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Spatial relationships between nitrogen status and pitch canker disease in slash pine planted adjacent to a poultry operation

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Local emissions from poultry production appear to significantly contribute to the spatial distribution of N and pitch canker disease in managed slash pine ecosystems.

Abstract

Pitch canker disease (*Fusarium circinatum* Nirenberg & O'Donnell) causes serious shoot dieback, reduced growth and mortality in pines found in the southern and western USA, and has been linked to nutrient imbalances. Poultry houses with forced-air ventilation systems produce nitrogen (N) emissions. This study analyzed spatial correlations between pitch canker disease and foliar, forest floor, soil, and throughfall N in a slash pine (*Pinus elliottii* var. *elliottii* Engelm.) plantation adjacent to a poultry operation in north Florida, USA. Tissue and throughfall N concentrations were highest near the poultry houses and remained elevated for 400 m. Disease incidence ranged from 57–71% near the poultry houses and was spatially correlated with N levels. Similarly, stem mortality ranged from 41–53% in the most heavily impacted area, and declined to 0–9% at distances greater than 400 m. These results suggest that nutritional processes exacerbate changes in disease susceptibility and expression in slash pine.

Keywords: N deposition; Poultry emissions; *Pinus elliottii*; Forest disease; *Fusarium circinatum* Nirenberg & O'Donnell; Spatial correlations

1. Introduction

Pitch canker, a sometimes serious fungal disease of *Pinus* spp., caused by *Fusarium circinatum* Nirenberg & O'Donnell, is strongly influenced by the physiological (especially nutritional) status of its host pines. Pitch canker causes localized infections that lead to resin-soaking of the xylem tissues and associated shoot dieback (Dwinell et al., 1985; Blakeslee et al., 1980, 1999). Severe outbreaks of the disease may cause reductions in stem growth, stem deformity and tree mortality (Blakeslee and Oak, 1979). The pitch canker fungus impacts pine species in both the southern and western United States (Dwinell and Phelps, 1977; Correll et al., 1991).

A number of factors can influence the development of pitch canker in pine plantations. Environmental conditions, biotic agents and management practices that affect soil fertility, soil moisture, plantation density, insect vectors and tree wounding agents are known to affect pitch canker disease development (Matthews, 1962; Blakeslee et al., 1980; Fisher et al., 1981; Dwinell et al., 1985). In addition, genetic resistance and the interactions between genetics and environmental conditions can affect both the incidence and severity of this disease of southern pines (Blakeslee and Rockwood, 1978; Rockwood et al., 1988). Pitch canker infection in slash pine may occur at any stage of stand development (Barnard and Blakeslee, 2006), but tends to becomes more prevalent as

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the stand matures following canopy closure (Phelps and Chellman, 1976).

For decades, casual observations and limited research in Florida and elsewhere have noted elevated levels of both incidence and severity of pitch canker in susceptible pines subjected to high and/or imbalanced levels of fertility (Fisher et al., 1981; Fraedrich and Witcher, 1982; Anderson and Blakeslee, 1984). Previous investigations showed that high N additions to slash pine (*P. elliottii* var. *elliottii* Engelm.) plantations increased the severity of pitch canker (Claeson and Smith, 1977; Fisher et al., 1981; Fraedrich and Witcher, 1982; Solel and Bruck, 1989). One of the most damaging pitch canker outbreaks in southern pines was observed in a stand established adjacent to a poultry operation (Barnard and Blakeslee, 2006). Claeson and Smith (1977) also reported a strong relationship between nutrient gradients and the incidence of pitch canker in slash pine along radii from a poultry farm in Florida.

Poultry operations emit high levels of N (Skiba et al., 1998; Sutton et al., 1998; Pitcarin et al., 2002), and recent intensification in the number of poultry houses per farm and the conversion from passive (screen) to tunnel ventilation (fans) has concentrated poultry house N emissions. A combination of increasing acreages of susceptible pines and recent changes in poultry production practices have increased the potential risk for sudden and extensive outbreaks of pitch canker disease in pine plantations in Florida.

The spatial impact of poultry houses on pine N status and, particularly, its correlation with pitch canker is not well documented for the poultry-growing region of north Florida, or elsewhere in the southern USA. Elsewhere, studies have reported that poultry operations can significantly contribute to large gradients in N concentrations and deposition close to livestock buildings (Formosa and Singh, 2002; Pitcarin et al., 2002; Scudlark et al., 2005). For example, Fowler et al. (1998) concluded that annual ammonia (NH_3) deposition rates ranged from 10 kg NH_3-N ha^{-1} to 50 kg NH_3-N ha^{-1} within 230 m from the source livestock buildings. To better understand spatial relationships between N status within different ecosystem compartments, pitch canker incidence and tree growth our objectives were to: (i) characterize the spatial distribution of N in soils, forest floor, throughfall, and foliage in a 15-year old slash pine plantation adjacent to a poultry operation; (ii) analyze spatial correlations between ecosystem N status, pitch canker incidence and severity, and stand volume; and (iii) determine which N metrics were most useful for relating N and pitch canker in future studies or monitoring programs.

2. Methods

2.1. Site description

The study site was a 26 ha, 15-year-old slash pine plantation with an adjacent poultry operation located in Suwannee County in northern Florida. The stand was established on an old-field site and planted at a traditional pulpwood spacing of 1.8 × 3.0 m. The unthinned stand was bordered by pasture and an older slash pine stand to the north that also had pitch canker infection. Soils were mapped as Blanton fine sands (loamy, siliceous, semiactive, thermic Grossarenic Paleudults; Houston et al., 1965). The climate is subtropical and humid. Mean annual precipitation for the site is 1300 mm, and the mean annual maximum and minimum temperatures are 26.7 °C and 14.4 °C, respectively (NOAA, 1989). This site was chosen because: (1) pitch canker was less developed than in other candidate plantations; (2) it was in a susceptible age class (post canopy closure) to expect increases in pitch canker severity (Phelps and Chellman, 1976; Barnard and Blakeslee, 2006); and (3) the poultry operation and forest plantation were both under the same ownership.

