Effect of Indaziflam Application and Soil Manipulations on Pecan Evapotranspiration and Gas Exchange Parameters

Amir M. González-Delgado1 and Manoj K. Shukla
Plant and Environmental Sciences Department, New Mexico State University, P.O. Box 30003 MSC-3Q, Sken Hall, Las Cruces, NM 88003-8003

Brian Schutte
Department of Entomology, Plant Pathology and Weed Science, New Mexico State University, P.O. Box 30003 MSC-3AE, Sken Hall, Las Cruces, NM 88003-8003

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Abstract. Appropriate soil management practices and correct use of agrochemicals for crop protection are essential to alleviate stresses that affect the quality and yield of pecans [Carya illinoinsis (Wangenh.) K. Koch]. A greenhouse study was conducted to evaluate the effect of soil surface manipulation and indaziflam application on evapotranspiration (ET) and gas exchange parameters of pecan trees, and phytotoxicity effects of indaziflam on pecan trees. Trees were planted in large pots with a homogeneous porous media (HM), including the controls (C), preferential flow channels open at the soil surface (PF), and preferential flow channels with surface soil manually tilled to 5 cm depth [shallow tillage (ST)]. Trees with HM, PF, and ST were treated with 50 g a.i./ha of indaziflam in 2014 and 2015, whereas an application rate of 150 g a.i./ha was used for trees with HM and ST in 2016. All trees were irrigated about every 14 days with 7 L of water in 2014 and 2015, and 5 L in 2016. A water balance analysis determined the ET in different treatments in 2014 and 2015. Gas exchange parameters were measured before and after irrigation in 2015 and 2016. Photosynthetic rates in C, HM, PF, and ST were consistently significantly lower before than after irrigation. PF and ST did not decrease the available water content of the soil because there was no significant change in the volume of effluent, ET, and gas exchange parameters among the treatments. No herbicide injury symptoms and no influence on gas exchange parameters and ET were observed after using both application rates of indaziflam.

Pecan [Carya illinoinsis (Wangenh.) K. Koch] is an important crop of southern New Mexico, USA. Appropriate management practices are required to maintain the quality and yield of pecan while conserving water resources (Andales et al., 2006; Deb et al., 2011; Wang et al., 2007). Garrot et al. (1993) reported that pecan trees subjected to moderate water stress before irrigation showed reduced yield, nut weight, and tree growth. Plant water stress is influenced by weather, soil water availability, and tolerance capacity of species. Deb et al. (2012) reported that the stem water potential of pecan trees decreased with decreasing soil moisture content and increasing air temperature. Similarly, lower photosynthetic rate was observed in blue oak leaves (Quercus douglasii H. & A.) in midsummer as a result of seasonal changes in soil water content and temperature (Xu and Baldocchi, 2003). A previous study reported that maximum ET in a flood-irrigated pecan orchard was observed after budbreak during early summer (Sammis et al., 2004). However, evaporation was accounted for most of the water lost from the soil until 50% budbreak.

Plant water stress as a result of water deficit lowers photosynthetic rate during the growing season. High vapor pressure deficit between the plant and atmosphere combined with low soil water availability promotes the decline in plant water potential and stomatal conductance, and subsequently reduces the photosynthetic rate and transpiration (Sassaki et al., 1997; Turner et al., 1985). In addition, poor soil drainage, which can reduce soil oxygen levels, can exacerbate the decline in photosynthetic rate for pecans (Kallestad et al., 2007; Sparks, 2005). An increase of intercellular CO₂ concentration in pecan trees subjected to prolonged flooding leads to decreases in photosynthetic rates (Kallestad et al., 2007).

Soil tillage practices have an important influence on soil hydraulic properties (Shukla et al., 2003; Strudley et al., 2008). Schwel et al. (2011) evaluated the impact of conventional, reduced, and no-tillage on the soil hydraulic properties and found greater bulk density, as result of natural compaction, and soil moisture content for no-tillage. Similarly, Shiptalito et al. (2000) reported higher macropore flow in no-tillage than conventional tillage. Macropores play an important role in the movement and distribution of water through the soil profile, as well as ecological interactions such as plant and soil relationship (Beven and Germann, 1982; Kramer and Boyer, 1995). Several studies have reported deeper than expected herbicide leaching through preferential flow channels (Flury et al., 1995; Rao et al., 1974; Shukla, 2014).

