Suppression of Pecan Scab by Nickel

Bruce W. Wood¹, Charles C. Reilly, Clive H. Bock,
and Michael W. Hotchkiss

U.S. Department of Agriculture, Agricultural Research Service, Southeastern
Fruit and Tree Nut Research Laboratory, 21 Dunbar Road, Byron, GA
31008-0087

Additional index words. production, management, fungicides, triphenyltin hydroxide, nutrient elements, cultivars, resistance, fungi, *Fusicladium effusum*, fruit, pest management, nutrition, micronutrient, *Carya illinoensis*

Abstract. The economic cost of pecan scab, caused by *Fusicladium effusum* G. Winter, can substantially limit profitability of pecan [*Carya illinoensis* (Wangenh.) K. Koch] cultivation in humid environments. Laboratory, greenhouse, and field studies found nickel (Ni) to inhibit growth of *F. effusum* and reduce disease severity on fruit and foliage of orchard trees. Nickel was toxic to the fungus in vitro at concentrations applied to orchard trees, and Ni sprays reduced scab severity on foliage of pecan seedlings in greenhouse experiments. Host genotype appears to influence Ni efficacy with fruit tissue of cultivars of intermediate resistance (i.e., ‘Desirable’) being most responsive to treatment and those most susceptible to scab (i.e., ‘Wichita’ and ‘Apache’) being least responsive. Addition of Ni as a nutritional supplement applied in combination with fungicides applied as air-blast sprays to commercial orchards reduced severity of scab on both leaves and fruit depending on cultivar and date of disease assessment (e.g., scab severity on fruit was reduced by 6% to 52% on ‘Desirable’ in an orchard setting). Nickel-supplemented fungicide sprays to ‘Desirable’ trees in commercial orchards also increased fruit weight and kernel filling, apparently from improved disease control. Although the efficacy of Ni was typically much less than that of triphenyltin hydroxide (TPTH), a standard fungicide used in commercial orchards, Ni treatment of tree canopies for increasing tree Ni nutrition slightly lowered disease severity. These studies establish that foliar Ni use in orchards potentially reduces severity of scab on foliage and fruit in scab-prone environments. The inclusion of Ni with fungicides for management of pecan scab might reduce disease severity over that conferred by fungicide alone, especially if targeted cultivars possess at least a moderate degree of scab resistance. Similar benefit from Ni sprays might also occur in host–fungi interactions involving other crops.

Pecan scab (Seyran et al., 2010), caused by *Fusicladium effusum* G. Winter, is the most important disease of pecan cultivated in humid environments (Wood and Reilly, 1999). Almost all cultivated genotypes exhibit a degree of scab susceptibility under conditions favoring infection (Goff et al., 2003). With more susceptible cultivars, wet conditions can result in severe epidemics (Sparks et al., 2009). Other environmental factors (e.g., soil moisture and temperature) affect timely availability of nutrient elements, which may also affect susceptibility to pecan scab, as occurs in other crops with either visual or physiological nutrient deficiencies (Huber and Graham, 1999).

The susceptibility of pecan leaves to infection by *F. effusum* is greatest when foliage is young (≈ 18 – 28 d old or less) (Gottwald, 1985; Turechek and Stevenson, 1998; Wood et al., 1988). Scabbed foliage, shoots, and fruit can exhibit lower photoassimilation (Gottwald

and Wood, 1985), yet it is the physical damage to developing fruit that makes the disease especially problematic. Infection can result in fruit abortion, poor kernel filling, smaller nuts/kernels, and altered nutmeat composition. Scab control in commercial orchards typically requires 3–18 fungicide cover sprays (Gottwald, 1985; Sparks, 1996; Turechek and Stevenson, 1998). Although appropriate fungicide use typically provides satisfactory scab control, protection is expensive, and disease control is often disappointing. In addition, fungicides might reduce carbon photoassimilation (Gottwald and Wood, 1985; Wood et al., 1985), which potentially influences flowering and crop load (Wood, 1989, 1995, 2011; Wood et al., 2003; Worley, 1979a, 1979b). Thus, there is need for improved scab disease management tools that increase efficacy and/or reduce control costs without adversely affecting tree health and production potential.

Toxicity, deficiency, or imbalances in either essential or beneficial nutrient elements can theoretically influence host susceptibility to fungal diseases through disruption of metabolic or physiological processes conferring disease resistance (Graham, 1983; Huber and Graham, 1999). Because timely availability of nutrient elements can influence disease severity, ensuring optimal nutritional physiology of

cells, tissues, and organs may reduce scab incidence and severity. Nickel is an essential nutrient element often disregarded by nutrient management programs, although it is integral to certain essential metabolic processes (Bai et al., 2006, 2007, 2008). Pecan appears to possess a relatively high Ni requirement with factors such as soil environment, weather, and certain orchard management factors potentially triggering transitory early-season Ni deficiency in orchard trees (Nyczepir et al., 2006; Wood, 2010; Wood et al., 2004a, 2004b, 2004c, 2006) when tissues of foliage, shoots, and fruit are most susceptible to scab infection.