The poultry operation consisted of four poultry houses on the northeast end of the plantation. Each poultry house was equipped with 10 fans (five on each side) and operated as a tunnel ventilation system. This system of ventilation allowed external air into the building through intake fans on the west end (south side) of each house. The exhaust fans ventilated the warmer, moisture laden internal air to the outside on the east corner (south side) of the houses. As chicken droppings decompose in the presence of elevated temperatures and moisture within the houses, NH_3 was externally ventilated, as were dust particles that contained dried droppings. The plantation's closest edge was approximately 45 m from the poultry houses (approximately 200 m from the ventilation fans) (Fig. 1). The edge adjacent to the poultry houses will hereafter be referred to as the plantation edge. Each unit housed 24,000 birds and was managed on a 10-week production cycle. The poultry houses had been operating for approximately 6 years.

2.2. Vegetation and soil sampling

Within the plantation, a systematic 50 m grid was established in 2003. In addition, random points (about 20% of the 74 systematic grid points) were established within the borders of the systematic grid, providing a total of 89 sampling points (Fig. 1). This sampling design accounted for the short and long scale dimensions of the stand. A 0.01 ha plot was established at each grid and random point location. Pine foliar, forest floor, and soil samples were collected from the plots during the spring of 2003. Foliar samples (last fully elongated flush) were collected from the upper one-third of the tree crown from two dominant or co-codominant trees in each plot using a pruning pole. Forest floor samples were collected from three 0.093 m^2 areas within each plot (i.e., tree planting row, inter row and halfway between these two sampling points) and combined to give one sample for each plot. The plantation was periodically raked for the commercial sale of pine straw, hence the forest floor was primarily Oi and, to a lesser degree, Oa horizons. Soil samples were collected with a shovel from beneath the forest floor locations to a 10 cm depth and combined for each plot.

All trees within each plot (i.e., grid and random points; $n \approx 18$ trees per plot) were assessed for size, mortality, pitch canker incidence, and pitch canker severity. Pitch canker incidence was defined for a plot as the average percentage of trees with pitch canker infection. Disease severity was addressed by classifying each live tree crown into one of five severity classes; 0 = no evidence of pitch canker, and 1, 2, 3 and 4 indicating, respectively, trace to 10%, >10% to 33%, >33 to 50%, and >50% of the crown damaged by or showing symptoms of pitch canker. Each of these severity classes was assigned a class intensity factory; i.e., simply the median (expressed as

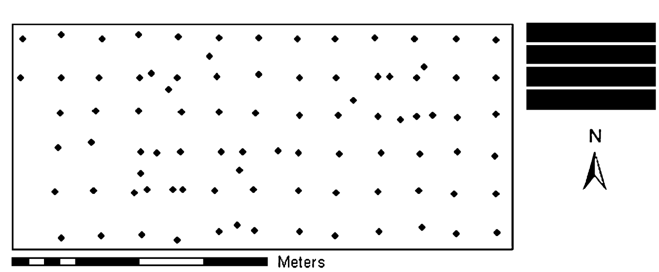

Fig. 1. Distribution of sample points in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

a decimal) of the range of percentages spanned by the respective classes (0 = 0, 1 = 0.05, 2 = 0.22, 3 = 0.42, and 4 = 0.75). Within each plot, disease incidence and severity were integrated into a pitch canker disease index using the following formula:

$$\text{Pitch canker disease index} = \text{disease incidence}\,(\%) \times \text{mean class intensity factor}$$

Diameter at breast height (dbh) was measured on all trees within each plot. Tree heights were measured on two corner trees and the center plot tree. Heights of the remaining plot trees were estimated using a regression based on dbh. Stand volume was calculated for each plot using the inventory data and an individual tree volume equation developed for site-prepared slash pine plantations (Bennett et al., 1959).

2.3. Throughfall and ammonia measurements

Throughfall was collected using a 1 m PVC pipe that was split in half (7.5 cm diameter). The collectors were placed under each plot's center tree with one end near the trunk and the other end extending away from the tree. The downward sloping half pipe had a water collection bottle attached at the far end. Mercuric chloride (1%) was added to the collection bottle to inhibit microbial activity. Throughfall was collected after each of four significant rainfall events that occurred during different stages of the poultry production cycle (Table 1). Passive diffusion tubes (Gradko International Ltd., Hampshire, England) were placed on the plot's center tree 1.4 m above the ground. Collections were performed for two separate time periods, with diffusion tubes left in place for approximately three weeks. Upon collection they were returned to Gradko International Ltd. for analysis of NH_3.

2.4. Plant, soil, and throughfall chemical analyses

Foliar and forest floor samples were dried at 70 °C to a constant weight and ground in a Wiley Mill to pass a 2 mm sieve. Soil samples were air-dried in a greenhouse and then passed through a 2 mm sieve. Approximately 25 g of sieved soil was finely ground using zirconium beads in a plastic scintillation vial on a Spex CertiPrep 8000 M Mixer/Mill. Foliar and forest floor samples were analyzed for total Kjeldahl N by digesting with sulfuric acid and a potassium sulfate and copper sulfate catalyst (Bremner, 1996). Ammonium (NH_4^+) was measured colorimetrically from the digestion solution and in the throughfall by a modified indophenol blue method on a Spectronic Unicam UV1 Spectrometer (Kempers, 1974). Soil samples were analyzed for total N and total carbon (C) using a Fisions Instruments NA 2500 Elemental Analyzer.

