Hardscape of Soil Surface Surrounding Urban Trees Alters Stem Carbon Dioxide Efflux

By Thomas E. Marler

Abstract. The diel patterns of stem carbon dioxide efflux ($E_s$) were quantified for 8 lignophyte tree species using paired trees, with one tree surrounded by hardscape from the bole to the canopy perimeter and the second tree surrounded by grass or mulch. Stem $E_s$ was measured at a height of 30 to 40 cm on the boles, and measurements were made about every 2 hours during 31-hour measurement campaigns. Nocturnal $E_s$ was similar for the hardscape trees and the trees without hardscape. Trees surrounded by hardscape exhibited daytime $E_s$ that was 73% greater than nocturnal $E_s$. In contrast, trees surrounded by grass or mulch exhibited daytime $E_s$ that was only 55% greater than nocturnal $E_s$. The diurnal maximum of $E_s$ was in the morning for trees surrounded by hardscape but was in the afternoon for trees growing in grass or mulch. The results indicated root-respired carbon dioxide was transferred to the bole through daytime transpiration, and more of this carbon dioxide was released from the bole surfaces for trees surrounded by hardscape.

Keywords. Carbon Cycle; Philippines; Stem Respiration.

BACKGROUND

Tree stems and the soils that support trees can act as sources of the greenhouse gas carbon dioxide ($CO_2$), and the efflux of $CO_2$ from stem and soil surfaces has been quantified under many experimental and observational settings. Tree stems and soils may also exhibit substantial $CO_2$ storage capacities; therefore, forested ecosystems are integral contributors to global carbon budgets (Geider et al. 2001). Ongoing attempts to factor trees into carbon budgets require accurate assessments of the magnitudes and temporal variations of soil and stem $CO_2$ fluxes.

The autotrophic and heterotrophic sources of $CO_2$ in forested ecosystems coexist and are difficult to separate when studying soil and stem $CO_2$ efflux. The interplay of $CO_2$ movements between rhizosphere soils and roots may be highly unpredictable. For example, root-respired $CO_2$ may exit the root surface to enter rhizosphere soils, diffuse to the soil surface, then contribute to soil surface $CO_2$ efflux (Kuzyakov 2006; Trumbore 2006). Contrarily, $CO_2$ in the bulk soil may diffuse to the rhizosphere, enter roots, be transported to stems via the transpiration stream, then contribute to stem $CO_2$ efflux ($E_s$)(Ford et al. 2007; Moore et al. 2008). The contribution of root-respired $CO_2$ to $E_s$ may be substantial in some scenarios (Bloemen et al. 2013; Kunert 2018; Tarvainen et al. 2018). The nature of these relationships may be altered by experimental manipulations. For example, stem girdling to stop basipetal transport of photosynthates from leaves to roots has been shown to reduce soil $CO_2$ efflux (Bloemen et al. 2014).

The contributions of urban trees to human health and biodiversity conservation issues are often overlooked (Egerer and Buchholz 2021). Urban trees may be exposed to stress factors that are unique to the urban environment (Czaja et al. 2020). For example, soil surface characteristics of natural forest communities are relatively homogeneous compared with those of urban spaces where hardscapes proliferate. The efflux of $CO_2$ from the soil surface is important for evacuating root-respired $CO_2$ from the rhizosphere, yet the per se influence of soil surface characteristics on $E_s$ have not been reported.

The objectives of this study were to determine the influence of hardscapes on $E_s$ of urban trees. The first hypothesis was that the differences in $E_s$ of trees surrounded by hardscape versus trees without hardscape
would be minimal at night due to the lack of transpiration. The second hypothesis was that daytime $E_s$ would be greater in trees surrounded by hardscapes than in trees surrounded by grass or mulch, because root-respired CO$_2$ would be unable to diffuse away from the rhizosphere due to the limited soil surface CO$_2$ efflux.

MATERIALS AND METHODS

This study was conducted in November 2021 in Angeles City, Philippines, where hardscapes commonly surround urban trees. The soils were modified by anthropogenic activity, but the background soil was a loam (fine loamy, smectitic, isohyperthermic, Vertic Equiaquent).

Roadside reconnaissance was conducted for several days to locate 2 appropriate trees for each species by using the following criteria. One of the trees was surrounded by hardscape that extended from the bole to at least the canopy perimeter. The second tree did not have any hardscape beneath the canopy, was similar in size to the hardscape tree, and was located less than 500 m from the hardscape tree. The non-hardscape trees were growing in grass or mulch. These criteria were used to locate tree pairs for 8 species.

