	Plots mowed	April 9, 2010
C	Applied 18.1kg N ac^{-1} (40 lb ac^{-1})	April 12, 2010
M S	Pigs removed	June 15, 2010
C M S	Soil sampling	June16-18, 2010 (post-Exp
C M S	Bulk density evaluation	June 18, 2010
C	Plots mowed	June 18, 2010

Ground cover measurements. Each of the 16 subplots was divided into three equally spaced transects beginning at a point 1 m from the lower left edge of each subplot column (Figure 4). Transects were spaced 4.1 m apart within the subplot column and numbered 1 through 12 from left to right. Endpoints of each transect were marked with 2.5 cm PVC pipe driven into the ground approximately 15 cm and extending above ground approximately 1.75 meters as a guide for measurement. Transects were traversed weekly for 12 weeks recording data upon every other step using a modified point-step method (Owensby, 1973). Groundcover readings were recorded as: vegetation alive; vegetation dead, or soil. Vegetation dead and alive recordings were combined and averaged per plot to determine percent ground cover.

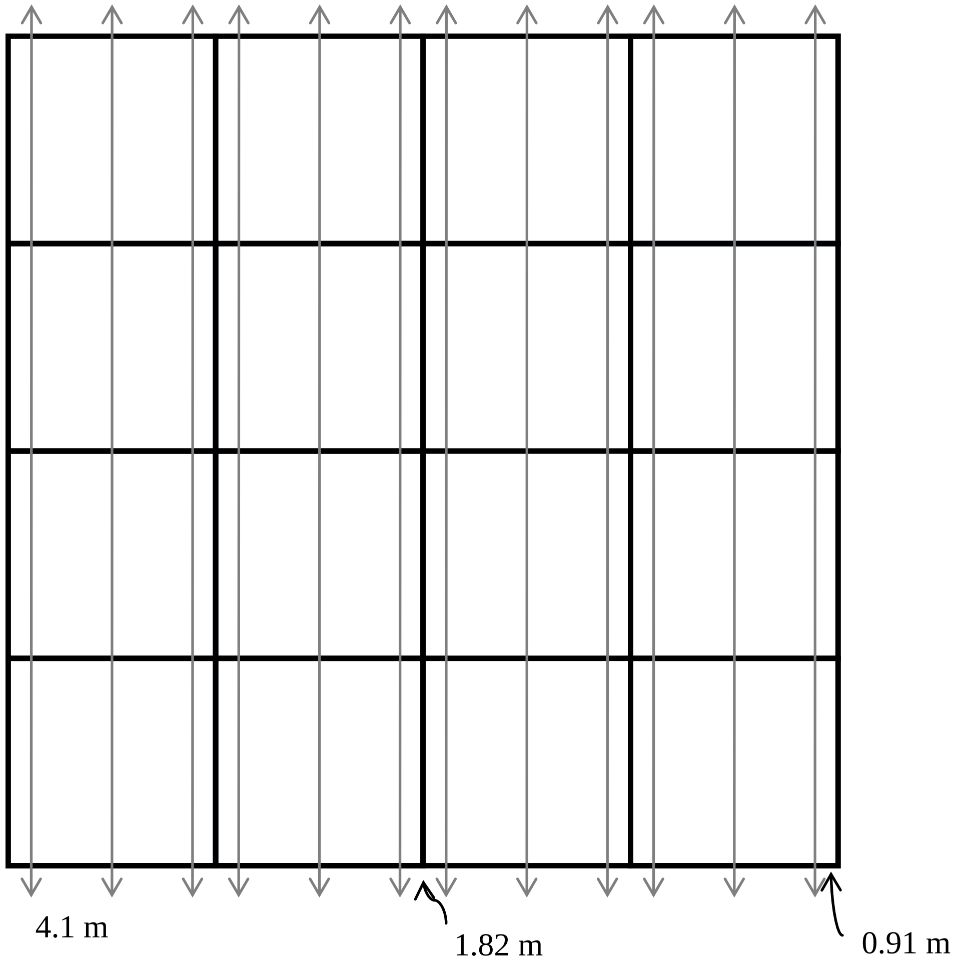

Figure 4
Transect system. Transects were equally spaced within subplot columns. Transects were traversed using a modified point-step system to obtain ground cover percentages.

Soil Sampling. Both shallow and deep samples were taken from each of the 16 subplots at four times over the course of the experiment: June 2009, October 2009, February 2010, and June 2010. For shallow sampling, 10 to 12 subsamples from 15-cm-depth were removed per subplot using an Oakfield soil sampling probe, composited, and mixed to ensure a homogenous sample, and then air dried for 3 days. Shallow samples were fumigated with methyl bromide to destroy seed viability of a federally-identified noxious weed seed (*Commelina benghalensis*), known to be present at the experiment site. Soil samples were subsequently sent to the North Carolina Department of Agriculture & Consumer Services (NCDA& CS) lab for analysis of P, as well as other nutrients (data not shown) using Mehlich 3 extraction.

For deep samples, 1-m-depth soil samples were taken from the center of each subplot using a truck-mounted hydraulic soil sampling and coring instrument (Model GSRPS Giddings Machine Company, Windsor, CO) with a 3.2-cm diameter coring tube. Each core was divided into 0-to-0.5 and 0.5-to-1 m portions, placed in labeled, individual double-bagged paper bags, and allowed to air dry in a greenhouse for approximately 1 week. Samples were then manually disaggregated to pass a 2 mm sieve, boxed, and stored at room temperature until analysis.

Inorganic N Analysis. An 8-g portion of each soil sample was combined with 40 ml of 1 M KCL solution and placed in a 120 ml acid-washed urine specimen cup. Cups were capped and placed horizontally in a Cole Palmer 51704 series orbital shaker table and agitated at 80 revolutions per minute for 1 hour at 21^{o}C. Upon completion of agitation, sample solutions were decanted through # 40 Whatman filter paper funnels into a separate urine specimen cup. Extract was poured into a 20 ml scintillation vial and frozen until N analysis could be completed. Samples were thawed, placed into 10 ml glass vials, and analyzed on a Quick Chem 8000 Lachat for nitrate-N (NO_3 -N) and ammonium-N (NH_4 -N). Results were reported in mg kg^{-1} of N_{min} (NO_3 -N + NH_4 -N). Blanks, consisting of the KCL extractant without soil, were included. Inorganic N levels obtained for the blanks were subtracted from the soil sample analysis result to account for possible N_{min} present in the filter paper. Results were multiplied by the ratio of extractant volume to soil mass ratio of 5:1 and reported in mg N kg^{-1}.

Phosphorus Loss Assessment. A phosphorus loss assessment was conducted for mobile and stationary treatments using the North Carolina Phosphorus Loss Assessment Tool (PLAT) (Osmond et al., 2008). PLAT scores are the sum of potential P losses from: 1) sediment carrying soil-bound P; 2) runoff carrying soluble P; 3) subsurface soluble P losses; and 4) runoff carrying surface applied (source) P. Soil test phosphorus (STP), crop type, soil series, soil erosion rate, organic P inputs, and soil hydrologic condition were input into the PLAT to determine a PLAT score and qualitative rating. Soil erosion rates were 3 and 5 tons ac^{-1} yr^{-1} of soil loss for shoulder slope and foot slope plot positions, respectively, using the Revised Universal Soil Loss Equation, version 2 (RUSLE 2) soil erosion loss prediction tool (NRCS, 2010).

Soil bulk density measurements. A soil BD sample was taken 1 m from the lower left corner of each subplot (Figure 5) for both experiments. Additional BD samples were taken post-Exp 2 to assess the influence of the shade structure for the stationary treatment as compared to mobile and control treatments. A hollow metal cylinder, approximately 1.5 mm thick, with interior dimensions 5-cm diameter by 4- cm depth, , as shown in Figure 15 (Appendix) was driven until flush with the soil using a hammer and a wooden block placed across the top of the ring to evenly distribute the force along the entire surface of the ring. The known volume of soil (95.03 cm^3) was dried for 24 hours at 90^{o}C, weighed, and soil weight divided by volume. Results were reported in g cm^{-3}.