2.5. Geospatial analyses

Interpolation methods were used to estimate values across the study site from plot observations by taking into consideration the spatial autocorrelation structure. Nitrogen variants, pitch canker and stand volume were estimated using either ordinary kriging (Webster and Oliver, 2001) or radial basis functions (splines) (Burrough and McDonnell, 1998) with the ArcGIS software (Environmental Systems Research Institute, ESRI Inc., 2006 Redlands, CA). Ordinary kriging is a commonly used method for interpolating values from sample data using regionalized variable theory in which the estimation weights are derived from the fitted variogram model (Grunwald, 2005). If a global trend (first or second order) was encountered for a specific variable it was removed before variogram modeling. If the data were skewed, transformations were preformed to normalize the data. Experimental, omnidirectional semivariograms were derived for each variable and models were fitted using a least squares fitting routine. A heuristic approach was used to test different fitted models, lag sizes, and number of observations within a given search neighborhood in order to minimize the mean prediction error and root mean square prediction errors using cross-validation.

Distributions that showed many zero values, so-called censored datasets (e.g., throughfall and passive diffusion tube measurements), had to be treated differently. Webster and Oliver (2001) and Saito and Goovaerts (2000) pointed out that log-normal, normal score transforms or other methods attenuate the impact of high values; however, they are not appropriate for censored data. Non-parametric interpolation techniques, such as indicator kriging, have been suggested to estimate values from censored distributions (Goovaerts, 1997; Saito and Goovaerts, 2000). Indicator kriging produces multiple output maps based on user-derived thresholds to transform each observation into a vector of indicators of exceedence. Because the objective of this project was to quantify spatial relationships between measured variables, an alternative method was in need to interpolate censored datasets to provide unique estimate maps. Burrough and McDonnell (1998) suggested splines as a non-parametric technique to interpolate observations because, unlike kriging, splines make no assumptions about the distributions of the data to be mapped. They are deterministic interpolators that provide estimated surfaces that are comparable to kriging. However, they do not quantify the underlying spatial autocorrelation structure, making them less flexible and more automatic than kriging. Completely regularized and multiquadric splines were tested and the method that minimized mean prediction errors and root mean square prediction errors was used for interpolations of a specific variable. All estimates derived from splines and ordinary kriging were made on a grid with 5 meter spatial resolution.

Correlations between the N parameters (foliar, forest floor, soil N), pitch canker incidence, pitch canker disease index, mortality, and stand volume were determined using a self-coded Java program that calculates the spatial, local, moving standardized covariance equal to the experimental correlation coefficient r_{slm} with bounds $-1 \le r_{slm} \le 1$ (Wackernagel, 2003; Grunwald et al., 2005). The method is called "local" because r_{slm} is constrained to a user defined window that is characterized by a specific length and width. "Moving" refers to the movement of the window across the study site in which r_{slm} is calculated using two variables (e.g. soil N and pitch canker disease index). The method is called "spatial" because it acknowledges the geographic locations of variable estimates. The program computed the correlation coefficient at each grid center point using all raster pixel values (variable estimates) within a given window around the grid center point. In essence, r_{slm} provided a localized measure of the strength of the spatial association between two variables, both in its magnitude and direction. Because r_{slm} is sensitive to the selection of a given window size we tested different window sizes and its effect on the percentage of area that showed high correlations between two variables.

Table 1
Throughfall collection and rainfall amounts for the four sampling dates in 2003

Collection date	Field collection period	Chicken production cycle	Throughfall amount collected (mm)	Rainfall amount one week prior to collection (mm)
June 24	June 19–June 24	Second week of cleaning	9.0	39.6
July 8	July 2 – July 8	Chickens 12 days old	52.1	19.1
July 24	July 21 – July 24	Chickens 28 days old	27.9	19.8
September 2	August 26 – Sept 2	Chickens 8 days old	48.5	Not available

3. Results

3.1. Nitrogen metrics

Throughfall N content was related to distance from the poultry houses (Fig. 2); it peaked nearest the poultry houses and declined with increasing distance. A complete poultry production cycle lasted 10 weeks: 8 weeks for the growing cycle and 2 weeks to clean the houses. The first throughfall collection (June 24) coincided with the cleaning phase and had the highest N content (27 to 46 mg N m^{-2}) near the plantation edge and declined with increasing distance. The lowest N contents (1 to 2 mg N m^{-2}) were reached about 300 m from the plantation edge. The next throughfall sampling (July 8) occurred when the poultry were approximately 12 days old. Again, N at the plantation's edge reached as high as 21 mg N m^{-2}, and then declined with increasing distance until no detectable N was measured, approximately 200 m from the plantation edge. The throughfall collection representing the most advanced phase of poultry development was taken on July 24th, 2003, when the chickens were about 28 days old. As before, the highest values (up to 29 mg N m^{-2}) were recorded within 100 m of the plantation edge, decreasing with increasing distance until it was low to non-detectable 350 m into the plantation. The last throughfall collection occurred at the initiation of the production cycle (September