The correct use of agrochemicals applied for crop protection is beneficial for controlling crop pests, minimizing the entry of agrochemicals into water resources, and avoiding crop damage. Previous studies reported that the application of fungicides and insecticides temporarily reduced the photosynthetic rate of pecan under greenhouse and field conditions (Wood et al., 1984, 1985). Therefore, inappropriate application of pesticides could significantly reduce the tree energy reserves affecting the productivity of pecans (Wood et al., 1985). Indaziflam is a cellulose biosynthesis inhibitor registered with Environmental Protection Agency in 2012 and is used for preemergence control of annual grass and broadleaf weeds. Indaziflam is a new herbicide, and there is limited information available on its fate and transport under laboratory and field conditions (González-Delgado et al., 2017; Guerra et al., 2014; Trigo et al., 2014). Information on phytotoxicity effects of indaziflam on pecan is especially limited (González-Delgado et al., 2015). It is important to monitor the influence of indaziflam application, soil, and irrigation management practices on pecan ET and photosynthetic rates in arid regions with limited water resources because of their vital influence on quality and yield of pecan. The objectives of this study were to evaluate the effect of soil surface manipulation and indaziflam application on ET, gas exchange parameters of pecan trees, and phytotoxicity effects of indaziflam on pecan trees.

Materials and Methods

Surface soil conditions. This greenhouse study started in July 2014 and was continued until Nov. 2016 at the New Mexico State University’s Fabian Garcia Science Center in Las Cruces, NM. The greenhouse was equipped with an exhaust, evaporative cooler pads on the east side, a heating system, and an automatic temperature control unit. In 2014,
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Hypothesized that indaziflam movement toward orchards treated with indaziflam. It was widely the variety ‘Wichita’ was reported in some created because injury to some pecan trees of flowed channels at the soil surface in 6 of the 12 interrupted the connection of the preferential channels were intended to facilitate indaziflam and water movement toward the roots. The lower sticks at opposite sides of the pots at a 45-degree angle toward the roots. The total depth of irrigation water (I), depth of deep percolation, and AS were used to determine the ET using Eq. [1] (Shukla, 2014).

\[ \text{ET} = P + I - DP - AS - RO \]  

There were no precipitation (P) and runoff (RO) because the trees were grown in a pot inside the greenhouse. On 5 Nov. 2014, 10 Nov. 2015, and 2 Nov. 2016, trees were moved to an outside facility to induce the dormancy stage. During the dormancy stage, trees were irrigated with 2 L of water, and no effluent came out of the pot bottom after irrigation. By 6 May, the 25% budbreak (end of dormancy stage) in the trees was observed, and all the trees were moved back to the greenhouse.

Gas exchange parameters of pecan trees. Gas exchange parameters [(photosynthetic rate (\(\mu\text{mol-m}^{-2}\cdot\text{s}^{-1}\)), intercellular \(\text{CO}_2\) concentration (\(\mu\text{mol-m}^{-2}\cdot\text{s}^{-1}\), vapor pressure deficit (kPa), transpiration (mmol-m\(^2\cdot\text{s}^{-1}\)), stomatal conductance (mol-m\(^2\cdot\text{s}^{-1}\)), leaf temperature (\(\circ\text{C}\)), and relative humidity (%)] were measured before and after irrigation using a LI-COR 6400-portable gas exchange system (LI-COR Biosciences, Inc., Lincoln, NE). The LI-COR 6400-portable gas exchange system was equipped at 400 \(\mu\text{mol-m}^{-2}\cdot\text{s}^{-1}\) for both control reference \(\text{CO}_2\) and flow rate. Gas exchange parameters were measured between 11:00 am and 2:00 pm about every 15 d from 13 July to 9 Nov. 2015 and from 12 July to 24 Sept. 2016. No data were collected between 21 Aug. and 8 Oct. 2015 because of adverse weather conditions and unavailability of the LI-COR 6400-portable gas exchange system. Photo-synthetic active radiation was consistently between 998 and 1000 \(\mu\text{mol-m}^{-2}\cdot\text{s}^{-1}\) using the 6400-02B light source. Measurements were made on fully expanded leaves to cover the entire chamber of the portable gas exchange system on sunny days. One-way analysis of variance was performed to determine the difference in ET, effluent, and gas exchange parameters among treatments using SAS 9.2 (SAS Institute Inc., Cary, NC).