As a transition metal physiochemically similar to copper (Cu)—an effective scab fungicide (Demaree and Cole, 1927)—Ni might also possess direct toxicity to *F. effusum*. Indeed, the fungicidal efficacies of Ni compounds were apparent by 1908, and by 1963, there were 149 or more scientific references noting Ni activity against certain fungal species (Anonymous, 1964). Nickel salts are especially efficacious with a U.S. patent (No. 2,971,880) issued to Rohm and Haas Co. (Keil and Frohlich, 1961) for use of Ni as a fungicide. Thus, timely foliar Ni application during canopy expansion for improving tree nutritional physiology, a growth phase when susceptible hosts are most likely to be infected, might confer benefits indirectly by increasing host resistance and directly by fungicidal activity against *F. effusum*. This study assesses efficacy of foliar Ni application in pecan orchards for managing pecan scab and its potential as an integrated pest management tool.

Materials and Methods

In vitro toxicity of nickel to *F. effusum*. Two experiments assessed the effect of Ni in vitro. In the first experiment, potato dextrose agar (PDA) was amended with different concentrations of Ni (0, 0.014, 0.028, 0.28, 0.56, 2.80, 5.60, and 28.0 g·L⁻¹), and using a petri plate-based assay (15 mL PDA/plate), the effect of Ni concentration on growth of *F. effusum* was measured; a well was created in the center of each agar plate using a transfer tube, and 0.1 mL of a conidia suspension of *F. effusum* was added (1.0×10^6 conidia/mL). The conidia suspension was prepared from 3-week-old colonies of *F. effusum* (isolated from ‘Desirable’ at Byron, GA) cultured on oatmeal agar. Each treatment was replicated three times and the experiment repeated once. Plates were incubated in the light (12-h day/12-h night) for 3 weeks before measuring the diameter of the culture of *F. effusum* around the well. In the second experiment, 250-mL Erlenmeyer flasks containing 50 mL potato dextrose broth were amended with Ni (0, 0.014, 0.028, 0.28, and 2.80 g·L⁻¹) and inoculated with 0.1 mL of a conidia suspension of *F. effusum* (1.0×10^6 conidia/mL) prepared as described for the plate assay. Each treatment was replicated three times. The flasks were incubated for 3 weeks in an orbital shaker at 27 °C. The fungal mass was measured by filtering the culture through No. 1 Whatman filter paper (Whatman International,

Received for publication 22 Sept. 2011. Accepted for publication 10 Feb. 2012.

The assistance of James Stuckey and Kirby Moncrief is gratefully acknowledged for data collection.

¹To whom reprint requests should be addressed; e-mail bruce.wood@ars.usda.gov.

Maidstone, U.K.) and dried in an oven at 80 °C for 24 h to measure mycelium dry weight. Data from both experiments were analyzed by analysis of variance (ANOVA) with Tukey's means separation ($P = 0.05$) using SAS Version 9.2 (SAS Systems, Cary, NC).

The effect of nickel spray concentration on severity of leaf and fruit scab. The effect of Ni on foliar scab was tested using 1-year-old seedlings of 'Desirable' grown in a potting soil mix (Metromix 330; SunGro, Bellevue, WA) in 20-cm square containers. The expanding foliage of seedlings were sprayed to runoff with Ni at a concentration of 0 (non-treated control), 0.025, 0.050, 0.100, 0.150, and 0.200 g·L⁻¹ Ni as (NiSO₄·7H₂O) and inoculated with *F. effusum* 10 d later. Inoculum was prepared in sterile distilled water from 3-week-old sporulating cultures of *F. effusum* grown on PDA and adjusted to 10⁶ conidia/mL. The seedlings were sprayed to runoff with the inoculum using a handheld sprayer and transferred to a Percival dew chamber (Percival Scientific, Inc., Perry, IA) for 48 h (≈12-h day/as 12-h night) at 27 °C, after which they were transferred to the greenhouse with a natural photoperiod. Seedlings were assessed for disease 4 weeks after inoculation by counting the total number of lesions on the two leaves that were approximately three-fourths expanded at the time of inoculation. The experiment design was fully randomized with each treatment replicated five times. The experiment was repeated once without the 0.025 g·L⁻¹ Ni treatment but with an additional Ni concentration of 0.400 g·L⁻¹. The data were analyzed with ANOVA and means separation using Tukey's honestly significant difference (HSD) test at $P = 0.05$. Experiments were analyzed separately because they had different ranges of Ni concentration, and a negative exponential function ($y = ae^{bx}$, where a = intercept, b = shape parameter of the curve) was applied to describe the relationship between these data (analyses were performed in SAS Version 9.2).

Influence of nickel on fruit scab of cultivars differing in scab resistance. Two field studies were initiated on orchard trees of three different pecan cultivars for assessing impact of supplementing a standard synthetic fungicide-based scab control program with Ni. Test cultivars differed in susceptibility to scab; i.e., 'Wichita' is extremely susceptible; 'Desirable' is moderately susceptible; and 'Apache' is intermediately susceptible to 'Wichita' and 'Desirable' (Goff et al., 2003).