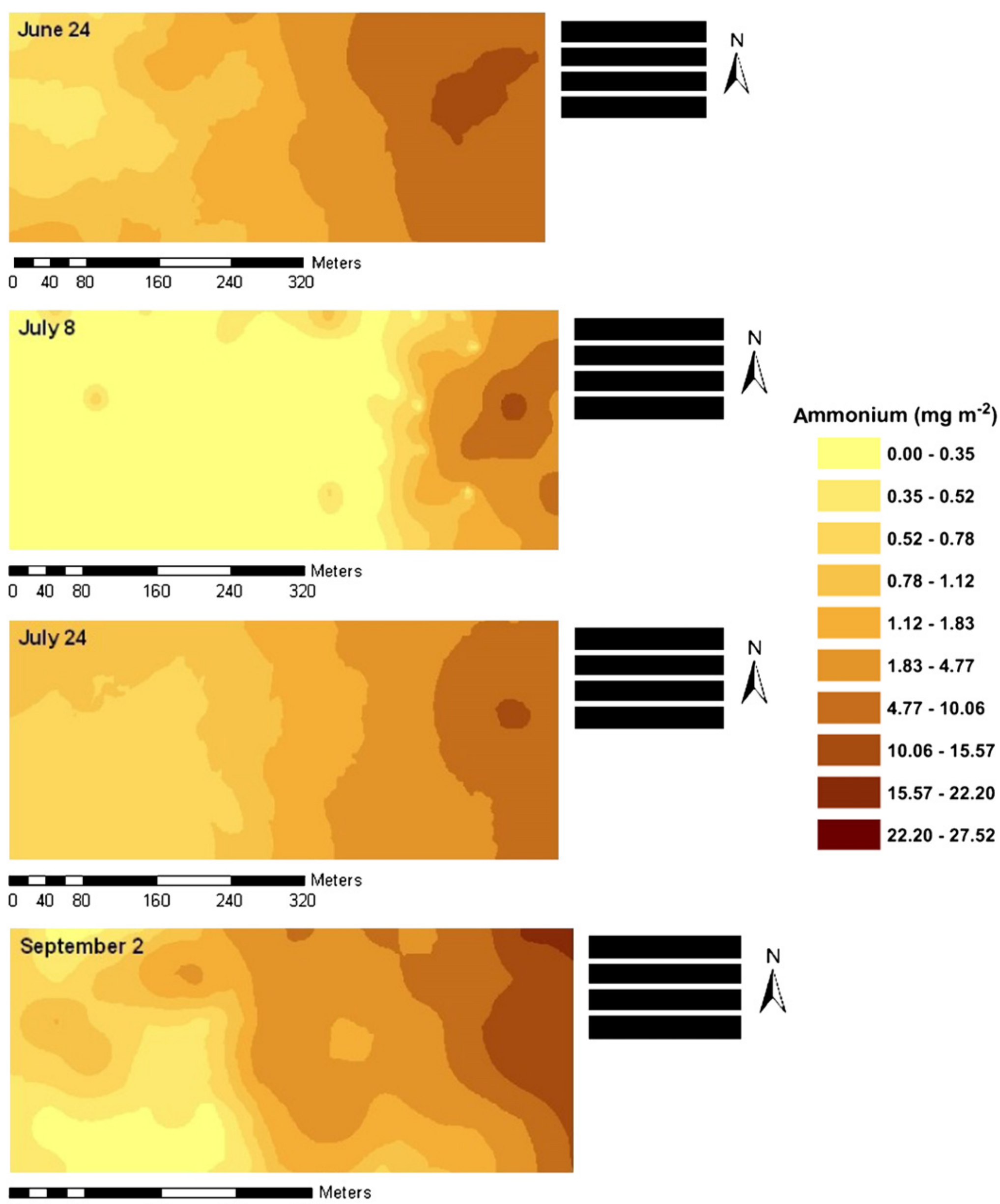

Fig. 2. Spatial distribution of throughfall ammonium-N (mg m^{-2}) collected on June 24, July 8, July 24, and September 2, 2003 in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

2) and the same consistent pattern emerged; the highest throughfall N content occurred within the first 100 m and the lowest detectable N occurred beyond 450 m within the plantation.

The NH_3 captured by passive diffusion tubes was evaluated twice: (i) during the two week cleaning of the poultry houses and lasting until the poultry were 6 days old; and (ii) when the poultry were 19 to 40 days of age. For the first collection, the most intense concentrations of NH_3 were found closest to the poultry houses and along the plantation's northern and southern edges. Ammonia concentrations averaged 19 $\mu g\ m^{-3}$ across the entire stand and were very high (from 86 to 288 $\mu g\ m^{-3}$) within 50 m of the poultry houses (data not shown). The center of the plantation experienced little or no detectable NH_3. The spatial pattern from the second sampling was less defined, with the highest levels found near the edge of the plantation opposite the poultry houses, and on the south side of the plantation (stand mean = 13 $\mu g\ m^{-3}$; range 0 to 36 $\mu g\ m^{-3}$).

Foliar N levels in the pine trees indicated well pronounced spatial patterns that appeared related to the position of the poultry houses. Foliar N ranged from 1.50 to 1.64% within 50 m of the plantation's edge (Fig. 3), and then decreased to values as low as 0.94 to 1.00% as distance from the poultry houses increased. At the rear of the plantation, which abutted a wetland and agricultural field, foliar concentrations were as high as 1.19%. Background levels of foliar N in slash pine plantations are typically in the range of 0.90 to 1.10% N (Pritchett and Gooding, 1975; Comerford and Fisher, 1982, 1984; Pritchett and Comerford, 1983). Background levels were reached at distances approximately 400 m from the plantation edge.

Forest floor N also exhibited heterogeneous spatial patterns that were similar to foliar N (Fig. 4). The highest concentrations occurred directly opposite the poultry houses within the first 50 m of the plantation and were as high as 1.34% N. Background levels for N are expected to be between 0.4 to 0.6% N for slash pine (Gholz et al., 1985b). Background concentrations were reached at approximately 300 to 350 m from the northeast corner of the plantation, opposite the poultry houses.