Albizia saman (Jacq.) Merr. and Swietenia macrophylla King are commonly used as boulevard trees in the Philippines, and these 2 species were included in the first measurement campaign (2021 November 2–3). Acacia auriculiformis A.Cunn. ex Benth., Premna odorata Blanco, and Terminalia catappa L. are commonly planted in parks and other municipal landscape settings, and these 3 species were grouped in a second measurement campaign (2021 November 5–6). Mangifera indica L., Manilkara zapota (L.) P.Royen, and Spathodea campanulata P.Beauv. are commonly found as roadside trees in residential communities, and these 3 species were included in a third measurement campaign (2021 November 9–10).

The hardscape characteristics were similar for the 8 specimens that were selected for the hardscape treatment (Figure 1). Concrete was used to construct parking or walking spaces after the trees were established. A period of at least 12 months had elapsed

Figure 1. Boles of 8 trees from the urban forest in Angeles City, Philippines surrounded by hardscape. (A) Acacia auriculiformis; (B) Albizia saman; (C) Mangifera indica; (D) Manilkara zapota; (E) Premna odorata; (F) Spathodea campanulata; (G) Swietenia macrophylla; (H) Terminalia catappa.
between the construction of the hardscape and the $E_s$ measurements.

For each of the species, a 31-hour measurement campaign was used to determine the diel variation of $E_s$ for the 2 trees. A CIRAS EGM-4 analyser fitted with an SRC-1 close system chamber (PP Systems, Amesbury, MA, USA) was used to quantify the diel patterns of $E_s$ using previously described methods (Marler and Lindström 2020). A stem height of 30 to 40 cm above the root collar was used for all measurements. The first measurement period was at about 15:00 hours on the first date, and measurements were repeated at approximately 2-hour intervals until about 22:00 hours of the second date. These methods encompassed more than 3 hours of the first photoperiod, an entire nocturnal period, an entire photoperiod, then more than 3 hours of the subsequent nocturnal period. The EGM-4 recorded air temperature and the chamber’s increase in CO$_2$ above ambient for a 2-minute period. The change in CO$_2$ was used to calculate $E_s$. Three periods of efflux at different radial locations were conducted for each tree during each measurement period. This procedure required less than 10 minutes per tree.

The stem surface temperature was measured with an infrared thermometer (Milwaukee Model 2267-20, Milwaukee Tool, Brookfield, WI, USA) for every measurement position. Relative humidity was determined with a sling psychrometer at the beginning and end of each measurement period. Stem diameter at the 30- to 40-cm height of measurements and total tree height were recorded one time for each tree.

Stem CO$_2$ efflux was greater during the photoperiod and depressed during the night, so the 4 greatest values of $E_s$ during the day measurements and the 4 lowest values of $E_s$ during the night measurements were compiled for each tree species. These data were treated as 4 replications and subjected to a 2-way factorial as a 2-soil surface type × 2-time period ANOVA (SAS Institute, Cary, NC, USA). Each species was analysed separately.

### RESULTS

The 8 tree species originated from 7 plant families (Table 1). Tree height ranged from 7.9 to 14.5 m, and bole diameter ranged from 34 to 83 cm. Sunrise ranged from 05:53 hours to 05:57 hours, and sunset ranged from 17:25 hours to 17:28 hours for the dates of the 3 measurement campaigns (Table 2). Relative humidity was similar among the measurements and ranged between night-time highs of 89% to 94% and daytime lows of 59% to 68%. Temperature was also similar throughout the study and ranged between night-time lows of 23.9 to 25.6 °C and daytime highs of 28.9 to 32.8 °C.

The soil surface main factor significantly influenced $E_s$ for every tree species except *A. auriculiformis* (Table 3). This result indicated the overall $E_s$ mean for the trees in hardwoods exceeded that of the trees in grass or mulch beds. The time of day main factor also significantly influenced $E_s$ for every tree species (Table 3). This result indicated the diurnal $E_s$ exceeded the nocturnal $E_s$ for each of the species. The interaction between soil surface type and time of day

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**Table 1.** Tree height and bole diameter (measured at 30 to 40 cm high) for 8 tree species growing in Angeles City, Philippines in November 2021. H = hardscape cover; GM = grass or mulch cover.