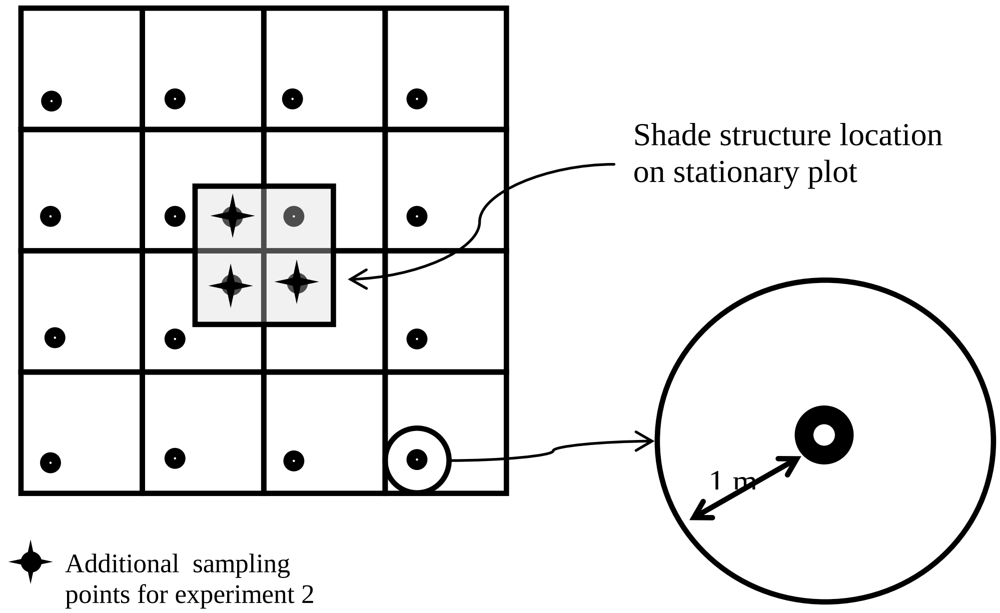

Figure 5
Soil bulk density sampling scheme for experiments1 and 2 indicated by circle. Note additional sampling locations in center of plot under shade structure location, common to stationary plots – sampling points entirely under shade structure.

Topography evaluation. To evaluate soil surface changes associated with treatments, we used a ground-based scanning lidar (light detection and ranging) system, a remote sensing technology that utilizes a laser pulse to measure the range to a distant target (Lefsky et al., 2002) and can be used to detect topographical changes (Hall et al., 2009). A Leica ScanStation 2 (Leica Geosystems, Herebrugg, Switzerland) was used to estimate topographical changes associated with pig treatments. Sitting atop a tripod, a laser range finder rotates 360 degrees horizontally while a mirror flips vertically reflecting the laser pulse up and down as shown in Figure 16 (Appendix). This combined motion scans the surrounding surface by sending out laser pulses at a rate of 50,000 s^{-1} (Leica Geosystems, 2009). The pulses are reflected off surrounding objects and the returned signal is recorded.

For each pulse the scanner records the X,Y,Z coordinates of the target. When the scan is complete, the system generates a cloud of points that are typically used to develop 3-D models. In this analysis, lidar-generated point clouds were used to develop a 3D model (DEM - Digital Elevation Model) of the soil surface pre- and post-Exp 1.

Prior to pig occupation, each treatment plot was scanned to establish the pre-Exp 1 topographical surface. Post-Exp 1, two additional scans were performed in each treatment plot and used to evaluate surface disturbance (e.g. compaction, wallows, movement) resulting from swine occupation.

To create surface topography from the lidar-generated point clouds, the raw point data collected was exported from the scan station and loaded into a Geographic Information System (GIS) (ArcGIS, ESRI, Redwoods California) for spatial post-processing and analysis. Before surface creation, all non-surface elevations collected by the lidar were removed; this included surrounding fence posts, fence wire, and feed and shade structures located within the plots. To distinguish and estimate the soil surface from the presence of existing surface vegetation < 5 cm tall (<2 in.) and the previous year's crop residue, the points were transformed into a raster grid using a procedure that selected the minimum lidar spot elevation within a 0.1-m by 0.1-m cell. This maximized the likelihood that each cell within the raster represented the bare-earth surface. These cells were then transformed back into points and spatially interpolated. An Inverse Distance Weighted (IDW) interpolation method was utilized to develop gridded surface elevations within each plot (i.e., a DEM).

Statistical evaluation. The statistical software package SAS 9.3.1 (SAS Institute, Cary, NC) was used in analyses of data using the command PROC MIXED to produce Type 3 fixed effects, least square means, difference of least square means, and contrasts from which statistical inferences were made. Least square means of ground cover and bare soil percentages were calculated and comparisons performed to determine treatment differences within and between experiments using initial ground cover percentage as a covariate.

Differences in N_{min} and STP, individually, between the following soil sampling periods were calculated: pre-Exp 1vs post-Exp 1; post-Exp 1 vs pre-Exp 2; pre-Exp 2 vs post-Exp 2, in order to account for any residual soil N_{min} or STP present at project onset, allowing us to determine effect of the pig occupation on N_{min} and STP. Initial soil N_{min} and STP were used in separate analyses as covariates to explain error associated with the baseline conditions prior to each experiment. In order to capture trends in N_{min} and STP dispersion due to infrastructure rotation, four interior subplot positions were compared to 12 exterior subplot positions in each treatment plot. Additionally, mean variance of N_{min} within plot by treatment comparisons were made and differences between sampling periods were calculated. Difference values within and between experiments were log transformed due to non-normal residuals. The log was taken on the total N_{min}, mean N_{min} variances, and STP differences, after a constant was added to bring the minimum difference to a value of one.

Bulk density was compared both: 1) temporally, using between-treatment data to determine if BD changes occurred due to treatment effects (Exp 1 and 2), and 2) spatially, using comparisons within-treatment subplots to determine if BD varied within treatment groups (Exp 2 only). In Exp 2, where additional BD data was recorded, the four interior subplots BD were compared to the exterior 12 subplots.   All means comparisons described as “differences” were statistically different at the $\alpha = 0.05$ level of significance.

Results and discussion

Ground cover. Ground cover data are presented in Figure 6. Mean ground cover percent across each experiment was not different between mobile and stationary treatments. As expected, mean ground cover percentage was higher for control treatments than for mobile and stationary treatments for Exp 1, 85.1% and 60%, respectively. The Exp 2 control (84%) also had greater ground cover than the pig (70.1%) treatments as shown in Table 3 (Appendix). Percent ground cover for the Exp 2 rye/ryegrass mobile and stationary treatments declined at a slower rate than the hybrid sudangrass used in Exp 1. Hybrid sudangrass ground cover percentage (Exp 1) fell below the recommended sustainable ground cover percentage of 75% at Week 4 and remained below this threshold for the remainder of the experiment. However, ryegrass/rye was maintained at or above 75% ground cover until week 8, after which it dropped dramatically and continued a decline in ground cover percentage until the end of the experiment. No differences in mean bare soil, mean alive ground cover, or mean dead ground cover percentages between mobile and stationary treatments were identified in either experiment (Figure 14) (Appendix). There was no difference in mean ground cover between Exp's 1 and 2 at 68.4% and 73.4%, respectively; this comparison confounded vegetation species within the different experiments.

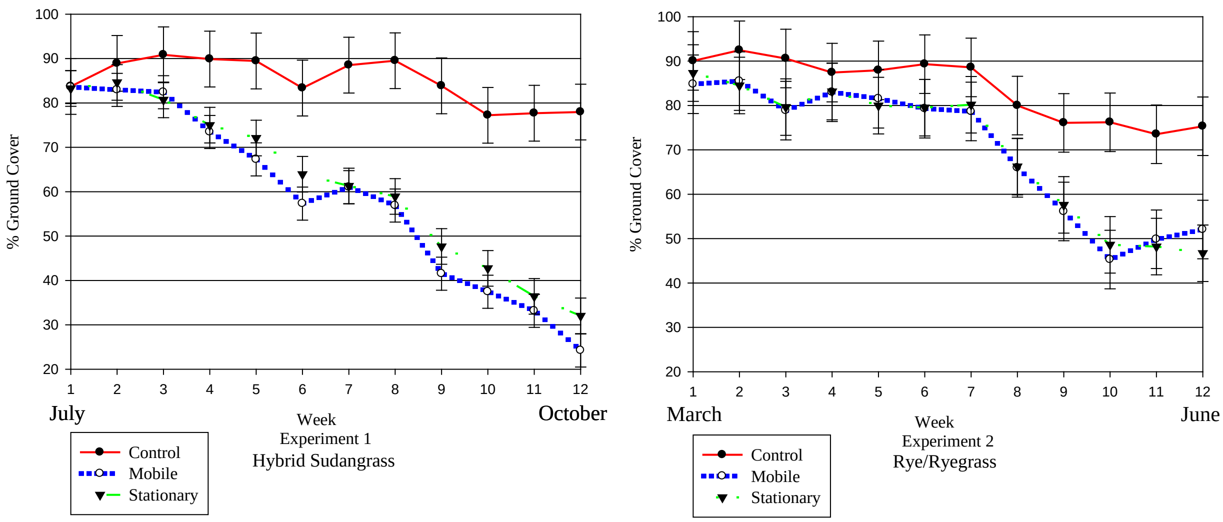

Figure 6
Effects of treatment on changes in percent ground cover across experiments 1 and 2. Error bars represent standard error.