In the first study, trees were ≈8 years old, spaced at 9 × 9-m, and managed for nutrient elements and pests according to recommendations for commercial orchards (Hudson et al., 2002). Trees were drip-irrigated as needed from July to September. There were two fungicide treatments (i.e., TPTH; SuperTin-WP; at 0.548 mL·L⁻¹) alone vs. SuperTin plus Ni (Nickel-Plus™; NIPAN LLC, Valdosta, GA, at 2.5 mL·L⁻¹) in a six single-tree block design per cultivar. Treated trees were sprayed at ≈2-week intervals beginning soon after budbreak in early April to the end of July. Disease severity on fruit was assessed visually

for percent fruit surface diseased in early August. Because the three cultivars were not randomly dispersed within the orchard, data were analyzed separately for each cultivar. Analysis was by ANOVA using Tukey's HSD for means separation at $P = 0.050$ (analyses were performed in SAS Version 9.2).

In the second study, a factorial experiment assessed impact of Ni on pecan scab. A mixed cultivar 13-year-old orchard of 'Desirable', 'Wichita', and 'Apache' trees spaced 10 × 10 m was commercially managed for water, pests, and nutrition (Hudson et al., 2002) with the first factor (fungicide treatment) at four levels: 1) non-treated control; 2) TPTH (SuperTin; at 0.548 mL·L⁻¹); 3) Ni (Nickel-Plus™ at 2.5 mL·L⁻¹); and 4) TPTH plus Ni at the previously stated rate; and the second factor (scion cultivar) at three levels 1) 'Desirable'; 2) 'Apache'; and 3) 'Wichita'. The experiment design was completely randomized using single-tree replicates with three replicates of each treatment ($n = 36$). Fungicide applications were made at 14-d intervals to individual trees using an air-blast sprayer beginning 1 Apr. until 7 July (total of seven applications). Variables measured were scab severity (percent of leaf and fruit surfaces diseased) and nut volume. Scab was assessed during early August and nut volume during October. Statistical analysis was by ANOVA to explore main effects (fungicide, cultivar) and interactions (fungicide × cultivar). Linear regression analysis was used to investigate the relationship between disease in early August and nut volume in October (analyses were performed in SAS Version 9.2).

Influence of nickel on fruit scab of a highly susceptible cultivar Wichita. A field study assessed the effect of Ni and TPTH on scab severity on 'Wichita', a highly scab-susceptible cultivar, using ≈30-year-old trees with trees spaced at 14 × 14 m and managed for nutrient elements and pests as for commercial pecan orchards (Hudson et al., 2002). Trees were irrigated as needed from June to September.

The experimental consisted of four treatments [i.e., non-treated control; Ni (Nickel-Plus™; at 2.5 mL·L⁻¹); TPTH (SuperTin-WP;

at 0.548 mL·L⁻¹) fungicide; and TPTH + Ni treatments] structured as a randomized complete block with single trees as blocks (i.e., 15 blocks) and a single fruit-bearing branch being the experimental unit for each treatment ($n = 60$). Branches sampled were from the sun-exposed midcanopy and situated to protect against spray contamination from other treatments and had at least three fruiting clusters. Treatments were applied using a pressurized hand sprayer and applied until leaf drip. Sprays were applied at ≈2-week intervals from soon after budbreak in early April to the end of July during early morning to facilitate treatment efficacy. Fruit were assessed for scab severity in early August. Statistical analysis was by ANOVA with means separation by Tukey's HSD. In addition, a Student's t test was used to compare the TPTH + Ni and the TPTH treatments at $P = 0.050$ (analyses were performed in SAS Version 9.2).

Influence of nickel supplemented fungicides on fruit scab and nut quality of 'Desirable' in commercial orchards. The hypothesis that addition of Ni suppresses pecan scab and benefits fruit quality was assessed using 26 'Desirable' orchards located in mid- and southern Georgia. Because test orchards were managed by several different farm managers, orchard trees were treated with different commercial fungicides typically used for pecan scab. The fungicides applied generally included TPTH (SuperTin at 0.279 to 0.548 mL·L⁻¹) as a major component, but also included one or more sprays of Elast (dodine), Orbit/Super-Tin Co-Pack (propiconazole plus triphenyltin-hydroxide), Enable (fenbuconazole), and Enable/AgriTin Co-Pack and Sovran (kresoxim-methyl). These fungicide programs represent the non-treated control, or "Farm Treatment" (FT). Treated plots received Nickel (Ni, as Nickel-Plus™) in addition to the FT at 2.5 mL·L⁻¹ with volume of spray solution varying from 467 to 934 L·ha⁻¹ and with application varying from single-sided to double-sided sprays. The FT + Ni treatment had Ni included in the spring applications with summer application

Fig. 1. The effect of nickel (Ni) concentration on growth of *Fusicladium effusum* in vitro using a plate well assay (A), Expt. 1: F -value = 38 ($P < 0.0001$), least significant difference (LSD) = 2.4; Expt. 2: F -value = 52 ($P < 0.0001$), LSD = 4.61; and measuring fungal mass in a potato dextrose broth liquid culture assay (B); Expt. 1: F -value = 20 ($P < 0.0001$), LSD = 0.08. Expt. 2: F -value = 56 ($P < 0.0001$), LSD = 0.05. For each experiment, different letters indicate significant differences according to Tukey's means separation ($P = 0.05$).

being left up to the farm manager. The number and timing of applications varied among orchards; however, in general, applications were made at 14- to 21-d intervals from budbreak in April until late July to early August.