<table>
<thead>
<tr>
<th>Species</th>
<th>Family</th>
<th>H height (m)</th>
<th>GM height (m)</th>
<th>H diameter (cm)</th>
<th>GM diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acacia auriculiformis</em></td>
<td>Fabaceae</td>
<td>12.4</td>
<td>12.5</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td><em>Albizia saman</em></td>
<td>Fabaceae</td>
<td>14.5</td>
<td>14.4</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td><em>Mangifera indica</em></td>
<td>Anacardiaceae</td>
<td>10.6</td>
<td>10.2</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td><em>Manilkara zapota</em></td>
<td>Sapotaceae</td>
<td>8.4</td>
<td>8.2</td>
<td>37</td>
<td>36</td>
</tr>
<tr>
<td><em>Premna odorata</em></td>
<td>Lamiaceae</td>
<td>8.8</td>
<td>8.6</td>
<td>42</td>
<td>41</td>
</tr>
<tr>
<td><em>Spathodea campanulata</em></td>
<td>Bignoniaceae</td>
<td>7.9</td>
<td>8.1</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td><em>Swietenia macrophylla</em></td>
<td>Meliaceae</td>
<td>9.2</td>
<td>9.4</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td><em>Terminalia catappa</em></td>
<td>Combretaceae</td>
<td>8.5</td>
<td>8.3</td>
<td>37</td>
<td>38</td>
</tr>
</tbody>
</table>
The relative patterns of \( E_s \) throughout the diel cycle were similar for every species (Figure 2). In general, nocturnal \( E_s \) was similar for the 2 soil surface types, and daytime \( E_s \) was greater for hardscape trees than for trees growing in grass or mulch. The greatest difference in \( E_s \) during daytime hours occurred in mid- to late-morning when the hardscape trees exhibited their diel \( E_s \) maxima, and the least difference in \( E_s \) during daytime occurred in late afternoon when the trees with grass or mulch cover exhibited their diel \( E_s \) maxima.

The amplitude of the increase in daytime \( E_s \) above that of night-time \( E_s \) was greater for hardscape trees than for grass or mulch trees, and this difference varied among the tree species (Table 4). The relative increase in daytime \( E_s \) above that of night-time \( E_s \) averaged 55% and ranged from 29% to 61% for trees surrounded by grass or mulch. In contrast, the relative increase in daytime \( E_s \) above that of night-time \( E_s \) averaged 73% and ranged from 50% to 112% for trees surrounded by hardscape. The disparity in this relative increase for hardscape versus grass or mulch soil surfaces was least for \( A. \) auriculiformis and greatest for \( S. \) campanulata.

**DISCUSSION**

The soil surface characteristics of urban landscapes are heterogeneous, and these soil surface conditions may exert control over \( E_s \) magnitude and timing for urban trees. In this study, 8 tree species revealed a lack of difference in nocturnal \( E_s \) for trees surrounded by hardscapes and trees surrounded by grass or mulch, confirming the first hypothesis. In contrast, the magnitude of daytime \( E_s \) of these same trees was greatly

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### Table 2. Environmental characteristics of 8 tree species growing in Angeles City, Philippines in November 2021. HR = hour; RH = relative humidity.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sunrise (HR)</th>
<th>Sunset (HR)</th>
<th>Maximum RH (%)</th>
<th>Minimum RH (%)</th>
<th>Maximum temperature (°C)</th>
<th>Minimum temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acacia auriculiformis</em></td>
<td>05:55</td>
<td>17:27</td>
<td>89</td>
<td>59</td>
<td>32.8</td>
<td>25.0</td>
</tr>
<tr>
<td><em>Albizia saman</em></td>
<td>05:53</td>
<td>17:28</td>
<td>94</td>
<td>62</td>
<td>28.9</td>
<td>23.9</td>
</tr>
<tr>
<td><em>Mangifera indica</em></td>
<td>05:57</td>
<td>17:25</td>
<td>94</td>
<td>68</td>
<td>30.0</td>
<td>25.6</td>
</tr>
<tr>
<td><em>Manilkara zapota</em></td>
<td>05:57</td>
<td>17:25</td>
<td>94</td>
<td>68</td>
<td>30.0</td>
<td>25.6</td>
</tr>
<tr>
<td><em>Premna odorata</em></td>
<td>05:55</td>
<td>17:27</td>
<td>89</td>
<td>59</td>
<td>32.8</td>
<td>25.0</td>
</tr>
<tr>
<td><em>Spathodea campanulata</em></td>
<td>05:57</td>
<td>17:25</td>
<td>94</td>
<td>68</td>
<td>30.0</td>
<td>25.6</td>
</tr>
<tr>
<td><em>Swietenia macrophylla</em></td>
<td>05:53</td>
<td>17:28</td>
<td>94</td>
<td>62</td>
<td>28.9</td>
<td>23.9</td>
</tr>
<tr>
<td><em>Terminalia catappa</em></td>
<td>05:55</td>
<td>17:27</td>
<td>89</td>
<td>59</td>
<td>32.8</td>
<td>25.0</td>
</tr>
</tbody>
</table>

### Table 3. Factorial ANOVA values for \( F \)-test and associated \( P \)-value for the main factor of soil surface type (S), the main factor of day versus night (T), and the interaction between the 2 factors (S × T).