The lack of difference in ground cover between mobile and stationary treatments may be explained by the creation of new wallows encouraged by the movement of the shade structures themselves. It was observed that the mobile treatment wallows located beneath shade structures were created by the pigs within a week of rotating the structure, commonly holding water and restricting vegetation re-growth. Areas beneath shade structures never regained vegetation, even when the structures were moved to new locations, preventing further nutrient uptake in those areas. In the stationary treatment, vegetation destruction was observed to be heaviest around shade and feed structures. There were other areas within the plot where the pigs created wallows and rooted extensively, but like the mobile treatment, vegetation around the shade structure did not recover. Reasons for loss of vegetation in control plots include the seasonal senescence of vegetation and the periodic clipping and removal of forage associated with normal hay management.

The delayed period of ground cover demise in Exp 2, appears to be related to vegetation growth habits. When the rye in Exp 2 began to senesce and fall to the ground, a subsequent mulching effect occurred resulting in additional ground cover. With the additional access to sunlight, annual ryegrass began to flourish. This additional pig forage source contributed to the biomass of ground cover present, prolonging the time it took for pigs to destroy thecover through consumption and trampling. Hybrid sudangrass, planted in Exp 1, grew very tall, erect, and had a dense canopy when mature. However, the stem density, as planted in this experiment, left much of the soil uncovered within the plant understory. A similar mulching effect occurred upon senescence of the hybrid sudangrass, but, aside from resident weeds, there was no understory vegetation to add additional cover. Subsequently, between pig consumption and trampling, hybrid sudangrass ground cover diminished at a more rapid pace than did the rye/ryegrass combination. This observation suggests a benefit to inter-planting compatible companion vegetation species in order to provide extended surface soil protection on PRP operations.

Pasture vegetation in PRP operations serves not only as a source of nutrition for pigs, but provides other benefits such as soil protection and nutrient scavenging. Vegetative ground cover and prevention of nutrient loss through uptake by standing vegetation can decrease the amount of available nutrients prone to loss by removal through uptake (Butler et al., 2006, 2007). Mean study-wide ground cover percentages for stationary and mobile treatments fell within a range of 58.4 to 70.1% ground cover, respectively. These measurements are comparable to those found by Butler et al., who suggested that a basal ground cover of 45% and a canopy cover of 70% offer adequate cover. Experiment 1 and Exp 2 mean ground cover percentages for mobile and stationary treatments together declined weekly at an average rate of 4.6 and 3 percentage points respectively, whereas, the control treatments declined at only 0.48 and 1.22 percentage points respectively, demonstrating the effect of pig occupation on the ground cover. Reduced ground cover, specifically, vegetative ground cover, reduces nutrient uptake, ultimately leading to potential losses of N and accumulation of P in the soil.

Soil inorganic N. In Exp 1, in evaluation of post- minus pre-experiment data, showed greater N_{min} at the 0-to-50 cm depth in both the stationary and mobile treatments relative to control plots (Table 4 (Appendix). On average, N_{min} present on stationary and mobile treatments for Exp 1 was 98% greater than the control and means ranged from 9.45 to 13.75 mg N kg^{-1} (Table 4). No differences in mean N_{min} content were found between mobile and stationary treatments, regardless of soil sampling date. In Exp 1, mean exterior plot N_{min} concentration (13.60 mg N Kg^{-1}) was 135% higher than interior plots (5.77 mg N kg^{-1}). Treatment by subplot position interactions were not significant.

Figure 7 shows mean total inorganic N concentrations in the upper 50 cm at each soil sampling date. After each pig occupation, soil N concentrations increased relative to pre-experiment levels, however the increase in N following Exp 2 for stationary and mobile treatments was less than observed after Exp1. Post- minus pre-experiment inorganic soil N concentrations in Exp 2were 6.42, 6.22, and 7.43 mg N kg^{-1} for control, mobile, and stationary, respectively as compared to 5.87, 13.75, 9.45 mg N kg^{-1} for control, mobile and stationary, respectively for Exp 1. In Exp 1, N_{min} concentrations were higher in exterior subplot positions than in interior subplot positions, 13.6 and 5.77 mg N kg^{-1}, respectively.

Treatment or subplot position was found not to affect soil N concentrations for Exp 2. The lack of treatment and interior versus exterior differences in Exp 2 may have resulted from the field disking following Exp1, homogenizing nutrient concentrations. Concentrations of N_{min} between treatments became more similar with time and the second pig occupations. Data analyses revealed a high degree of variability within sampling periods. Coefficients of variation (CV) for mean N_{min} concentrations were 198, 96, 187, and 184 for pre-Exp 1, post-Exp 1, pre-Exp 2, and post-Exp 2, respectively likely leading to the lack of observed differences between the treatments or sampling positions. Treatment effects diminished with depth for both experiments, and thus, only N_{min} data from the upper 0.5 m is presented here. Mean inorganic variance results are presented in the Appendix, but due to a lack of difference by treatment, are not discussed.

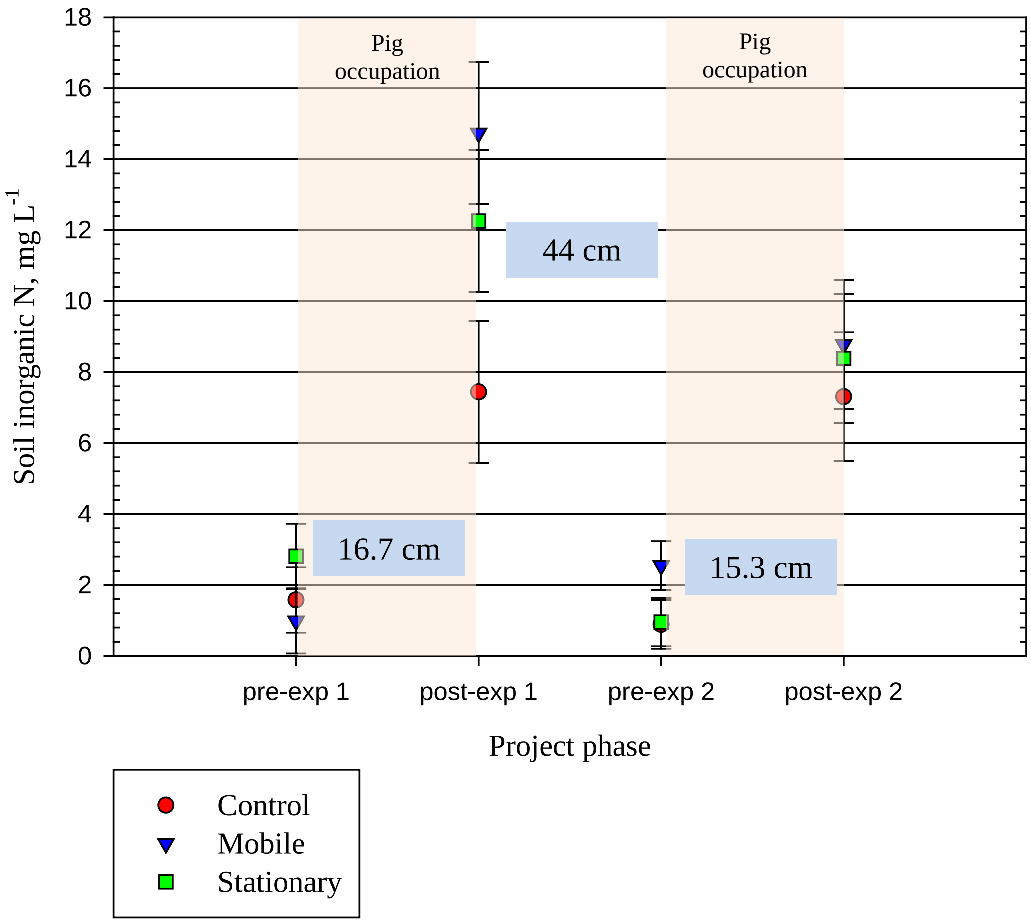

Figure 7
Soil inorganic N concentrations in the upper 0.5 m across time and experiments with rainfall data.

The higher N_{min} concentration detected for mobile and stationary treatments above control treatments is reasonable as the control treatment was under a different fertilization and management scheme. Control treatments received 143.7 and 142.3 kg N ha^{-1} for Experiments 1 and 2, respectively, whereas mobile and stationary treatments received the equivalent of 289.1 and 266.2 kg N ha^{-1}, respectively through a combination of pig waste and fertilizer N. The greater N_{min} concentrations detected in exterior subplot positions over interior subplot positions in Exp 1 agrees with findings that pigs deposit wastes away from their lounging areas (Olsen et al., 2001; Quintern and Sundrum, 2006; Salomon et al., 2007; Stolba and Gush, 1989). The finding of a 135% increase in exterior subplot positions versus interior supblot positions in experiment 1 supports findings by Watson et al. (1998) of a four-fold increase of N_{min} in pig preferential excretory vs non-preferred excretory sites.

