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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

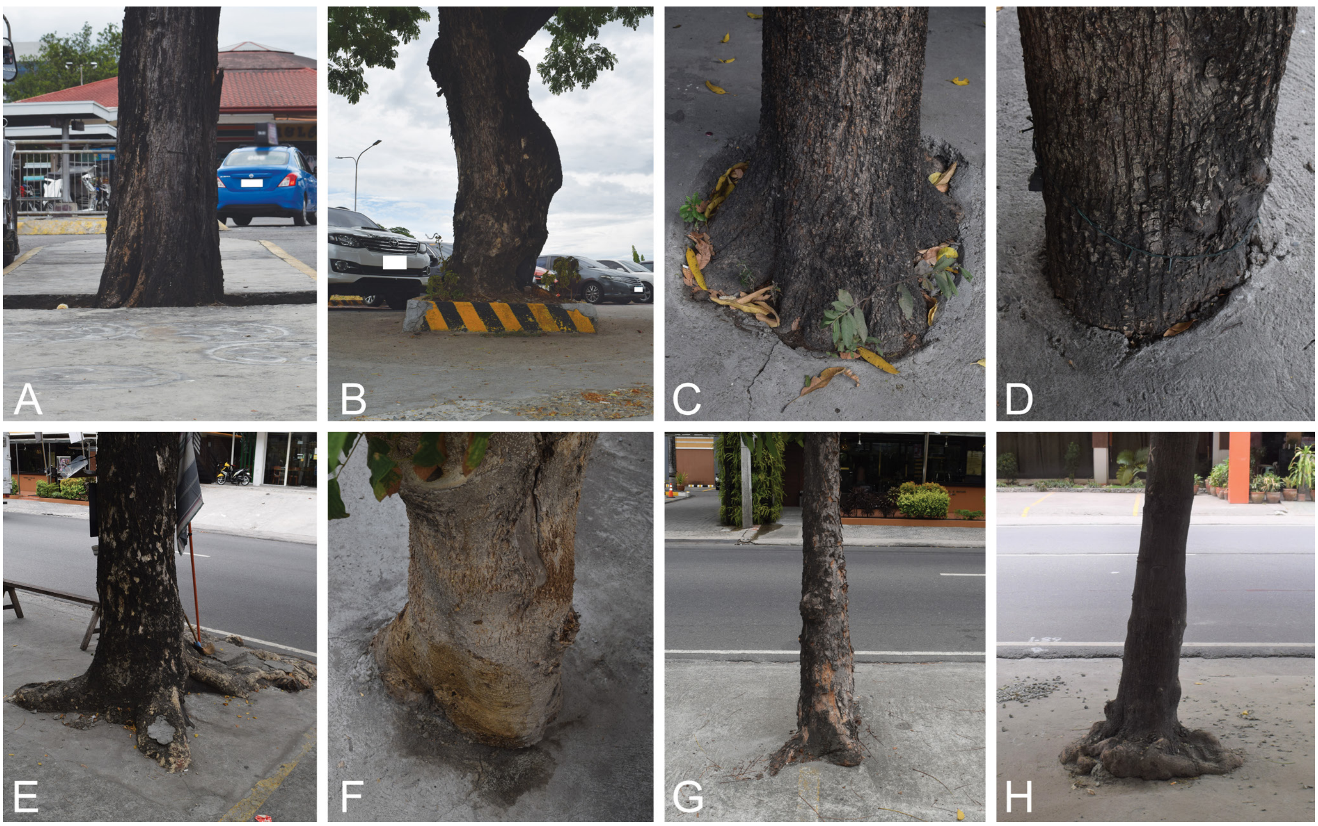

Figure 1. Boles of 8 trees from the urban forest in Angeles City, Philippines surrounded by hardscape. (A) *Acacia auriculiformis*; (B) *Albizia saman*; (C) *Mangifera indica*; (D) *Manilkara zapota*; (E) *Premna odorata*; (F) *Spathodea campanulata*; (G) *Swietenia macrophylla*; (H) *Terminalia catappa*.

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 hardscapes 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

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.

Species	Family	H height (m)	GM height (m)	H diameter (cm)	GM diameter (cm)
Acacia auriculiformis	Fabaceae	12.4	12.5	38	39
Albizia saman	Fabaceae	14.5	14.4	83	82
Mangifera indica	Anacardiaceae	10.6	10.2	34	35
Manilkara zapota	Sapotaceae	8.4	8.2	37	36
Premna odorata	Lamiaceae	8.8	8.6	42	41
Spathodea campanulata	Bignoniaceae	7.9	8.1	37	39
Swietenia macrophylla	Meliaceae	9.2	9.4	38	40
Terminalia catappa	Combretaceae	8.5	8.3	37	38

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

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

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).