The experimental design consisted of the two treatments (FT control vs. FT + Ni) structured as a randomized complete block consisting of 26 orchards with orchards varying in size from ≈ 4 to 81 ha ($n = 52$). Half of each orchard was treated with either of the two treatments with treatments being randomized. Fruit were assessed for scab in early August for all 26 orchards; and nuts were sampled at harvest from several orchards at one farm (Jaros Farm) to assess nut quality traits (i.e., marketable kernels; nuts per pound; and kernel quality of poorly filled nuts). The experiment unit was a random sample of fruit from the lowest sun-exposed portion of the canopy from 30 trees per orchard. The nut quality traits were measured and recorded from a 5-kg sample of fruit from

each orchard. Data were analyzed with ANOVA (using SAS Version 9.2).

Results

Toxicity of nickel on *F. effusum* in vitro.

Ni completely inhibited growth of *F. effusum* at concentrations greater than $0.028 \text{ g}\cdot\text{L}^{-1}$ (greater than 0.49 mm) in solid and liquid media culture (Fig. 1A–B). Although *F. effusum* grew at concentrations of Ni up to $0.028 \text{ g}\cdot\text{L}^{-1}$, growth was reduced compared with the non-treated control. For purposes of comparison, Ni was applied at $0.1375 \text{ g}\cdot\text{L}^{-1}$ ($\approx 2.4 \text{ mm}$) in the field experiments [$2.5 \text{ mL}\cdot\text{L}^{-1}$ Ni as nickel lignosulfonate containing 5.4% Ni (Nickel PlusTM)]; thus, this amount of foliar-applied Ni is directly toxic to *F. effusum* and establishes a concentration threshold for direct toxicity.

The effects of nickel spray concentration on severity of leaf and fruit scab. There was a significant effect of Ni concentration on the number of lesions of scab on leaves of greenhouse-grown seedlings (Table 1). In Expt. 1, leaves treated with Ni concentrations of 0.150 and $0.200 \text{ g}\cdot\text{L}^{-1}$ (2.64–3.51 mm) had fewer lesions compared with the control, and in Expt. 2, leaves treated with Ni at 0.200 and $0.400 \text{ g}\cdot\text{L}^{-1}$ (3.51–7.03 mm) had fewer lesions compared with the control, although in neither experiment was there a significant difference among Ni concentrations in the number of lesions. There was substantial variability in lesion counts at all Ni concentrations with a negative exponential function describing the relationship between the Ni concentration and the number of lesions of scab per leaf (Fig. 2). Lesions on leaves receiving higher concentrations of Ni were visibly smaller and appeared to have reduced sporulation (but this was not measured).

Influence of nickel on fruit scab of cultivars differing in scab resistance. Ni reduced fruit scab severity of ‘Apache’ and

‘Desirable’ but not for ‘Wichita’ (Table 2). When Ni-supplemented TPTH was applied to ‘Apache’, 26% of the fruit surface area was diseased or an average of 48% of TPTH alone. In the case of ‘Desirable’, a moderately susceptible cultivar, supplementing TPTH with Ni also reduced scab severity on fruit by 4% compared with TPTH alone (with 86% of the fruit surface area diseased compared with TPTH alone).

In the second study, the ANOVA showed all main effects and interactions were significant (Table 3). Ni alone significantly reduced the severity of leaf scab on ‘Wichita’ only (Fig. 3A) and significantly reduced severity of fruit scab on ‘Desirable’ only (Fig. 3B). Only on ‘Desirable’ did Ni alone significantly increase nut volume compared with the control (Fig. 3C). In all cases the biggest response was to Ni + TPTH or TPTH alone on the most susceptible cultivar, Wichita. Although there was an effect on fruit scab severity and nut volume on ‘Apache’ and ‘Desirable’, it was not as great. Ni did not appear to have an additive or synergistic effect in reducing scab severity in this experiment (i.e., there was generally no significant difference between Ni + TPTH and TPTH alone, except for severity of scab on foliage of ‘Apache’, in which TPTH alone was more effective). The relationship between severity of scab on fruit and nut volume from non-treated trees, Ni-treated trees, TPTH-treated trees, and Ni + TPTH-treated trees of the three cultivars showed TPTH to be the most effective treatment, but Ni treatments alone also tended to have a slightly greater but overlapping nut volume compared with the control (Fig. 4A–C).