Fluctuations in soil N content (Figure 7) may be attributed to several factors. The initial spike in N_{min} concentrations at the post-Exp 1 sampling likely resulted from the approximate 235 kg ha^{-1} of N applied to the plots via pig wastes. The subsequent steep decline in N_{min} content post-winter (pre-Exp 2) may be attributed to NO_3 -N leaching over the winter months, utilization by the growing forage crop, volatilization of N from surface manure, denitrification, or homogenization of N likely occurring when manure hot spots were mixed by disking with lower N regions of the treatment plot. In a study on grazing sows, Ericksen et al. (2002) documented a range of 320 kg ha^{-1} to 500 kg ha^{-1} NO_3 -N loss due to leaching over an 18-month period on sandy soils similar to coastal plain soils. Nitrate loss due to leaching during winter seasons has been shown by Olarewaju, et al (2009) on agricultural land. Post-Exp 2 N_{min} levels increased, but not to the same level as post-Exp 1, although pig stocking was equal with Exp 1and additional N was applied to all plots in March 2010. This can be explained by the extended period of vegetative cover for Exp 2 above that observed in Exp 1. The percentage of vegetative ground cover may have affected the N levels remaining in the soil at the end of each experiment. Living ground cover for mobile and stationary treatments, as shown in Figure 13 (Appendix), was higher post-Exp 2 than post-Exp1. A higher concentration of N was likely tied up in vegetative biomass at the end of Exp 2 than in

Exp 1. This may explain higher levels of N_{min} remaining in the soil post-Exp 1, since ground was bare and N was not being utilized by a growing crop. Additionally, N tied up in biomass may have begun to mineralize in the soil following the earlier demise of vegetation in Exp 1.

Differences in soil N deposition patterns between experiments (interior versus exterior comparisons) may be partially explained by pig seasonal behavior. The two experiments were performed over two seasons – Exp 1 in the summer (July 23 – October 15), - Exp 2 in the spring (March 23 – June 15). Wallowing and lying behavior has been shown to increase as ambient temperatures rise, and is especially pronounced above 15^{o}C (Huynh et al., 2005; Olsen et al., 2001) thus, pig behavior patterns may have changed in response to ambient temperature differences between experiments. During the summer in Exp 1, mean ambient daily temperature during pig occupation was 22.5^{o}C (experiment range: 11.3 to 28.9^{o}C) (NC State Climate Office, 2010), and it was observed, but not documented, that pigs in all treatments spent the majority of the time observed under shade structures. During the spring in Exp 2, mean ambient daily temperature was 20.2^{o}C (range of 8.1 to 28.9 ^{o}C) and pigs were observed to wander more freely and not confine themselves to shade structures for cooling during the day as they did in Exp 1. Pig characteristic excretory behavior of depositing wastes away from their lounging area may have been less defined in Exp 2 as pigs spent more time actively exploring the plots.

Soil test phosphorus. Concentrations of STP were not different between treatments, likely due to the great variability in mean STP soil test data. Coefficients of variation (CV) for STP data were 49, 50, 47, and 40 for pre-Exp 1, post-Exp 1, pre-Exp 2, and post-Exp 2, respectively. Interior and exterior subplot position STP did not differ within any phase of this study as shown in Table 10 (Appendix). Treatment by subplot position interactions were not significant. Total Phosphorus inputs from pig waste were estimated to be 40 kg P ha^{-1} for each experiment as the stocking rates were identical for both experiments. It is well known that soil P is slow to change with only one year of applied organic P such as manure, especially in North Carolina soils. Kamprath (1999) showed in a 14-year study that applying 40 kg P ha^{-1} yr^{-1}on cropped (corn/soybean rotation) Ultisols in North Carolina maintained initial STP levels (Mehlich 1-extracted) and that reducing the P inputs only very slowly reduces soil P concentrations, supporting findings of maintained soil P across the entire year-long experiment.

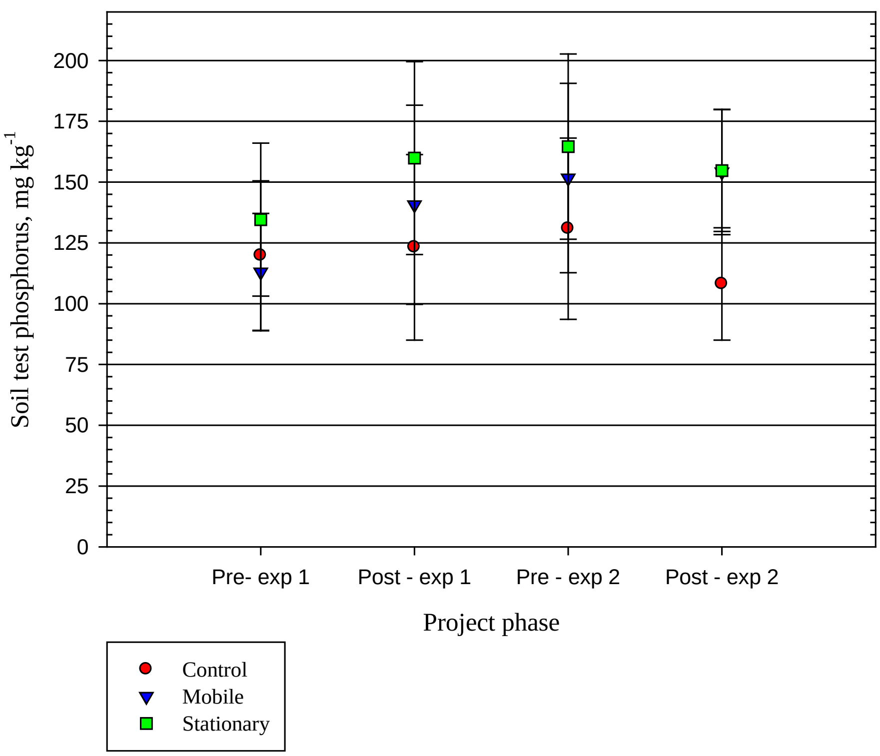

Figure 8
Mean soil test phosphorus (STP) levels over project phase by treatment.

Although this study found no significant increase in STP, it is important to consider the implications of long-term successive pig occupations on pastures. For this study, one pig group contributed 40 kg P ha^{-1}over a 12-week period. Over a one year period, a farmer could theoretically have 4.3 pig cycles on a single site, or an application rate of 173.1 kg P ha^{-1} $year^{-1}$ from a finishing pig operation with a below average stocking density of 74 pigs ha^{-1}. If successive occupations occur over years without a means of P removal, P values could increase to a level that they begin to cause environmental degradation (Hansen et al., 2002).

PLAT. PLAT ratings were low and medium for treatments blocked in foot slope and shoulder slope landscape positions, respectively for both experiments. Phosphorus loss associated with soil loss was estimated to be minimal since estimated soil losses were at or below acceptable soil loss tolerances for each soil series. Soil test phosphorus concentrations were below the soil-specific threshold value that would trigger a high PLAT rating. Organically applied P through pig manure was 40 kg P ha^{-1} for stationary and mobile treatments, contributing only a small value to the overall PLAT rating. The medium rating result is associated with Wickham Series soils which have a low nutrient holding capacity and thus, more likely to leach soluble P than the other soil series in this study.

The PLAT ratings do not accurately model a continuous pig operation with no rotation, as is a likely scenario in North Carolina. Medium ratings suggest that a land manager should monitor P inputs and engage in practices that prevent future P loss. However, it is important to note that these results do not fully represent an operation that keeps pigs on the pasture in succession as noted above. Soil test P would likely increase with continued pasturing of the pigs and eventually STP values would likely trigger a high PLAT rating. A high PLAT rating allows only enough applied P for crop removal (Osmond et al., 2008). Since crops are not removed in PRP operations, the field should no longer be used for pig production to minimize P loss potential.

Compaction. Mean bulk density data are presented in Table 2. Following occupation by the second set of pigs, Exp 1 showed no difference in whole-plot soil BD among the control, mobile, or stationary treatments. In Exp 2, the stationary treatment interior subplot position BD was greater than other treatment-position combinations. A significant treatment by subplot interaction was detected for Exp2.

Table 2
Effects of treatment and plot positions (Internal vs External) on soil bulk density, post-experiments 1 and 2.