The spatial pattern of total soil N was not as pronounced as those for throughfall, foliage, and forest floor. The highest values were found at the edge of the plantation, but the pattern was dissimilar to the other N metrics. Soil N peaked at the southern to central edge, and not the northeastern edge. Concentrations within the first 50 m from the stand edge were as high as 0.12% N. Yet, soil under the majority of the plantation ranged between 0.08 and 0.09% N (data not shown). Typical N concentrations for similar soils ranged from 0.04 to 0.15% (Pritchett and Smith, 1972). Therefore, levels of total soil N were mostly within background levels. The muted spatial pattern relative to the poultry house locations and the convergence to a common soil N concentration suggests that total soil N was not greatly influenced by the poultry houses.

3.2. Tree metrics

Tree mortality was highest within 300 m from the plantation edge, reaching 41 to 53% (Fig. 5). A second area of significant mortality was found adjacent to an older plantation abutting the north end of the study area. Outside these areas of high mortality, background levels ranged between 0 and 9%. The spatial distribution of stand volume was inversely related to tree mortality (Fig. 6). When mortality was low, stand volumes were high and ranged from 169 to 191 $m^3\ ha^{-1}$. In areas where mortality was high, stand volumes were lower and ranged from 78 to 94 $m^3\ ha^{-1}$.

Although the spatial relationship between pitch canker incidence and distance from the poultry houses were evident nearest the poultry houses (Fig. 7), the relationship was strongest for pitch canker disease index (Fig. 8), which takes into account disease severity. The highest severity occurred in the northeast corner of the stand proximal to the poultry houses (pitch canker disease index = 0.26 to 0.33), with a distinct gradient radiating out about 300 m from the plantation edge (Fig. 8). Severity then decreased with increasing distance until pitch canker disease index was less than 0.04 at 400 to 500 m from the plantation edge. In the middle portion of the stand, where incidence was high (Fig. 7), disease severity levels were moderate (0.17 to 0.21). The importance of new or pre-existing pitch canker infections originating from the older, adjacent stand and its impact on the spatial relations of disease development in the sampled stand is unknown and a potentially confounding influence. However, the pitch canker fungus is a facultative parasite and the progression of disease expression

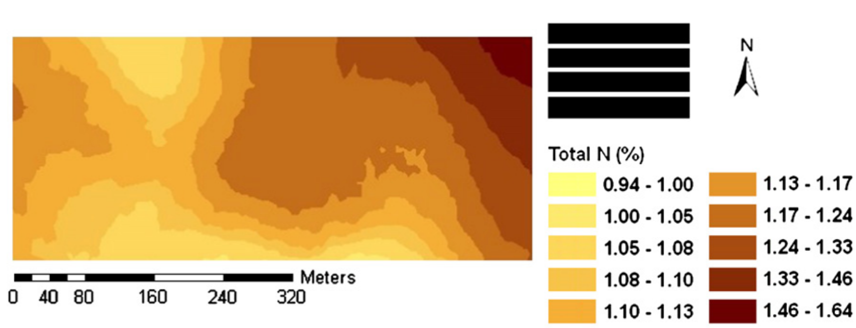

Fig. 3. Spatial distribution of foliar nitrogen concentrations (%) sampled from the upper third of the crown from dominant and codominant slash pine planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

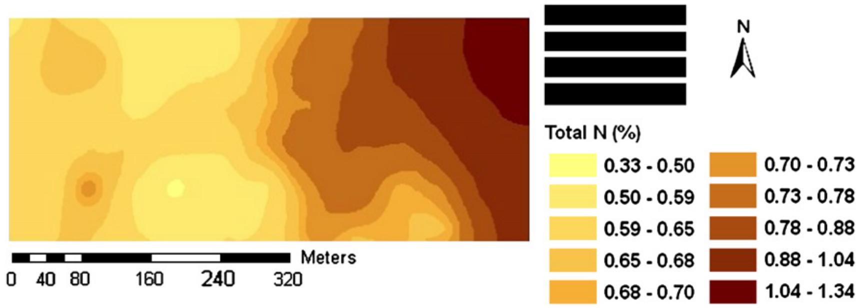

Fig. 4. Spatial distribution of forest floor nitrogen concentrations (%) in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

can be inherently variable within stands as new infection centers develop.

3.3. Prediction performance

The mean prediction error indicated slight underestimations of foliar N, forest floor N, soil N, soil C, pitch canker incidence, pitch canker disease incidence, stand volume, NH_3 diffusion 1, and throughfall (Sept. 2); overestimations occurred for all other variables (Table 2). Slight underestimations are expected from interpolations based on ordinary kriging that tends to smooth out high values. The mean prediction error was lowest for foliar N with −0.00004, soil N with −0.0008, and pitch canker disease index with −0.0002, providing excellent predictions. These mean prediction errors have to be interpreted relative to the observation range which was for example much smaller for foliar, forest floor and soil N when compared to stand volume. The highest mean prediction error (−0.3812) was found for NH_3 diffusion 1, which also showed a wide range of values across the site. The root mean square prediction error was lowest for soil N with 0.018 and highest for NH_3 diffusion 1 with 23.4 (Table 2).