Influence of nickel on fruit scab of a highly susceptible cultivar, Wichita. Nearly half (46%) of the fruit surface of the non-treated control of cultivar Wichita exhibited scab lesions. Both Ni and TPTH reduced the

Table 1. Analysis of variance of the effect of nickel (Ni) application concentration on the number of lesions of pecan scab (caused by *Fusicladium effusum*) on leaves of pecan seedlings from ‘Desirable’ previously inoculated with conidia of *F. effusum* and grown in a greenhouse.

Ni concn ($\text{g}\cdot\text{L}^{-1}$)	Number of scab lesions per leaf ²	
	Expt. 1	Expt. 2
0	233.1 ab	330.5 x
0.025	167.4 abc	— ³
0.050	124.9 abc	200.2 xy
0.100	108.1 abc	107.2 xy
0.150	56.5 c	170 xy
0.200	54.2 c	70.2 yz
0.400	—	33.4 yz
$P > F$	0.007	0.02

²Means with followed by different letters are significantly different from each other at the $P = 0.05$ level using Tukey’s means separation test (lsmeans statement used in SAS).

³No data taken at this concentration.

Fig. 2. The relationship between nickel (Ni) concentration and severity of pecan scab (caused by *Fusicladium effusum*) in two experiments on greenhouse-grown seedlings of ‘Desirable’ inoculated with a conidia suspension of the pathogen. Negative exponential function, $y = ae^{bx}$ (where a = intercept, b = shape parameter of the curve, and R^2 = coefficient of determination (proportion of variability accounted for by X)). For Expt. 1, $a = 219.8$, $b = -0.008$, $R^2 = 0.55$, and for Expt. 2, $a = 309.7$, $b = -0.007$, $R^2 = 0.38$.

Table 2. Effect of a nickel (Ni) (as Nickel-PlusTM) supplement combined with triphenyltin-hydroxide (TPTH; SuperTin) on severity of pecan scab (caused by *Fusicladium effusum*) on fruit.²

Fungicide treatment	Scab severity (percent fruit surface area diseased)		
	Wichita	Apache	Desirable
TPTH ²	80	54	29
control			
TPTH + Ni	75	26	25
$P > F$	0.6 ^w	0.01	0.02

²Pecan trees were treated with air-blast sprays, from an axle-fan ground sprayer, at 2-week intervals from early April until late July in GA. Treatments were tested on three different pecan cultivars [‘Wichita’ is extremely scab-susceptible; ‘Desirable’ is moderately susceptible; and ‘Apache’ is intermediate to the two (Goff et al., 2003)].³

³Fruit were assessed for scab in early August; the triphenyltin-hydroxide treatment was the farm treatment and was applied at a rate of $0.548 \text{ mL}\cdot\text{L}^{-1}$. Nickel was applied as Nickel PlusTM ($2.5 \text{ mL}\cdot\text{L}^{-1}$).

^wTPTH = triphenyltin-hydroxide (SuperTin-WP).

^wMean difference is by analysis of variance at stated P level.

Table 3. Analysis of variance comparing the effect of nickel (Ni) alone, triphenyltin-hydroxide (TPTH; SuperTin) alone, and TPTH + Ni and a non-treated control for the severity of scab (caused by *Fusicladium effusum*) on foliage and fruit (in early August) and for nut volume (in October) on different cultivars of pecan in Byron, GA.

Variable	Source	Mean square ^y	F-value ^z	Pr > F ^z
Percent leaf area diseased	Treatment	10.6	11.4	0.0004
	Cultivar	37.5	40.5	<0.0001
	Cultivar × treatment	3.6	3.9	0.002
Percent fruit area diseased	Treatment	21,813.4	398.4	<0.0001
	Cultivar	5,466.8	99.9	<0.0001
	Cultivar × treatment	1,891.1	34.5	<0.0001
Nut volume (cm ³)	Treatment	73.9	31.9	<0.0001
	Cultivar	12.3	5.3	0.008
	Cultivar treatment	16.3	7.0	<0.0001

^zDegrees of freedom for treatment = 3, cultivar = 2, treatment × cultivar = 6, and error = 60.

^yThe *P* value indicates the probability of the *F*-value being significant, i.e., there are differences among cultivars and fungicide treatments.

Fig. 3. The effect of nickel (Ni) and triphenyltin-hydroxide (TPTH; SuperTin) alone and in combination on severity of pecan scab on foliage (A) and fruit (B) and on fruit volume (C) in August on three cultivars of pecan in Byron, GA, 2009. SES of the means are shown for percent leaf area diseased (= 0.393), percent fruit area diseased (= 3.02), and nut volume (cm³) (= 0.621).

severity of scab when used alone or in combination (Table 4). Severity of fruit scab when treated with Ni alone was only 63% that of the non-treated control. Fruit treated with TPTH exhibited only 37% the scab severity of the non-treated control. When Ni was used in combination with TPTH, fruit surfaces were

nearly scab-free with only 6.3% of the surface diseased with the treatment being different from TPTH alone by Student's *t* test but not with the conservative Tukey's HSD test, suggesting a possible additive effect of Ni in reducing severity of scab over that of TPTH alone on 'Wichita' fruit.