		Post - Experiment 1		Post - Experiment 2	
		Soil Bulk Density		Soil Bulk Density	
Treatment		g cm3 -1	SE	g cm3 -1	SE
Control		1.57a*	0.029	1.46a	0.030
Mobile		1.57a	0.029	1.50a	0.030
Stationary		1.60a	0.029	1.64b	0.030
	Position within plot				
Control	Interior	-	-	1.47A	0.038
	Exterior	-	-	1.46A	0.029
Mobile	Interior	-	-	1.49A	0.038
	Exterior	-	-	1.51A	0.029
Stationary	Interior	-	-	1.76B	0.039
	Exterior	-	-	1.51A	0.029

*Means within a column comparison with the same letter are not statistically different (p=0.05)

The BD data from the more detailed sampling protocol undertaken following Exp 2 showed significantly higher compaction levels on interior subplot positions for stationary plots where shade structures were located than identical positions in mobile and control plots, suggesting that rotation of shade structure in mobile treatments would result in reduced compaction levels. No significant differences were found in soil compaction across whole treatment plots in either experiment when averaging across interior and exterior positions even when comparing plots with pigs to control plots. This result may be due to pig behavior and specifically to rooting behavior, where animals often dig and move the soil in search of grubs and plant roots. This rooting of the soil by the pigs likely ameliorated some of the compaction associated with the pig wallowing behavior in this experiment.

The interior subplot positions on the stationary treatment were highly disturbed, as this was a favored lounging area under the shade structure, likely disrupting vegetation regrowth. Soils that have been compacted may impede root growth and soil water infiltration (Hillel, 2004) leading to limited nutrient uptake and perched or ponded water, which may not be conducive to survival of the chosen vegetative cover. In a compaction study of congregational zones in cattle pastures, Sigua and Colman (2009) found that soil moisture and soil penetrability increased with distance away from concentrated activity areas. The decreased moisture and increased compaction in these heavy use areas led to the destruction of up to 50% vegetative cover (Sigua and Coleman, 2009), similar to conditions that exist in pig pastures. Compaction in pig pastures often leads to surface water ponding and subsequent creation of wallows, while other heavy use areas around feeding troughs become denuded of vegetation from trampling.

Topographic changes. The Leica ScanStation 2 allowed detailed elevation data collection on each pig plot. It was anticipated that a comparison between pre-Exp 1 and post-Exp 1 data would allow topographic change quantification between these two time points, however the two data sets had insufficient common fixed data points to permit a precise data overlay. Additionally, data associated with fence posts and existing vegetation created challenges in assessing actual ground surface images.

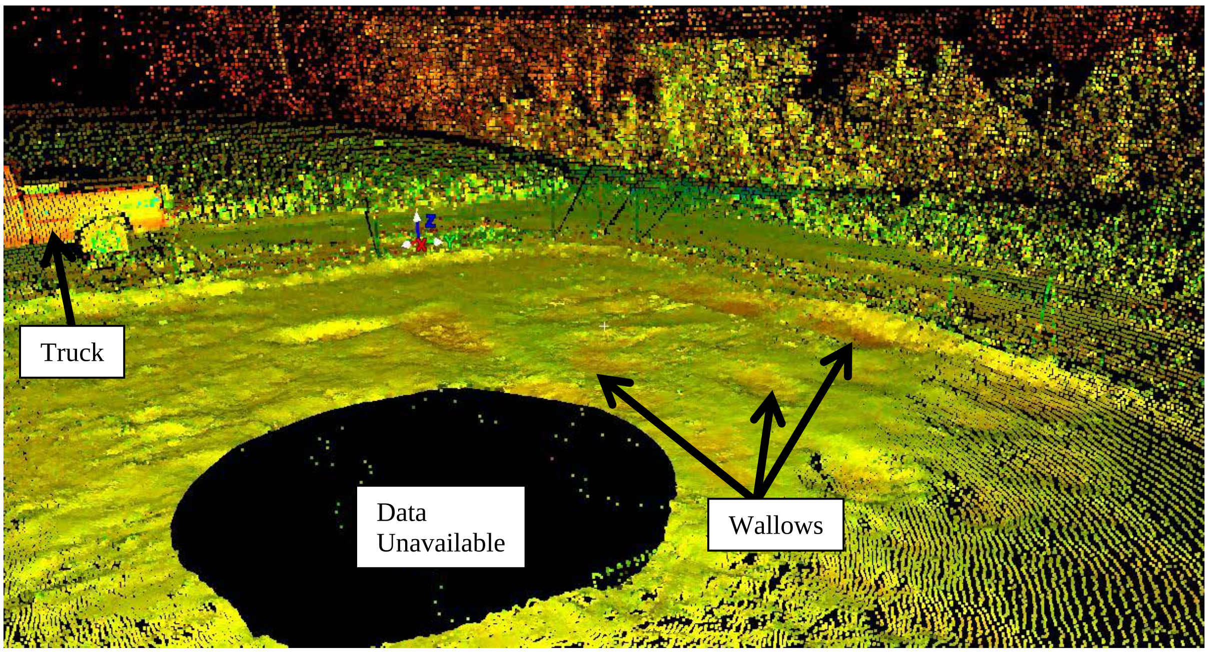

Figure 9
Lidar point cloud showing the post-experiment 1 wallows. The unavailable data represents the area around the scanner tripod that is "invisible" to the scanner.

A high resolution (small grid cell size) interpolation of the elevation surface revealed localized scanning inaccuracies. These inaccuracies likely resulted from errors in the co-registration of multiple point clouds or from a systematic error resulting from an off-level scanner head. The errors were observed as concentric rings outward from the scanner positions and were increasingly pronounced as the distance from the scanner position increased (Figure 9). Within adjacent rings, elevations differed by approximately 0.5 m, well outside acceptable bounds. Between plots, this error ranged between 0.2 and 0.5 m with greater errors observed in Block 1.

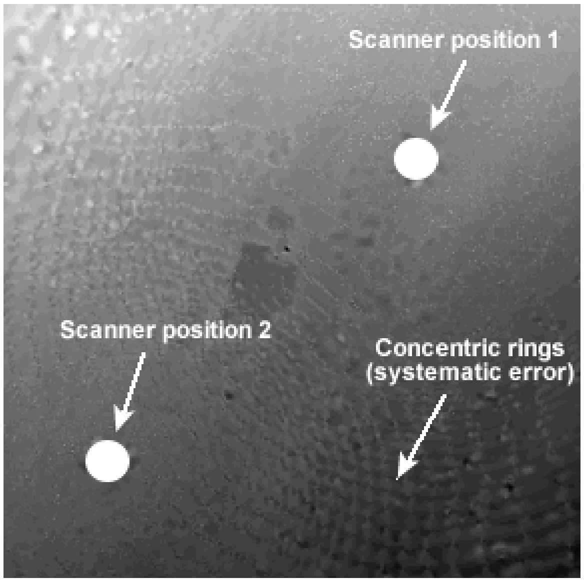

Figure 10
Systematic error in the raw lidar data within a stationary treatment paddock. Higher elevations are indicated with lighter shading with lower elevations expressed with darker shading. Errors are seen as concentric rings away from the scanner location and worsen with distance.

To reduce error, the interpolated cell size was increased until the artifacts disappeared (Figure 10). The cell size was increased in 0.25 meter intervals until the artifacts were no longer visible. This procedure reduced the resolution of the elevation model, but did allow for a general examination of the disturbed surface.