3.4. Spatial correlations

Results of the spatial, local, moving correlation procedure relating foliar N and pitch canker incidence and foliar N and forest floor N are shown in Fig. 9. These maps illustrate that correlations between variables differed spatially. This spatial statistical technique: (i) quantified the extent of the area that was highly correlated; (ii) identified the strength of correlation; and (iii) indicated the spatial distribution and variability of the correlation structure. In general, high correlations (>0.7) were found in proximity to the poultry houses for all variables. Interestingly, high and low local correlation patterns coincided across the site for the correlation data pairs foliar N − pitch canker incidence and foliar N − forest floor N (Fig. 9). This suggests that in addition to the distance from a geographic location within the site to the poultry houses other mechanisms are operating to generate those spatial patterns. Other drivers responsible for generating the emerging spatial patterns might include climatic factors (e.g. wind), land use management, and adjacent land use. The spatially explicit correlations facilitate to better understand the relationships between pitch canker incidence and underlying environmental factors, whereas global correlations calculated across the whole site would mask out local variations. Although the area that showed a local correlation coefficient of >0.7 (indicating strong relationships) between foliar N and pitch canker incidence was only 28% (Table 3), it supports the hypothesis that causative relationships exist. The clusters of high correlations (>0.7) (Fig. 9) found across the site suggests that pitch canker is spreading in concentric patterns preferably into those areas where high foliar N was found. This interplay of factor relationships documented within a spatial context enables one to understand multi-factorial behavior in detail.

Correlation results for other variables are summarized in Table 3 and illustrate that the relationship between the N metrics and pitch canker were most pronounced when compared to other data pairs. Foliar N had the greatest area correlated

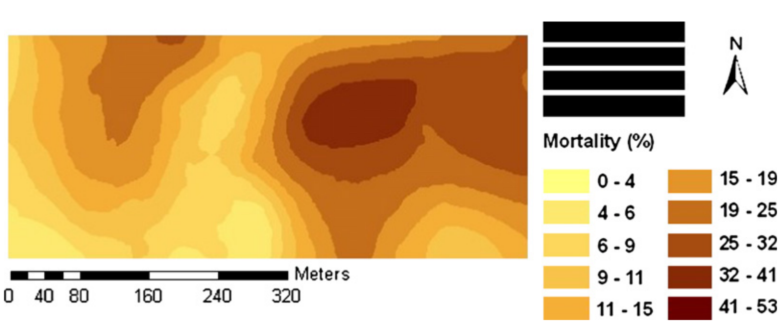

Fig. 5. Spatial distribution of slash pine tree mortality (%) in a stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

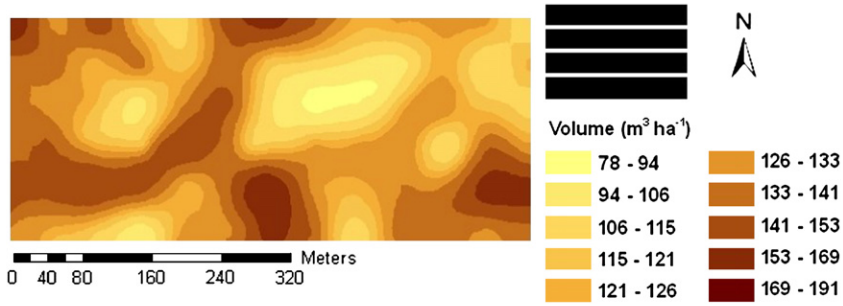

Fig. 6. Spatial distribution of stand volume (m^3 ha^{-1}) in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

with pitch canker incidence (28%), followed by forest floor N (19%), soil N (15%), and throughfall N (9–12%). In contrast, pitch canker disease index had the largest areas of high correlation with forest floor N (30%), throughfall N (18–21%), foliar N (17%), and soil N (12%). The large areas of correlations below 0.7 and above −0.7 documented in Table 3 suggest that multiple environmental factors interact to form these complex spatial correlation patterns.

4. Discussion

Based on the spatial analyses it is clear that the poultry operation increased the N status of the adjacent pine plantation. This increase was likely caused by airborne (dry and wet deposition) compounds such as volatilizing NH_3, throughfall, particulates, or by leachates from the forest floor and soil. The pine foliar samples collected closest to the poultry houses had N concentrations among the highest reported for slash pine in the southeastern USA (Gholz et al., 1985a; Jokela et al., 1990; Harding and Jokela, 1994). Likewise, the forest floor samples collected closest to the poultry houses had N concentrations comparable to live foliage. These results are analogous to those of Claeson and Smith (1977), who studied a passive ventilated poultry operation adjacent to a slash pine stand. They also noted that, in addition to elevated foliar levels of N, P, and K, the surface soil horizon at the farm boundary contained elevated levels of P, but lower levels of Ca, Mg, and K than at a greater distance from the poultry houses. Skiba et al. (1998) studied the deposition of N from poultry houses and noted that deposition rates rapidly declined with distance from the buildings, with levels being reduced by at least 50% 100 m downwind; background levels were measured approximately 300 m from the poultry houses. Similarly, Pitcarin et al. (2002) reported that annual mean concentrations of NH_3 close to poultry buildings were high (60 μg m^{-3}) and declined to 3 μg m^{-3} 650 m from the buildings.

Interestingly, as measured by the spatial correlations, the N inputs did not appear to increase stand volume growth. While slash pine is known to respond to N fertilization on similar soils (Jokela et al., 1991), the offsetting effect of increased pitch canker related mortality associated with the high N levels negated any positive effect on stand volume growth. Deployment of pitch canker resistant slash pine families on such sites may have altered these trends, although progeny testing of resistant families have typically occurred on sites of lower N fertility. For example, little is known regarding the impact of these large horizontal gradients in both concentration and deposition of N on the genetic resistance of slash pine to this pathogen. However, Rockwood et al. (1988) suggested that a long-term strategy of developing new clonal orchards using pitch canker resistant stock could reduce incidence in future stands by 50% or more.

The correlations between N metrics and pitch canker were complex. Overall, results from this study demonstrated that pitch canker disease development was related to N loading, particularly when measured using foliar and forest floor N. Implications of these high positive correlations between N loading and pitch canker are that enriched N status of the plant may predispose the host to increased pitch canker infection and severity of symptoms (e.g., stem deformation, mortality).