Results and Discussion

The average cumulative effluent from the pots of the C, HM, PF, and ST treatments ranged from 3.51 ± 0.65 to 7.73 ± 2.2 cm in 2014 and from 6.64 ± 0.8 to 8.85 ± 1.2 cm in 2015 (Fig. 1A). For both years, HM had the highest cumulative volume of effluent compared with the C, PF, and ST treatments. However, no significant differences in leachate volumes were seen among the treatments.

Macropores are reported to increase deep percolation (Beven and Germann, 1982; Mori and Hirai, 2014; Shipitalo et al., 2000; Zhou et al., 2012). In this study, the absence or presence of PF channels did not show an increase in the cumulative volume of effluent. No increases in the deep percolation in the PF and ST treatments could be due to the PF channels being only up to 17 cm depth from surface, smaller total volume of PF channels, likely collapse of the PF channels, and predominant lateral infiltration into the soil matrix. Mori and Hirai (2014) reported that empty macropores collapsed during the infiltration process after conducting a solute transport experiment with and without fibrous materials in the macropores. Zhou et al. (2012) reported higher infiltration in soils with macropores open at the soil surface than those closed at the surface or no macropores.

Average cumulative ET values for the C, HM, PF, and ST treatments ranged from 21 ± 3.8 to 28 ± 1.1 cm in 2014 and from 55 ± 6.7 to 75 ± 2.4 cm in 2015 (Fig. 1B). Cumulative ET in 2015 was ≈3 times greater than the cumulative ET in 2014 because six more ET measurements were included in the water balance analysis conducted in 2015. The C and HM treatments had lower cumulative ET than PF and ST treatments; however, cumulative ET was not significantly different among the C, HM, PF, and ST treatments. Soil evaporation could have increased by the subsoil exposed to the atmosphere in plots with PF channels and tillage (Cattle, 1999).

PF flow channels were expected to increase pecan root exposure to indaziflam and cause phytotoxicity. However, no visual phytotoxicity effects on pecan trees were observed in 2014. Gas exchange parameters were also measured in 2015 to determine if they were influenced by the second indaziflam application (50 g a.i./ha). But no phytotoxicity effects were observed in 2015 also using an application rate of 50 g a.i./ha.
Therefore, in 2016, the pecan trees with HM and ST were treated with 150 g a.i./ha of indaziflam and irrigated with 5 L of water to prevent the leaching of indaziflam and increase in the exposure time. No phytotoxicity effects were seen even after increasing the application rate from 50 to 150 g a.i./ha and decreasing the leaching to zero. The absence of phytotoxicity effects could not explain the sporadic injury symptoms reported by González-Delgado et al. (2015) for an application rate of 73.1 g a.i./ha. González-Delgado et al. (2015) reported that indaziflam was mostly detected in the unimpacted areas (no injury observed on pecan trees) of two pecan orchards 1 year after indaziflam application. A second field study reported that the percent mass recoveries of indaziflam was mostly higher in the unimpacted areas where the organic matter content was greater than that in the impacted area. This greenhouse study selected a sandy loam soil similar to the one found in the New Mexico pecan orchard in González-Delgado et al. (2017). Soil pH was also similar but organic matter content in the pots was greater (1.5 ± 0.2%) than that in field (0.60 ± 0.03%). This small difference could partially explain the absence of phytotoxicity effects in young pecan trees exposed even to an application rate two times greater than the recommended application field rate of indaziflam. Schneider et al. (2015) reported increased sorption of indaziflam with increasing organic matter content after evaluating the phytotoxicity of indaziflam on bermudagrass.

Another soil condition that might have been different between the greenhouse and field was the absence of any material greater than 2 mm in greenhouse soil. Therefore, the macroporosity was expected to be greater in the pecan orchard than the greenhouse soil. In contrast to the first field study, no further phytotoxicity effects were observed for the application rates of 36.5 and 73.1 g a.i./ha during the second field study. The exact causes of the phytotoxicity observed after the first indaziflam applications in the two orchards are not fully known. However, root exposure to the indaziflam concentration which was much higher than the recommended rate likely caused injury.