Species	Surface type $F_{1,12}$	Surface type P	Time of day $F_{1,12}$	Time of day P	S × T $F_{1,12}$	S × T P
Acacia auriculiformis	4.39	0.058	233.88	< 0.001	8.96	0.011
Albizia saman	32.39	< 0.001	1217.20	< 0.001	44.63	< 0.001
Mangifera indica	2082.69	< 0.001	122.08	< 0.001	122.08	< 0.001
Manilkara zapota	2499.43	< 0.001	168.00	< 0.001	192.86	< 0.001
Premna odorata	1344.14	< 0.001	89.29	< 0.001	89.29	< 0.001
Spathodea campanulata	3051.92	< 0.001	387.92	< 0.001	467.31	< 0.001
Swietenia macrophylla	1098.69	< 0.001	144.23	< 0.001	122.08	< 0.001
Terminalia catappa	1382.40	< 0.001	86.40	< 0.001	60.00	< 0.001

also significantly influenced E_s for every tree species (Table 3). These results indicated that the influence of soil surface type on diurnal E_s was not similar to the influence of soil surface type on nocturnal E_s.

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

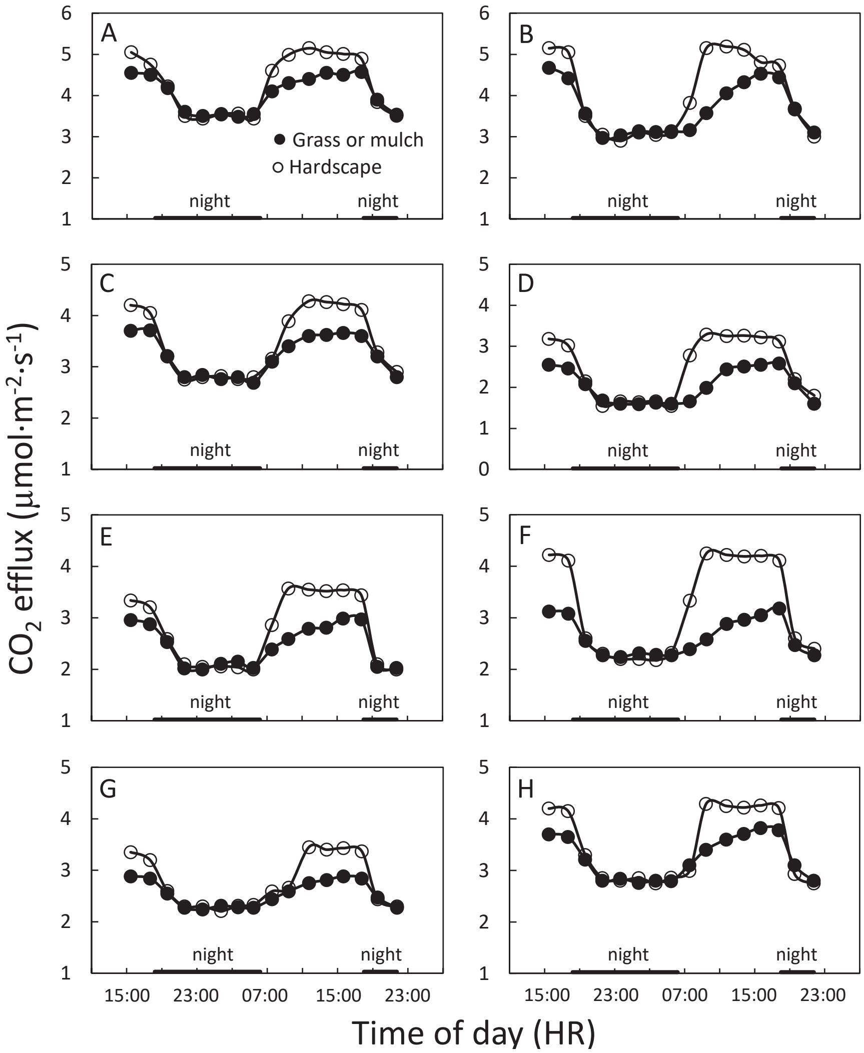

Figure 2. The diel cycle of stem carbon dioxide efflux for 8 tree species from the urban forest in Angeles City, Philippines in November 2021. Each circle marker is a mean of 3 measurements. (A) *Acacia auriculiformis*; (B) *Albizia saman*; (C) *Mangifera indica*; (D) *Manilkara zapota*; (E) *Premna odorata*; (F) *Spathodea campanulata*; (G) *Swietenia macrophylla*; (H) *Terminalia catappa*.