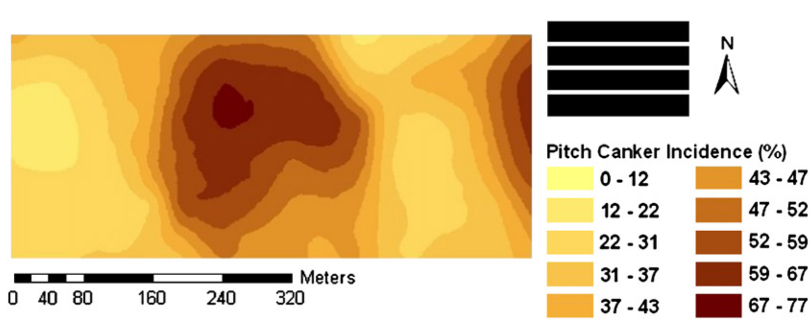

Fig. 7. Spatial distribution of pitch canker incidence (%) in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

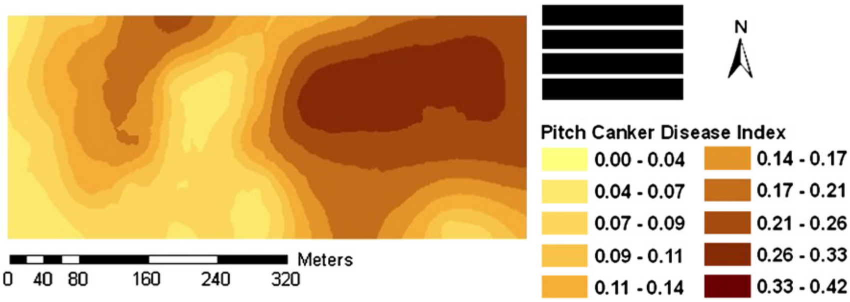

Fig. 8. Spatial distribution of pitch canker disease index in a slash pine stand planted adjacent to a poultry operation. Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

However, high N status of the host plant is neither a requirement for the disease, nor does it assure infection. Yet, high N loading: (i) makes the plant tissues more succulent, which may facilitate fungus entry; (ii) increases production of free amino acids and improves trophic conditions for the invading fungus; and (iii) reduces the level of plant metabolites that inhibit pathogen development (Hesterberg and Jurgensen, 1972). Fisher et al. (1981) showed that inorganic N and P fertilizer additions to a slash pine plantation infected with pitch canker increased mortality and decreased tree growth. Fraedrich and Witcher (1982) presented evidence that pitch canker development was related to N fertilization. Other fungal shoot diseases in conifers (e.g., *Sphaeropsis sapinea*, *Gremmeniella abietina*) have also been associated with elevated tissue N concentrations resulting from fertilizer additions (Patila and Uotila, 1990; Stanosz et al., 2004). This study was able to confirm these findings by identifying empirical relationships between N levels within the plantations and the severity of pitch canker modulated by the distance from the point N source (poultry houses). It is reasonable, therefore, to conclude that the poultry house N emissions impacted the N status of the adjacent plantation and predisposed it to increased pitch canker infection and severity.

As pitch canker is referred to as a wound pathogen, feeding injuries caused from eastern pine weevil (*Pissodes nemorensis* Germar), pine coneworms (*Dioryctria* spp.), pine tip moths (*Rhyacionia* spp.) and other agents may have played a role in the disease complex observed (Matthews, 1962; Dwinell et al., 1985). Knowledge is still limited, however, regarding the importance of insects as vectors of the fungus and the possible interactions that may exist between insect feeding and high fertility treatments in the slash pine – pitch canker pathosystem. With loblolly pine, Nowak and Berisford (2000) found no significant differences in Nantucket pin tip moth (*Rhyacionia frustrana* Comstock) damage as related to N fertilization, but intensive management practices may have reduced population stability through reductions in parasitism and tree growth (Nowak et al., 2003).

The N metrics that most efficiently indexed N loading and its effect on pitch canker were foliar N and forest floor N concentrations. These metrics showed similar spatial patterns. Foliar and forest floor N concentrations both increased by as

Table 2
Summary of specific options used for the interpolation of variables and cross-validation results expressed in form of the Mean Error and Root Mean Square Prediction Error

Variable	Method[a]	Model	Lag size/number	Nugget	Partial sill	Range	Neighbors	Mean error	Root mean square error
Foliar N	OK	Spherical	40/12	0.007	0.017	474.13	10	−0.0004	0.0976
Forest floor N	OK	Spherical	45/10	0.014	0.073	446.61	8	−0.0024	0.1175
Soil N	OK	Spherical	30/11	0.036	0.047	70.35	8	−0.0008	0.0191
Soil C	OK	Spherical	40/10	0.022	0.029	258.85	8	−0.0012	0.1774
Pitch canker incidence	OK	Spherical	20/10	139.350	265.450	198.49	8	−0.0704	14.78
Pitch canker disease index	OK	Spherical	35/10	0.003	0.008	270.87	10	−0.0002	0.0661
Tree mortality	OK	Spherical	28/10	60.167	114.470	222.04	10	0.2042	9.48
Stand volume	OK	Spherical	32/11	137.320	396.280	78.09	8	−0.1375	21.71
NH_3 Diffusion 1	RBF	Multi-quadratic					15 (including at least 10)	−0.3812	23.43
NH_3 Diffusion 2	OK	Spherical	30/10	39.396	38.782	195.06	11	0.0562	7.71
Throughfall June 24	OK	Spherical	40/12	5.623	17.058	474.13	10	0.0829	2.96
Throughfall July 8	RBF	Completely regularized					15 (including at least 10)	0.0098	2.19
Throughfall July 24	OK	Spherical	40/12	7.301	9.553	474.13	10	0.0637	3.00
Throughfall September 2	OK	Spherical	40/10	3.878	22.191	396.99	10	−0.0229	3.00

Note: Log 10 variable transformations were used for forest floor N, soil N, and soil C. All neighbors included at least four unless otherwise specified.
[a] Methods: Ordinary Kriging – OK; Radial Basis Function – RDB.