Influence of nickel-supplemented fungicides on fruit scab and nut quality of 'Desirable' in commercial orchards. Although the composition of the FT control varied among orchards, supplementing the FT with Ni generally reduced scab severity on 'Desirable' fruit by up to 13% with an overall mean reduction of 4% (Table 5). Supplementing the FT with Ni did not increase the percent of kernels classified as marketable; however, it did increase kernel weight and nut weight.

Discussion

These results indicate that under orchard conditions, supplementing fungicidal sprays with Ni can improve spray efficacy against fruit scab. The evaluation of Ni in the many commercial 'Desirable' orchards confirms findings by our laboratory, greenhouse, and field studies that supplementing fungicide sprays with Ni potentially reduces scab severity on fruit under certain conditions, especially for 'Desirable'. Thus, timely and repetitive Ni sprays for improving tree nutritional physiology can have a beneficial side effect of slightly reducing severity of pecan scab on foliage and developing fruit when used alone or in combination with TPTH and probably other scab fungicides. These experiments demonstrate Ni's potential use as a tool to help manage pecan scab in commercial orchards, although efficacy likely varies according to the innate resistance of the scion cultivar and overall tree nutritional health. The beneficial effect of Ni also potentially results in an increase in various measures of yield as demonstrated in these studies using indicators of nut volume, kernel quality, and weight as a result of improved disease control.

The greenhouse experiments suggest a relationship with the concentration of applied Ni and subsequent development of scab symptoms and are congruent with results on the

Fig. 4. The relationship between severity of pecan scab (caused by *Fusicladium effusum*) disease and nut volume on fruit from non-treated control trees, nickel (Ni)-treated trees, and triphenyltin-hydroxide (TPTH, SuperTin)-treated trees of 'Wichita' (A), 'Apache' (B), and 'Desirable' (C) in early August, Byron, GA. Linear function, $y = bx + a$ (where a = intercept, b = slope parameter). R^2 = coefficient of determination (proportion of variability accounted for by X).

effects of Ni in other crops (Anonymous, 1964). The results from the in vitro study showed that Ni completely inhibited growth of *F. effusum* at concentrations greater than 0.028 g·L⁻¹ (greater than 0.49 mM) and reduced growth significantly at lower concentrations. Ni was applied in the field at a standard rate of 0.1375 g·L⁻¹ (2.4 mM) and based on the in vitro data, this is sufficient to be directly toxic. Reasons for a lack response in scab severity to Ni application in some of the field experiments might be the result of cultivar effects or weathering loss of Ni on the leaf surface, thus precluding an opportunity for a direct effect on the fungus.

Thus, it appears that at least some of the observed effect of Ni reducing disease

severity is the result of a direct toxic effect on the pathogen. Indeed, previous reports that Ni is toxic to many different fungal pathogens (Anonymous, 1964, Keil and Frohlich, 1961; Smith, 1977) are supported by the present studies. Improving tree Ni nutritional physiology (Bai et al., 2006, 2007, 2008) might also enhance resistance and would be consistent with Ni's role as an essential nutrient element (Brown et al., 1987a, 1987b, 1990; Eskew et al., 1983, 1984) and observations that pecan seems to be especially sensitive to poor Ni nutrition (Nyczepir et al., 2006; Wood, 2010; Wood et al., 2004a, 2004b, 2004c, 2006). Furthermore, endogenous Ni interactions with other metals are poorly understood, especially transition metals, and improved understanding is needed to assess whether trees possess sufficient available Ni to ensure any natural host resistance mechanisms are fully active against *F. effusum*.

Correction of micronutrient deficiency generally has a greater effect on enhancing disease resistance of genotypes already possessing a degree of resistance compared with

those possessing little or no resistance (Huber and Graham, 1999), so if there is an effect of Ni in reducing scab severity through endogenous action, it might also be dependent on the innate resistance of the particular host cultivar. None of the Ni-treated trees in these experiments exhibited enough Ni deficiency to express visible morphological symptoms (e.g., mouse-ear, dwarfing, and weak shoots); however, there might well have been a hidden hunger at critical growth stages sufficient to enable infection and disease development. A previous Ni analysis of shuck and leaf tissue of responsive trees found that endogenous Ni concentrations were $\approx 1\text{--}3\text{ }\mu\text{g}\cdot\text{g}^{-1}$ dry weight (DW) at the time of susceptibility and thus above the $\approx 0.85\text{ }\mu\text{g}\cdot\text{g}^{-1}$ DW threshold usually associated with expression of morphological symptoms when other transition metal ions are at standard concentrations (Nyczepir et al., 2006). Because Ni bioavailability is influenced by tissue zinc, Cu, and iron concentration (Wood, 2010; Wood et al., 2004b), the nonbioavailability of Ni can be the result of an imbalance in the ratio of Ni to one or more divalent transition metals.