The photosynthetic rate, transpiration, stomatal conductance, and relative humidity were higher after irrigation than before (Fig. 2). However, the opposite trend was observed for vapor pressure deficit from 13 July to 9 Nov. 2015 and from 12 July to 24 Sept. 2016 (Fig. 3). Studies have also reported increases in photosynthetic rate, transpiration rate, and stomatal conductance with irrigation (Asseng et al., 1998; Reed and Loik, 2016; Shem et al., 2009; Toselli et al., 2014; Xue et al., 2003). Increases in the relative humidity at the leaf surface after irrigation was the result of an increase of leaf water content (Fig. 3). Low soil moisture content increased vapor pressure deficit, decreased the leaf water potential, and promoted stomata closure (Comstock and Mencuccini, 1998; Gunderson et al., 2002; Turner et al., 1984). Under water stress conditions, the decrease in stomatal opening limits CO₂ uptake that causes a reduction in photosynthetic activity and intercellular CO₂ concentration (Anderson et al., 1995; Gunderson et al., 2002; Osakabe et al., 2014; Sharma et al., 2017; Turner et al., 1984). In contrast, some other studies reported an increase of the intercellular CO₂ concentration in different tree species subjected to drought conditions (Brodribb, 1996; Kubiske et al., 1996). In this study, no clear trends in intercellular CO₂ concentrations were observed for treatments ≈ 14 d after the previous irrigation in 2015 and 2016. Higher intercellular CO₂ concentrations with increasing water stress were observed in some treatments before irrigation in 2015 on 13 July, 27 July, and 19 Oct., and also in 2016 on 26 July, 10 Aug., and 22 Sept. These could be explained by the reduction of carboxylation efficiency in the photosynthetic apparatus (Farquhar and Sharkey, 1982; Gomes et al., 2004). In 2015, leaf temperature did not show a clear trend with increasing water stress, but leaf temperature values were consistently higher 1 d before irrigation during 2016 (Fig. 3).

Photosynthetic rates 1 d before irrigation corresponded to the time of maximum water stress. Mostly, these values did not significantly decrease after indaziflam application on 27 July 2015 and 25 July 2016 and remained consistent with those collected before the herbicide applications. The data suggested that indaziflam applications had no permanent effects on gas exchange parameters, except on 12 Aug. 2016 when photosynthetic rate was lower than expected. The reduction in the photosynthetic rate was most likely the result of treating the leaves of the pecan trees with an insecticide “Admire Pro” (Imidacloprid) on 8 Aug. 2016 for aphid control. It was observed that the leaves were
covered by the protective coating of the insecticide for a longer period of time in 2016. However, photosynthetic rate values recovered to levels before the insecticide application after 6 weeks (Fig. 2B). Although trees were also sprayed with Sivanto (Propylene carbonate) on 23 June 2015 for aphid control, but no reduction in photosynthetic rate was noted at that time. Wood et al. (1997) reported reductions in the photosynthetic rate of pecan for about 14 d after treating with an organosilicon surfactant. Generally, trees planted in indaziflam sprayed pots with HM, PF, and ST did not show a significant difference in the measured gas exchange parameters for most days. However, the photosynthetic rate was mostly lower in the HM treatment than in other treatments in 2015. Similarly, the
photosynthetic rate was higher in ST than those with HM on 12 July, 12 Aug., 22 Sept., and 24 Sept. 2016. Greater plant biomass is reported in plots with artificial macropores than in control plots as a result of enhanced infiltration, nutrients, and oxygen (Mori et al., 2014). In this study, pots were filled with a sandy loam soil previously air-dried and sieved through a 2-mm sieve; therefore, the soil was free of organic debris and rocks that would normally influence the aeration process. The location of the preferential flow channels in pots with the PF and ST treatments might have contributed to a lower degree of stress as the result of greater aeration and easier root water uptake immediately after irrigation. Pecan trees are sensitive to poor soil drainage, and their productivity tends to decrease.
in areas under prolonged flooding conditions (Sparks, 2005).

Conclusions

There was no significant difference in the cumulative volume of effluent among the HM, PF, and ST treatments probably because of some degree of failure of the artificial preferential flow channels. Similarly, there was no significant difference in cumulative ET among treatments. Macropore channels did not seem to change soil water dynamics likely being present up to the partial soil depth. Less water stress was observed for pecan in ST and PF treatments likely because of quicker drainage and higher aeration than HM treatment. No phytotoxicity in pecan trees treated with 50 and 150 g a.i./ha of indaziflam suggested that indaziflam did not affect pecan trees subjected to water stress in this study under greenhouse conditions.

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