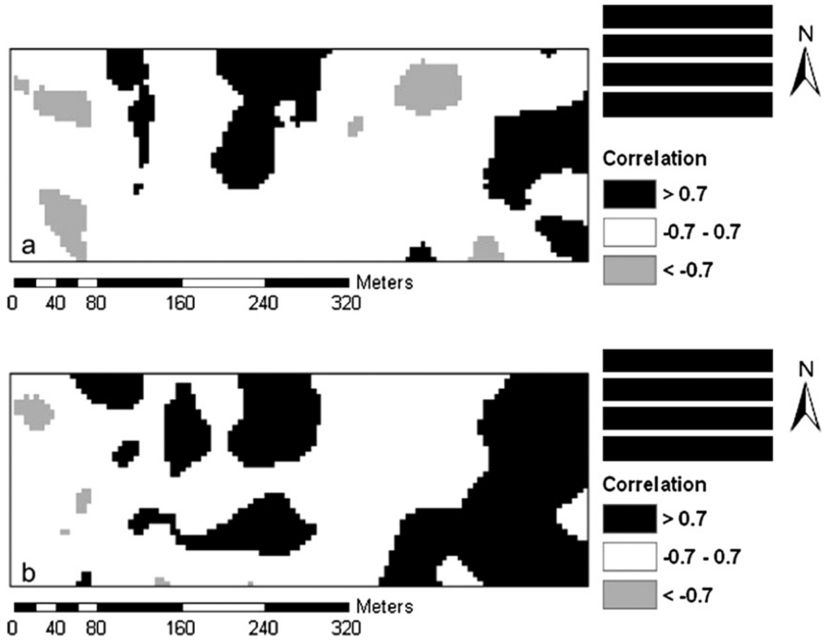

Fig. 9. Examples of the moving correlation maps showing the spatial relationship between: (a) foliar N and pitch canker incidence; and (b) foliar N and forest floor N. The maps show correlation coefficients between the variables that were positively high (>0.7), not considered important (−0.7 to 0.7) and negatively high (< − 0.7). Note: poultry houses are shown as black boxes and the air was ventilated externally by fans on the east (south) side.

much as 80% near the poultry houses. Forest floor N concentrations were extremely high at the front of the plantation. In fact, the forest floor N concentrations were equivalent to those typically found in live foliage; a result that has not been previously reported. Forest floor N was a sensitive variable for assessing N loading, was spatially correlated with pitch canker incidence, and was relatively easy and rapid to sample. It should be considered as a metric for evaluating N deposition in impacted areas in future studies. In contrast, soil N did not show strong spatial relationships with N loading or pitch canker incidence. This result may reflect the relatively short duration of the poultry operation at this site (6 years), and the periodic removal (raking) of pine litter for use in the landscaping industry. Although not an objective of this study, the high apparent N loading to this plantation warrants additional work on NO_3^- leaching through these sandy soils.

Table 3
Results of the moving correlation analysis

	Forest floor N	Soil N	Pitch canker incidence	Pitch canker disease index	Mortality	Stand volume	Throughfall N			
							June 24	Jul 8	July 24	Sept 2
Correlation coefficient	Foliar N									
>0.7	37	27	28	17	17	9	12	11	17	39
< − 0.7	1	<1	14	11	16	14	5	5	4	3
	Forest floor N									
>0.7		27	19	30	31	7	21	18	25	29
< − 0.7		3	10	4	6	17	5	5	5	6
	Soil N									
>0.7			15	12	14	4	4	5	9	21
< − 0.7			3	3	2	7	4	8	1	2
	Pitch canker incidence									
>0.7				12	15	8	10	10	9	12
< − 0.7				17	17	24	15	29	16	20
	Pitch canker disease index									
>0.7					96	4	18	16	13	21
< − 0.7					4	46	6	4	5	9

The table lists the aerial coverage in percent for different correlation data pairs and for correlation coefficients larger than 0.7 and below −0.7. Generally, the largest correlations were found in areas adjoining or in close proximity to the poultry houses.

5. Conclusions

The spatial patterns of N in a slash plantation adjacent to poultry houses for throughfall, forest floor and foliage were a result of elevated N emissions from the poultry facility. Foliar and forest floor N concentrations were among the highest recorded for this species within its native range. High pitch canker incidence and severity coincided with the high levels of plantation N, especially in close proximity to the poultry houses. Reduced levels in tissue N concentrations and lower levels of pitch canker disease were found approximately 400 m from the poultry houses. Presumably, the high N loading predisposed trees to both greater incidence and severity of this disease. The enhanced mortality associated with pitch canker overcame any potential productivity benefit that might have accrued from the increased N additions. Both foliar N and forest floor N appeared to be useful metrics for monitoring N loading and the potential for predicting pitch canker infection in proximity to poultry operations. Future research should focus on: (i) evaluating the performance of genetically resistant slash pine families to pitch canker under similarly N enriched sites; (ii) evaluate alternative species that are not susceptible to pitch canker disease for possible use as filter strips when placed adjacent to the pine plantations; and (iii) quantify the flux and fate of NO_3^- through soils from point sources associated with poultry production facilities.

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