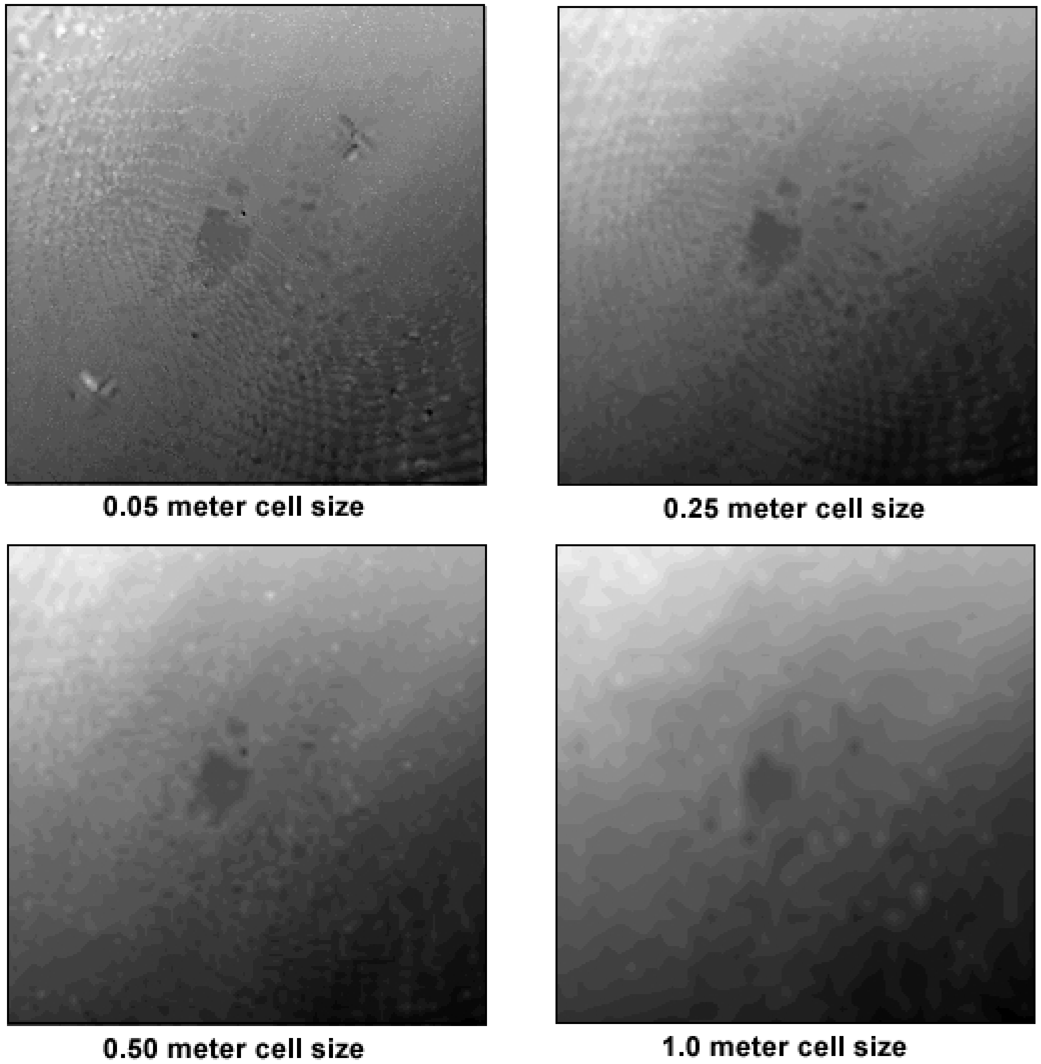

Figure 11
Systematic error removal within a stationary treatment paddock. Higher elevations are indicated with lighter shading with lower elevations expressed with darker shading. Known artifacts were removed by increasing the interpolated cell size until the systematic error was no longer apparent.

The analysis of one of the stationary paddocks demonstrates the utility of ground based lidar in the identification of pasteurized-pig land disturbance. Plot 1 was set up with a shade structure in the middle of the plot, where extensive pig lounging occurred, and consequently underwent the most disturbance from swine activity. This is observed in the DEM as a localized, large wallow in the middle of the plot (Figure 12). Additional wallows adjacent to the large, centrally located wallow are observed in the higher resolution DEM's (Figure 11). Due to the erroneous data in the post-pig scan and the consequential coarse resolution grid, a quantitative analysis of the volume of disturbed land would yield scientifically unreliable results. Instead, this analysis provides a partial proof-of-concept: if reduced error lidar scans can be achieved, it should be possible to use this technique to quantify treatment differences in surface topography at fine spatial resolution in studies of PRP and other management practices.

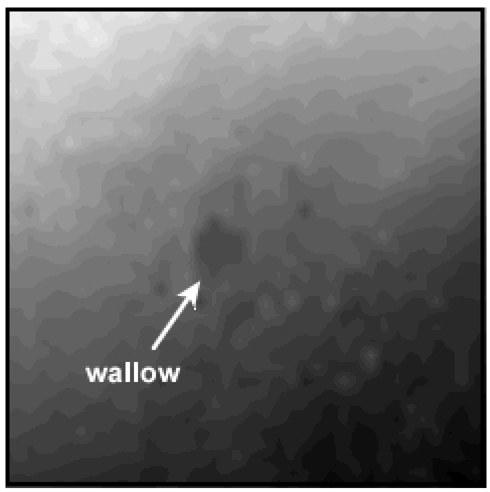

Figure 12
Visual identification of wallow using lidar-generated 3D surface model within block1 plot 1. Higher elevations are indicated with lighter shading with lower elevations expressed with darker shading.

Conclusions

A 12-month study was conducted to evaluate the effects of a rotational shade, water, and feed structures and plot position on overall N and P deposition in a pastured-pig operation, ground cover maintenance, soil bulk density, and topography. Shade/waterer structures were rotated weekly for 12 weeks within a rotational scheme and compared to a stationary structure system and also to a managed hay operation.

There were no differences in percent ground cover between mobile and stationary treatments across two pig occupations in different seasons, summer and spring. Infrastructure rotation did not reduce ground cover that was destroyed by pig activities, and may actually contribute to nutrient losses by exacerbating losses of vegetation that may otherwise scavenge available nutrients. Ground cover percentages were significantly reduced by pig occupation regardless of experiment week within experiment. The percent ground cover for the rye/ryegrass combination (Exp 2) on mobile and stationary treatments declined less quickly than the hybrid sudangrass used in Exp 1. It is possible that the contribution of additional organic material to the soil from the first pig occupation may have increased soil organic matter and thus improved vegetative vigor for Exp 2, therefore confounding the significance of the prolonged ground cover. It is, nevertheless, reasonable that the planting of compatible species in combination will provide both early season and late season soil cover and is worthy of further consideration. In addition, stocking rates may need to be reduced to maintain at least 75 % ground cover during pig occupation on PRP operations.

Both mobile and stationary treatments showed higher concentrations of N_{min} than the control (hay) treatment. There was no difference in N_{min} distribution between the mobile and stationary infrastructure treatments. However, higher concentrations of N_{min} were found in exterior plot positions compared to interior positions of pig plots in Exp 1, regardless of implementation of rotational infrastructure. This difference was not sustained in subsequent comparisons, suggesting some benefit to structure rotation as nutrient loads became more homogenized with time. Based on the results of this study, there is insufficient evidence to support the hypothesis that the rotation of infrastructure within PRP operations will result in better distribution of the soil N_{min} nutrient components. Salomon et al. (2007) found infrastructure rotation ineffective in distributing nutrients, although their rotation schedule was once per year with average stocking rates of 94 fattening pigs ha^{-1} as compared to this study with 74 fattening pigs ha^{-1} and weekly infrastructure rotation. Other studies have suggested that a more intense infrastructure rotation schedule may be effective in nutrient distribution (Eriksen, 2001; Quintern and Sundrum, 2006). More research on pastured pig operations over an extended time period may be required to support this theory. However, observations from this study suggest that rotating the infrastructure could exacerbate vegetation loss, thus increasing N and P loading and likely losses.

No differences were detected in the STP, regardless of infrastructure management on either experiment. This further suggests that rotation of infrastructure within pastured-pig operations may not add any environmental benefit, and calls into question the number of cycles that landowners should manage pastured-pig operations on the same site. Based on the results of this study, there is not sufficient evidence to support the hypothesis that the rotation of infrastructure within PRP operations will result in better distribution of the STP nutrient components. However, data analyses revealed a high degree of variability within sampling periods. The PLAT ratings were interestingly lower than expected, but these results may be limited by the soil P loading rate applied through pig occupation. A longerterm study with successive pig occupations will be necessary to determine if PLAT rating will increase over time on these operations.

Soil compaction levels showed no treatment differences for Exp 1; however using a more targeted sampling scheme for Exp 2, it was determined that areas under a stationary shade structure had significantly higher BD's than the areas not under the shade structure, validating the hypothesis that rotation of shade structure would result in reduced compaction levels compared to a stationary structure. Mobile and control compaction levels were not different in Exp 2, also suggesting a benefit to the rotation of infrastructure. However, the rotation of infrastructure in mobile treatments led to the destruction of vegetation beneath shade structures, affecting the potential for vegetative utilization of available soil nutrients in PRP systems, potentially leading to losses of N_{min} and the accumulation of STP, as previously noted.

Topography changes were documented qualitatively and visual evidence was provided demonstrating the presence of topography changes resulting from pig occupation on pastures. Sufficient evidence was not obtained in this study to support or negate the hypothesis that rotation of infrastructure would create a more even distribution of wallows within plots. However, this analysis provides a partial proof-of-concept indicating that if lidar scans can be completed with less error, they may offer significant value to understanding the effects of PRP and other management on the soil surface.

The weekly rotation of infrastructure performed during both experiments was both labor intensive and time consuming. Few farmers would expend this amount of energy and time to rotate structures unless a tangible benefit could be realized. This study contributes to the ongoing research surrounding the best management of PRP operations. Further, farm-scale research may be needed to determine if findings from this study hold true on larger field areas, typically found on commercial farms.