<table>
<thead>
<tr>
<th>Species</th>
<th>Surface type ( F_{1,12} )</th>
<th>Surface type ( P )</th>
<th>Time of day ( F_{1,12} )</th>
<th>Time of day ( P )</th>
<th>S × T ( F_{1,12} )</th>
<th>S × T ( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acacia auriculiformis</em></td>
<td>4.39</td>
<td>0.058</td>
<td>233.88</td>
<td>&lt; 0.001</td>
<td>8.96</td>
<td>0.011</td>
</tr>
<tr>
<td><em>Albizia saman</em></td>
<td>32.39</td>
<td>&lt; 0.001</td>
<td>1217.20</td>
<td>&lt; 0.001</td>
<td>44.63</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Mangifera indica</em></td>
<td>2082.69</td>
<td>&lt; 0.001</td>
<td>122.08</td>
<td>&lt; 0.001</td>
<td>122.08</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Manilkara zapota</em></td>
<td>2499.43</td>
<td>&lt; 0.001</td>
<td>168.00</td>
<td>&lt; 0.001</td>
<td>192.86</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Premna odorata</em></td>
<td>1344.14</td>
<td>&lt; 0.001</td>
<td>89.29</td>
<td>&lt; 0.001</td>
<td>89.29</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Spathodea campanulata</em></td>
<td>3051.92</td>
<td>&lt; 0.001</td>
<td>387.92</td>
<td>&lt; 0.001</td>
<td>467.31</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Swietenia macrophylla</em></td>
<td>1098.69</td>
<td>&lt; 0.001</td>
<td>144.23</td>
<td>&lt; 0.001</td>
<td>122.08</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><em>Terminalia catappa</em></td>
<td>1382.40</td>
<td>&lt; 0.001</td>
<td>86.40</td>
<td>&lt; 0.001</td>
<td>60.00</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

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increased by the presence of hardscapes, confirming the second hypothesis. These findings indicated that diffusive CO\(_2\) movement from the soil surface to the atmosphere was inhibited for the trees surrounded by surface hardscape, thereby reducing the escape of CO\(_2\) from root respiration through the soil system to the atmosphere. The disparity in daytime and night-time \(E\) behaviours indicated that active transpiration was required for diurnal xylem sap flow to transfer this respired CO\(_2\) out of the root zone and into the boles.

There is evidence that CO\(_2\) from soil heterotrophic respiration may enter plant roots for transport out of the soil system via the xylem (Ford et al. 2007; Moore et al. 2008). This study’s findings illuminate the possibility that trees perform ecosystem services for the...
soil heterotroph community in urban spaces covered by hardscapes. Indeed, the muted gas exchange on the soil surfaces of hardscapes may create anaerobic conditions in a soil matrix where oxygen is consumed and CO₂ is liberated. The hypoxia would become more acute for the heterotrophs if the CO₂ was unable to escape through the tree xylem. In turn, this may lead to a feedback loop where the resulting absence of beneficial soil microbiota would lead to declines in tree health in urban spaces where hardscapes occur.

The magnitude of influence of hardscapes on daytime $E_\delta$ was heterogeneous among the 8 tree species. For example, the *M. zapota* trees exhibited daytime $E_\delta$ that was 112% greater than night-time $E_\delta$, but this metric was only 50% for the *A. auriculiformis* trees. Relative radial CO₂ conductance in tree stems may differ among arborescent species and has been proposed as one factor that explains differences in $E_\delta$ (Wang et al. 2019). The differences in radial CO₂ conductance from stem xylem to the stem surfaces may explain the differences in $E_\delta$ that were reported among the species in this study.