In conclusion, this work indicates that timely application of Ni otherwise used for tree nutrition management objectives can also reduce severity of scab on both pecan foliage and fruit under certain orchard conditions. Efficacy varies as a result of cultivar genotype, perhaps with the bioavailability of Ni within susceptible tissues. Additional research is needed regarding the relationship between relative tissue Ni concentration and expression of scab resistance. Nickel therefore merits consideration as an orchard management input possessing potential for improving integrated management of pecan scab in commercial orchards. Nickel may also merit inclusion as an integrated component of management programs in other horticultural or agronomic crops where *Fusicladium* sp. or other fungal sp. limit crop yield and/or quality. Additional research is needed to understand the Ni effect on scab and the interaction and timing of Ni spray concentration in relation to disease

development and physiological age of the host.

Literature Cited

- Anonymous. 1964. Nickel compounds as fungicides. The International Nickel Company, Inc., New York, NY. ICB-39.
- Bai, C., C.C. Reilly, and B.W. Wood. 2006. Nickel deficiency disrupts metabolism of ureides, amino acids, and organic acids of young pecan foliage. *Plant Physiol.* 140:433–443.
- Bai, C., B.W. Wood, and C.C. Reilly. 2007. Nickel deficiency affects nitrogenous forms and urease activity in spring xylem sap of pecan. *J. Amer. Soc. Hort. Sci.* 132:302–309.
- Bai, C., B.W. Wood, and C.C. Reilly. 2008. Insights into the nutritional physiology of nickel. *Acta Hort.* 772:365–368.
- Brown, P.H., R.M. Welch, and E.E. Cary. 1987a. Nickel: A micronutrient essential for higher plants. *Plant Physiol.* 85:801–803.
- Brown, P.H., R.M. Welch, E.E. Cary, and R.T. Checkai. 1987b. Beneficial effects of nickel on plant growth. *J. Plant Nutr.* 10:2125–2135.
- Brown, P.H., R.M. Welch, and J.T. Madison. 1990. Effect of nickel deficiency on soluble anion, amino acid, and nitrogen levels in barley. *Plant Soil* 125:19–27.
- Demaree, J.B. and J.R. Cole. 1927. Dusting with monohydrated copper sulphate and lime for control of pecan scab. USDA Circular no. 412.
- Eskew, D.L., R.M. Welch, and E.E. Cary. 1983. Nickel and essential micronutrient for legumes and possibly all higher plants. *Science* 222: 691–693.
- Eskew, D.L., R.M. Welch, and W.A. Norvell. 1984. Nickel in higher plants: Further evidence for an essential role. *Plant Physiol.* 76: 691–693.
- Goff, W.D., M.L. Nesbitt, and C.L. Browne. 2003. Incidence of scab and foliage condition on pecan cultivars grown without fungicide or insecticide sprays in a humid region. *HortTechnology* 13:381–384.
- Gottwald, T.R. 1985. Influence of temperature, leaf wetness period, leaf age, and spore concentration on infection of pecan leaves by conidia of *Cladosporium caryigenum*. *Phytopathology* 75: 190–194.
- Gottwald, T.R. and B.W. Wood. 1985. Decreased net photosynthesis and dark respiration rates of pecan fruit and foliage in response to infection by *Cladosporium caryigenum*. *Plant Dis.* 69: 800–803.
- Graham, R.D. 1983. Effect of nutrient stress on susceptibility of plants to disease with particular reference to the trace elements. *Adv. Bot. Res.* 10:221–276.
- Huber, D.M. and R.D. Graham. 1999. The role of nutrition in crop resistance and tolerance to diseases, p. 169–197. In: Rengel, Z. (ed.). *Mineral nutrition of crops: Fundamental mechanisms and implications*. Food Products Press, New York, NY.
- Hudson, W., P. Bertrand, and S. Culpepper. 2002. Georgia pecan pest management guide. Georgia Coop. Ext. Serv. Bul. No. 841.
- Keil, H.L. and H.P. Frohlich. 1961. Rust eradication. United States Patent Office Patent # 2,971,880.
- Nyczepir, A.P., B.W. Wood, and C.C. Reilly. 2006. Association of *Meloidogyne partityla* with nickel deficiency of mouse-ear of pecan. *Hort-Science* 41:402–404.
- Seyran, M., C. Nischwitz, K.J. Lewis, R.D. Gitaitis, T.B. Breneman, and K.L. Stevenson. 2010.

Table 4. Effect of triphenyltin-hydroxide (TPTH; SuperTin) treatments, with and without a nickel (Ni) (as Nickel-Plus™) supplement, on the severity of pecan scab (caused by *Fusicladium effusum*) on the surface of 'Wichita' fruit.^a

Fungicide treatment	Scab severity (percent fruit surface diseased)
Non-treated control	46.4 a ^b
Nickel	29.5 b
TPTH ^c	16.9 bc
TPTH + Ni	6.3 c ^w

^aBranches of trees were treated with a hand sprayer to leaf drip. Treatments were applied at 2-week intervals from early April until late July in GA. Fruit were assessed for scab in early August. Treatment rates are described in the "Materials and Methods."

^bTPTH = triphenyltin-hydroxide (SuperTin-WP).

^cTreatment means followed by different letters are statistically different by Tukey's honestly significant difference ($P = 0.05$) after arcsine transformation.