Further Considerations

Although the effect of rotational infrastructure systems on nutrient distribution for this study was not conclusive, it is evident that PRP can destroy annual vegetation, particularly at the stocking rate we utilized. When vegetation is not present, animal applied nutrients are not ideally utilized. In consideration of these findings, a lower stocking rate is recommended on perennial vegetation for shorter periods of time to facilitate vegetative growth and regrowth, and thus, nutrient utilization and removal from the PRP site. Below is an illustration of a proposed optimized PRP system for fattening pigs:

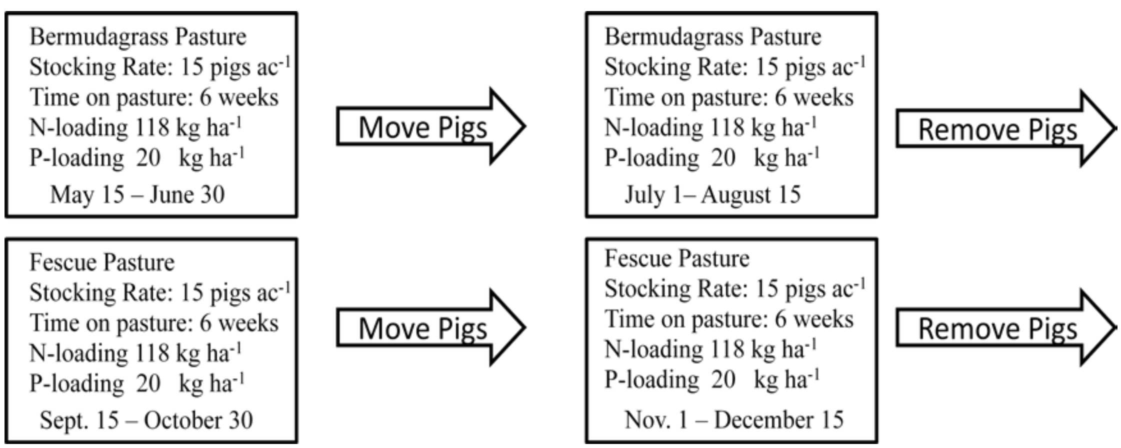

Figure 13.
Proposal for an optimal pasture-raised fattening pig operation.

This system will minimize the damage to the perennial grass while allowing both the regrowth (and nutrient utilization), harvest, and removal from this site, minimizing the risk for nutrient losses. According to the NC Realistic Yield table, bermudagrass required 335 kg N ha^{-1} to maximize its potential yield whereas fescue requires 206 kg N ha^{-1} on a typical Goldsboro series soil type (NCSU Extension et al., 2010). Therefore, not all of these forages N-needs for bermudagrass will be satisfied with the N inputs from the animal waste and additional N will be needed during early season and certain periods between or after pig occupations. However, fattening pigs at this stocking rate will apply approximately 20 kg P ha^{-1} through waste. Most North Carolina agricultural fields, and certainly animal livestock pastures historically fertilized with animal wastes, have adequate to excessive STP levels in their soils for crop growth. With this proposed system, the estimated P removal rate by bermudagrass and fescue is 90 and 71kg P ha^{-1} (NCSU Extension et al., 2010), respectively, if these crops are removed as hay. This will, allow for the slow decline of the excessive STP levels instead of increasing with continued pig occupation, therefore decreasing the risk for P-losses. Further research is needed to examine the outcome of implementing this type of proposal. Additional financial analysis may also be required to determine the financial feasibility of such an operation.

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APPENDIX

Table 3
Effects of treatment on changes is ground cover percentage by week for experiments 1 and 2.

	Week	Control		Std. Error	Mobile		Std. Error	Stationary		Std. Error
Exp 1	1	83.7		6.28	83.6		3.72	83.3		4.01
	2	88.9		6.28	82.9		3.72	84.6		4.01
	3	90.8		6.28	82.4		3.72	80.7		4.01
	4	89.9		6.28	73.4		3.72	75.0		4.01
	5	89.4		6.28	67.3		3.72	72.1		4.01
	6	83.3		6.28	57.3		3.72	63.9		4.01
	7	88.5		6.28	61.0		3.72	61.3		4.01
	8	89.5		6.28	56.9		3.72	58.9		4.01
	9	83.8		6.28	41.5		3.72	47.7		4.01
	10	77.2		6.28	37.4		3.72	42.7		4.01
	11	77.7		6.28	33.1		3.72	36.4		4.01
	12	77.9		6.28	24.2		3.72	32.0		4.01
	Exp 1 Mean	**85.1**	**a**†	**5.73**	**58.4**	**b**	**2.69**	**61.6**	**b**	**3.07**
Exp 2	1	90.0		6.59	84.8		6.59	87.3		6.37
	2	92.4		6.59	85.5		6.59	84.5		6.37
	3	90.6		6.59	78.8		6.59	79.6		6.37
	4	87.4		6.59	83.0		6.59	83.1		6.37
	5	87.9		6.59	81.5		6.59	80.0		6.37
	6	89.3		6.59	79.3		6.59	79.5		6.37
	7	88.6		6.59	78.6		6.59	80.2		6.37
	8	80.0		6.59	65.9		6.59	66.2		6.37
	9	76.1		6.59	56.1		6.59	57.6		6.37
	10	76.2		6.59	45.3		6.59	48.6		6.37
	11	73.5		6.59	49.8		6.59	48.2		6.37
	12	75.3		6.59	52.0		6.59	46.7		6.37
	Exp 2 Mean	**84.0**	**a**	**5.93**	**70.1**	**b**	**5.93**	**70.1**	**b**	**5.68**

Notes: †Letters with the same character are not statistically different.

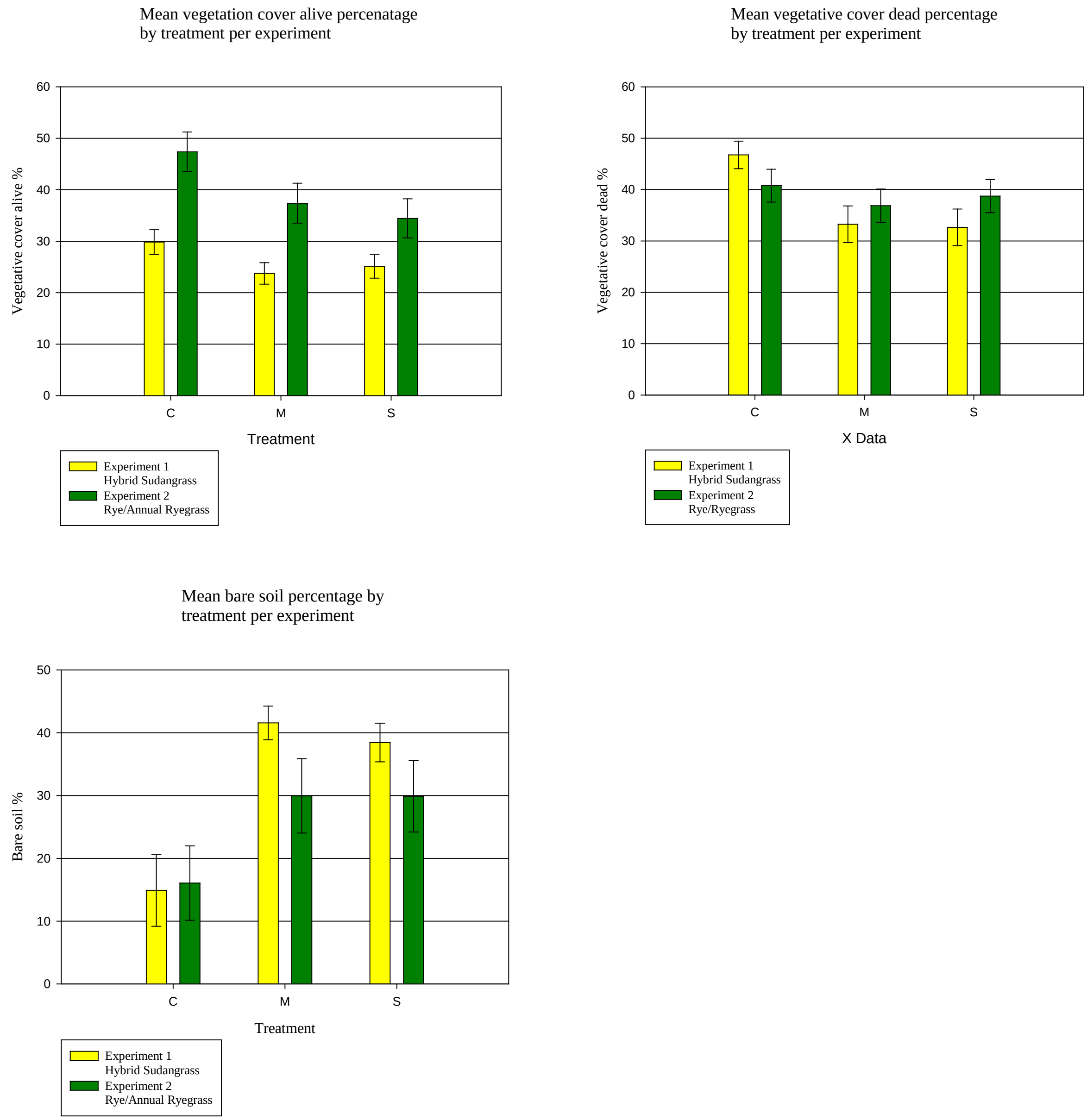

Figure 14
Effects of treatment on ground cover percentage by ground cover type.