The differences in $E_\delta$ between hardscape versus grass or mulch soil surfaces were not restricted to absolute amplitude, but also included time of day differences. An afternoon maximum in $E_\delta$ for the grass or mulch trees conformed to previous reports (e.g., Marler and Lindström 2020) and may be explained by a hysteresis effect of the time required for transfer of CO₂ from root tissues into root xylem, transfer of CO₂ to stem xylem, then radial diffusion of CO₂ to the stem surfaces. In contrast, a morning maximum in $E_\delta$ for the hardscape trees was unique and may signify an overabundance of CO₂ in the root-soil matrix by the end of the night period, which reduced the duration of hysteresis.

The published reports of diel variation in tree $E_\delta$ are highly contrasting. For example, the greatest $E_\delta$ has been reported during the daytime for some tree species (Yang et al. 2012; Bužková et al. 2015; Kunert and Edinger 2015). In contrast, the greatest $E_\delta$ has been reported during the night-time for other species (Kunert 2018; Salomón et al. 2018; Tarvainen et al. 2018). The characteristics of the soil surfaces surrounding the experimental trees in these publications were not described. The findings indicate that this deficiency in methods should be corrected in future publications that report tree stem respiration traits, as soil surface characteristics may exert a direct influence on $E_\delta$. Trees with pachycaul growth form exhibited reduced $E_\delta$ compared to lignophyte trees (Marler 2022). The influence of soil surface characteristics on diurnal $E_\delta$ for these pachycaul trees may contrast with that for lignophyte trees.

Understanding the carbon cycle has become crucial because of the increases in atmospheric greenhouse gases such as CO₂. Accurate modelling of ecosystem respiration (e.g., Salomón et al. 2022) requires a full understanding of the tree and habitat characteristics that exert control over $E_\delta$. The results of this study indicated that soil surface gas exchange beneath a tree’s canopy may be a key driver of tree stem CO₂ efflux and therefore must be included in future attempts to model the influence of trees on ecosystem respiration.

**LITERATURE CITED**


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Conflicts of Interest:
The author reported no conflicts of interest.

Résumé. Les schémas diurnes d’émission (Ε₂) de dioxyde de carbone provenant de troncs ont été quantifiés pour 8 espèces d’arbres lignophytes en utilisant des duos d’arbres comprenant un arbre entouré d’un revêtement en dur du tronc jusqu’au périmètre de la canopée et un second arbre entouré de gazon ou de paillis. L’Ε₂ des tiges a été mesuré à une hauteur de 30 à 40 cm sur les troncs et les mesures ont été effectuées environ toutes les 2 heures pendant des périodes de 31 heures. L’Ε₂ nocturne était similaire pour les arbres, qu’ils soient entourés de revêtement ou non. Les arbres entourés d’un revêtement en dur présentaient un Ε₂ supérieur de 73% à l’Ε₂, nocturne. Par opposition, les arbres entourés de gazon ou de paillis présentaient un Ε₂, supérieur de 55% seulement à l’Ε₂, nocturne. Le maximum diurne d’Ε₂, se situait le matin pour les arbres entourés d’un revêtement, mais l’après-midi pour les arbres poussant dans le gazon ou le paillis. Les résultats indiquent que le dioxyde de carbone absorbé par les racines a été transféré au tronc par la transpiration diurne et qu’une plus grande quantité de dioxyde de carbone a été libérée via l’écorce du tronc pour les arbres entourés d’un revêtement en dur.


Resumen. Se cuantificaron los patrones del flujo de dióxido de carbono del tallo (E₂) para 8 especies leñosas utilizando árboles pareados, con un árbol rodeado de paisaje desnudo desde el tallo hasta el perímetro del dosel y el segundo árbol rodeado de hierba o mantillo. El tallo E₂, se midió a una altura de 30 a 40 cm y las mediciones se realizaron aproximadamente cada 2 horas durante las jornadas de medición de 31 horas. Nocturnal E₂, fue similar para los árboles de paisaje desnudo y los árboles sin paisaje desnudo. Los árboles rodeados de paisajes desnudos exhibieron E₂, diurnos que eran 73% mayores que los E₂, nocturnos. En contraste, los árboles rodeados de hierba o mantillo exhibieron E₂, diurnas que fueron un 55% mayores que las E₂, nocturnas. El máximo diurno de E₂, era por la mañana para los árboles rodeados de paisajes desnudos, pero lo fue en la tarde para los árboles que crecen en la hierba o el mantillo. Los resultados indicaron que el dióxido de carbono respirado por la raíz se transferió al tallo a través de la transpiración diurna y la mayor parte de este dióxido de carbono se liberó de las superficies del tallo para los árboles rodeados de paisajes desnudos.