^wThe TPTH + Ni treatment mean is significantly different from the TPTH treatment mean by Student's *t* test at $P = 0.050$.

Table 5. Effect of addition of nickel (Ni) (as Nickel-Plus™) to standard farm practice [farm treatment (FT)] fungicide sprays for controlling pecan scab (caused by *Fusicladium effusum*) on trees of 'Desirable' in orchards in mid- and southern Georgia.^a

Fungicide treatment	Scab severity (percent fruit surface area diseased) ^x	Fruit/nut Parameters ^y		
		Marketable kernels (%)	Shell-out of light kernels ^w (%)	Nut wt (no./pound)
Farm treatment (FT) control	30	88	25	60
FT + Ni	26	86	41	57
$P > F$	0.0220	0.4020	0.0002	0.0240

^aOrchard trees were treated with commercial pecan fungicides as judged appropriate by farm managers. represents the Farm Treatment (FT, or control) and involves the application of different fungicides typically used for pecan scab management with the number of applications and types and concentrations of fungicides varying among the different orchards tested; however, all included triphenyltin-hydroxide (SuperTin) as a major component of their spray program. The FT + Ni treatment had Ni included in the spring applications with summer application being left up to the farm manager.

^yFruit quality values are from a single large orchard in mid-Georgia.

^xMeans are from 26 orchards managed by six different farm managers scattered throughout mid- and southern Georgia. Mean difference is by analysis of variance at stated *P* level.

^wThis refers to percentage shell-out of a subclass of marketable kernels determined to be somewhat poorly filled (i.e., light kernels) but otherwise without substantial blemish.

- Phylogeny of the pecan scab fungus *Fusicladium effusum* G. Winter based on the cytochrome-b gene sequence. *Mycol. Prog.* 9:305–308.
- Smith, W.H. 1977. Influence of heavy metal leaf contaminants on the in vitro growth of urban-tree phylloplane-fungi. *Microb. Ecol.* 3:231–239.
- Sparks, D. 1996. A climatic model for pecan production under humid conditions. *J. Amer. Soc. Hort. Sci.* 121:908–914.
- Sparks, D., I.E. Yates, P.F. Bertrand, and T.B. Brenneman. 2009. The relative impacts of elevation and rainy days on the incidence of scab damage of pecan nuts in the southeastern USA. *J. Hort. Sci. Biotechnol.* 84:137–142.
- Turechek, W.W. and K.L. Stevenson. 1998. Effects of host resistance, temperature, leaf wetness, and leaf age on infection and lesion development of pecan scab. *Phytopathology* 88:1294–1301.
- Wood, B., T. Gottwald, and J. Payne. 1984. Influence of single applications of fungicides on net photosynthesis of pecan. *Plant Dis.* 68:427–428.
- Wood, B. and C. Reilly. 1999. Pecan scab disease and its control. *Pestic. Outlook* 10:12–15.
- Wood, B.W. 1989. Pecan production responds to root carbohydrates and rootstock. *J. Amer. Soc. Hort. Sci.* 114:223–228.
- Wood, B.W. 1995. Relationship of reproductive and vegetative characteristics of pecan to previous-season fruit development and post-ripening foliation period. *J. Amer. Soc. Hort. Sci.* 120: 635–642.
- Wood, B.W. 2010. Nickel deficiency symptoms are influenced by foliar Zn:Ni or Cu:Ni concentration ratio. *Acta Hort.* 868:163–169.
- Wood, B.W. 2011. Influence of plant bioregulators on pecan flowering and implications for regulation of pistillate flower initiation. *HortScience* 46:870–877.
- Wood, B.W., P.J. Conner, and R.E. Worley. 2003. Relationship of alternate bearing intensity in pecan to fruit and canopy characteristics. *HortScience* 38:361–366.
- Wood, B.W., T.R. Gottwald, and C.C. Reilly. 1988. Pecan phylloplane chemicals influence germination of pecan scab conidia. *J. Amer. Soc. Hort. Sci.* 113:616–619.
- Wood, B.W., J.A. Payne, and T.R. Gottwald. 1985. Inhibition of photosynthesis in pecan leaves by fungicides. *Plant Dis.* 69:997–998.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2004a. Mouse-ear of pecan: I. Symptomatology and occurrence. *HortScience* 38:87–94.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2004b. Mouse-ear of pecan: II. Influence of nutrient applications. *HortScience* 38:95–100.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2004c. Mouse-ear of pecan: A nickel deficiency. *HortScience* 39:1238–1242.
- Wood, B.W., C.C. Reilly, and A.P. Nyczepir. 2006. Field deficiency of nickel in trees: Symptoms and causes. *Acta Hort.* 721:83–98.
- Worley, R.E. 1979a. Pecan yield, quality, nutlet set, and spring growth as a response to time of fall defoliation. *J. Amer. Soc. Hort. Sci.* 104: 192–194.
- Worley, R.E. 1979b. Fall defoliation date and seasonal carbohydrate concentration of pecan wood tissue. *J. Amer. Soc. Hort. Sci.* 104: 195–199.