Table 4
Effects of treatment and plot position (Internal vs External) on changes in soil inorganic N (NO_3 + NH_4) from 0 – 50 cm depth across the three phases of this study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE					
	Post-Experiment 1 minus Pre-Experiment 1		Pre-Experiment 2 minus Post-Experiment 1		Post-Experiment 2 minus Pre-Experiment 2	
	Inorganic N (mg kg^{-1})	SE	Inorganic N (mg kg^{-1})	SE	Inorganic N (mg kg^{-1})	SE
Treatment						
Control	5.87a*	2.07	-6.55a	1.89	6.42a	1.83
Mobile	13.75b	2.07	-12.19a	1.89	6.22a	1.83
Stationary	9.45b	2.07	-11.31a	1.89	7.43a	1.83
Position within plot						
Exterior	13.60A	1.20	-12.92a	1.09	7.30a	1.33
Interior	5.77B	2.07	-7.12a	1.89	6.08a	1.83

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 5.
Effects of treatment and plot position (Internal vs External) on changes in soil inorganic N (NO_3 + NH_4) from 50 – 100 cm depth across the three phases of this study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE					
	Post-Experiment 1 minus Pre-Experiment 1		Pre-Experiment 2 minus Post-Experiment 1		Post-Experiment 2 minus Pre-Experiment 2	
Treatment	Inorganic N Mean (mg kg^1)	SE	Inorganic N Mean (mg kg^1)	SE	Inorganic N Mean (mg kg^1)	SE
Control	-0.30a	1.11	1.20a	1.47	0.47a	1.57
Mobile	0.54a	1.06	2.96a	1.34	-1.81a	1.57
Stationary	1.16a	1.09	1.20a	1.41	0.10a	1.57
Position within plot						
Exterior	0.33A	0.90	2.39A	0.89	-0.77A	1.36
Interior	0.60A	1.00	1.18A	1.26	-0.05A	1.46

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 6.
Effects of treatment on inorganic N (NO_3 + NH_4), from 0 – 50 cm depth on within-plot variance at each phase of the study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE							
	Pre-Experiment 1		Post-Experiment 1		Pre-Experiment 2		Post-Experiment 2	
Treatment	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE
Control	3.19a*	9.01	68.54a	53.61	3.11a	4.51	60.85a	23.97
Mobile	1.67a	9.01	193.94a	53.61	16.71a	4.51	41.12a	23.97
Stationary	16.60a	9.00	199.21a	53.61	7.06a	4.51	142.82a	23.97

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 7.
Effects of treatment on inorganic N (NO_3 + NH_4), from 50 - 100 cm depth on within-plot variance at each phase of the study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE							
	Pre-Exp 1		Post-Exp 1		Pre-Exp 2		Post-Exp 2	
Treatment	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE	Inorganic N Mean Variance (mg kg^{1})	SE
Control	7.00a	3.24	2.58a	1.53	11.04a	5.25	5.91a	4.12
Mobile	2.32a	3.24	1.98a	1.53	37.02a	5.25	9.60a	4.12
Stationary	3.30a	3.24	3.74a	1.53	17.00a	5.25	11.54a	4.12

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 8.
Effects of treatment on changes in soil inorganic N ($NO_3 + NH_4$) from 0 – 50 cm depth across the three phases of this study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE					
	Post-Experiment 1 minus Pre-Experiment 1		Pre-Experiment 2 minus Post-Experiment 1		Post-Experiment 2 minus Pre-Experiment 2	
Treatment	Inorganic N Mean Variance (mg kg^1)	SE	Inorganic N Mean Variance (mg kg^1)	SE	Inorganic N Mean Variance (mg kg^1)	SE
Control	72.53	66.25	65.30	43.45	60.03	25.69
Mobile	194.48	66.25	148.47	43.45	62.21	25.69
Stationary	243.36	66.25	196.68	43.45	140.98	25.69

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 9.
Effects of treatment on changes in soil inorganic N ($NO_3 + NH_4$) from 50 - 100 cm depth across the three phases of this study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are Least Square means.

	PHASE					
	Post-Experiment 1 minus Pre-Experiment 1		Pre-Experiment 2 minus Post-Experiment 1		Post-Experiment 2 minus Pre-Experiment 2	
Treatment	Inorganic N Mean Variance (mg kg^1)	SE	Inorganic N Mean Variance (mg kg^1)	SE	Inorganic N Mean Variance (mg kg^1)	SE
Control	8.76a	2.24	18.85a	6.42	9.89a	3.86
Mobile	3.59b	2.24	41.98a	6.42	20.91a	3.86
Stationary	6.94a	2.24	20.74a	6.42	17.14a	3.86

*Means within a column comparison with the same letter are not statistically different (p=0.05).

Table 10.
Effects of treatment and plot position (Internal vs External) on changes in soil test phosphorus (STP) across three phases of this study. Statistical differences were calculated using the log transformed data as stated in methods. Data presented are least square means.

		PHASE					
		Post-Experiment 1 minus Pre-Experiment 1		Pre-Experiment 2 minus Post-Experiment 1		Post-Experiment 2 minus Pre-Experiment 2	
Treatment		**Soil Test Phosphorus Mean, mg kg^{-1}**	SE	**Soil Test Phosphorus Mean, mg kg^{-1}**	SE	**Soil Test Phosphorus Mean, mg kg^{-1}**	SE
Control		-6.21a	10.6	10.42a	6.73	-28.05a	23.71
Mobile		4.61a	11.31	13.62a	5.36	-0.65a	15.63
Stationary		5.82a	10.33	11.07a	6.96	-12.06a	15.24
	Position within plot						
	Exterior	5.82A	10.33	12.72A	5.56	-7.58A	14.75
	Interior	0.51A	10.94	12.90A	6.72	-12.66A	15.05
Control	Exterior	-5.09A	10.6	10.65A	6.73	-28.59A	23.71
Control	Interior	-7.32A	12.22	10.19A	9.37	-27.52A	25.09
Mobile	Exterior	3.67A	11.31	17.64A	5.36	0.80A	15.64
Mobile	Interior	5.55A	13.04	9.59A	7.46	-2.11A	16.54
Stationary	Exterior	3.74A	12.62	5.33A	6.96	-5.43A	15.24
Stationary	Interior	0.81A	0.813	16.82A	9.69	-18.68A	16.14

*Means within a column comparison with the same letter are not statistically different (p = 0.05).

Figure 15
Soil bulk density measurement tools. Metal ring and wood block used to evenly distribute pressure delivered by hammer when pressing ring into the soil.

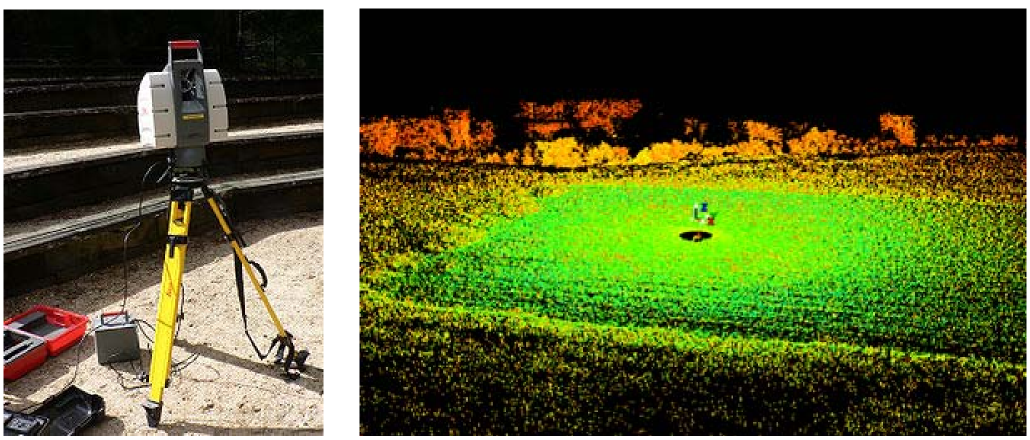

Figure 16
LEICA ScanStation 2 and a lidar-generated point cloud representing plot 1.