Table 4. The percentage increase in daytime stem carbon dioxide efflux (E_s) above that of night-time E_s for 8 tree species growing in Angeles City, Philippines in November 2021.

Species	Grass or mulch	Hardscape
Acacia auriculiformis	39%	50%
Albizia saman	29%	78%
Mangifera indica	29%	55%
Manilkara zapota	61%	112%
Premna odorata	50%	79%
Spathodea campanulata	42%	95%
Swietenia macrophylla	29%	56%
Terminalia catappa	38%	56%

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_s 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 CO_2 is liberated. The hypoxia would become more acute for the heterotrophs if the CO_2 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_s was heterogeneous among the 8 tree species. For example, the *M. zapota* trees exhibited daytime E_s that was 112% greater than night-time E_s, but this metric was only 50% for the *A. auriculiformis* trees. Relative radial CO_2 conductance in tree stems may differ among arborescent species and has been proposed as one factor that explains differences in E_s (Wang et al. 2019). The differences in radial CO_2 conductance from stem xylem to the stem surfaces may explain the differences in E_s that were reported among the species in this study.

The differences in E_s 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_s 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 CO_2 from root tissues into root xylem, transfer of CO_2 to stem xylem, then radial diffusion of CO_2 to the stem surfaces. In contrast, a morning maximum in E_s for the hardscape trees was unique and may signify an overabundance of CO_2 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_s are highly contrasting. For example, the greatest E_s 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_s 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_s. Trees with pachycaulous growth form exhibited reduced E_s compared to lignophyte trees (Marler 2022). The influence of soil surface characteristics on diurnal E_s for these pachychaulous 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 CO_2. 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_s. The results of this study indicated that soil surface gas exchange beneath a tree's canopy may be a key driver of tree stem CO_2 efflux and therefore must be included in future attempts to model the influence of trees on ecosystem respiration.

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The author reported no conflicts of interest.

Résumé. Les schémas diurnes d'émission (E_s) 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'E_s 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'E_s nocturne était similaire pour les arbres, qu'ils soient entourés de revêtement ou non. Les arbres entourés d'un revêtement en dur présentaient un E_s diurne supérieur de 73% à l'E_s nocturne. Par opposition, les arbres entourés de gazon ou de paillis présentaient un E_s diurne supérieur de 55% seulement à l'E_s nocturne. Le maximum diurne d'E_s 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 ce dioxyde de carbone a été libérée via l'écorce du tronc pour les arbres entourés d'un revêtement en dur.

Zusammenfassung. Die tageszeitlichen Muster des Kohlendioxidausstoßes (E_s) aus den Stämmen wurden für 8 Lignophyten-Baumarten anhand von Baumpaaren quantifiziert, wobei ein Baum vom Stamm bis zum Kronenrand von einer harten Oberfläche und der zweite Baum von Gras oder Mulch umgeben war. E_s wurde in einer Höhe von 30 bis 40 cm an den Stämmen gemessen, und die Messungen erfolgten etwa alle 2 Stunden während der 31-stündigen Messkampagnen. Das nächtliche E_s war bei den Bäumen mit und den Bäumen ohne Bodenbelag ähnlich. Bäume, die von Hardscape umgeben waren, wiesen tagsüber ein E_s auf, das 73% höher war als das nächtliche E_s. Im Gegensatz dazu wiesen Bäume, die von Gras oder Mulch umgeben waren, tagsüber ein E_s auf, das nur 55% höher war als das nächtliche E_s. Das tageszeitliche Maximum von E_s lag bei Bäumen, die von Hardscape umgeben waren, am Morgen, bei Bäumen, die in Gras oder Mulch wuchsen, jedoch am Nachmittag. Die Ergebnisse deuten darauf hin, dass das von den Wurzeln aufgenommene Kohlendioxid durch die Transpiration während des Tages in den Baumstamm übertragen wird und dass bei Bäumen, die von Hardscape umgeben sind, ein größerer Teil dieses Kohlendioxids von den Stammoberflächen freigesetzt wird.

Resumen. Se cuantificaron los patrones del flujo de dióxido de carbono del tallo (E_s) 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 E_s 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 E_s fue similar para los árboles de paisaje desnudo y los árboles sin paisaje desnudo. Los árboles rodeados de paisajes desnudos exhibieron E_s diurnos que eran 73% mayores que los E_s nocturnos. En contraste, los árboles rodeados de hierba o mantillo exhibieron E_s diurnas que fueron un 55% mayores que las E_s nocturnas. El máximo diurno de E_s 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 transfirió 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.