

JP1.1 ECOSYSTEM RESPIRATION OF SUBURBAN LAWNS AND ITS RESPONSE TO VARYING MANAGEMENT AND IRRIGATION REGIMES

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1. INTRODUCTION

Urban greenspace including residential lawns represents an important fraction of land cover in cities. The magnitude of respiration from vegetated surfaces has been shown to be dependent on biophysical factors, including soil volumetric water content (θ), soil organic carbon (SOC) content and soil temperature (T_s), which are manipulated in the highly managed ecosystems created on urban lawns (Luo and Zhou 2006).

A recent investigation of emissions on urban turfgrass by Allaire et al. (2008) showed that management practices have important effects on Net Ecosystem Exchange (NEE), and concluded that frequency of mowing is a dominant control when abiotic drivers are constant. However, this study explored a limited range of θ and T_s conditions. Koerner and Kloepatek (2002) found θ to be a major contributing factor to urban soil respiration under limiting soil moisture conditions, such as in arid urban regions. A similar moisture limitation in semi-arid grasslands has been shown to lead to enhancement of soil respiration by as much as 50% following irrigation (Mariko et al. 2007). Systematic data focusing on the relationship between environmental controls and urban ecosystem respiration (R_{eco}) is rare. However, an understanding of the nature of this response is necessary to incorporate this biogenic source into models of the urban carbon cycle and to develop management strategies that promote carbon sequestration.

In this study, we seek to determine which physical factors and environmental controls explain most variability in the ecosystem respiration (R_{eco}) of residential lawns. Using closed chamber measurements of R_{eco} collected in two suburban neighbourhoods in Vancouver, BC, Canada, we examined the relationship between R_{eco} and θ and T_s , and used it to model respiration where these controls are known. The total annual flux of CO₂ produced by ecosystem respiration was calculated for the residential lawns under study, and we considered the contribution of R_{eco} of lawns to total NEE measured by eddy covariance (EC) above the urban surface.

2. STUDY SITES AND METHODS

2.1 Study Sites

The study examined respiration of eight residential

lawns in two neighbourhoods in Vancouver, BC, Canada, treated with varying irrigation and management regimes (Table 1). A total of 390 measurements of each R_{eco} , T_s , and θ were made between July and December of 2008. All sites were within the footprint of eddy covariance (EC) systems monitoring CO₂ exchange at the local-scale (Crawford et al., 2009), and were equipped with long term soil hydrology monitoring stations, making continuous measurements of T_s , θ , soil heat flux density and surface wetness (Christen et al., 2009).

Four sites (OR1-4) were in the 'Vancouver-Oakridge' neighbourhood (49°13'N, 123°8'W), where lawn management is intensive, and characterized by regular automatic and/or manual irrigation, resulting in high values of θ . The remaining urban sites (SS1-4) were in the 'Vancouver-Sunset' neighborhood (49°13'N, 123°5'W), treated with manual irrigation or no irrigation at all. Average θ at sites in this neighbourhood are correspondingly lower. Details of management and site conditions are described in Table 1.

Additionally, respiration and climatic conditions at two unmanaged grassland sites (non-irrigated and non-fertilized) in the region were measured for reference conditions. A site on Westham Island (WI) at 49°5'N 123°9'W was unmanaged for a full year preceding the initiation of the measurement period and was colonized by a diverse set of tall grasses and low ground cover. Measurements at the UBC Farm (UF) at 49°15' N 123°14'W were taken within a plot that had been fallowed for several seasons, but mowed within one month prior to the measurement period.

Five locations at each of the ten sites were marked and sampled repeatedly throughout the six-month measurement period to provide a representative range of θ , T_s , and phenology.

2.2 Site Conditions

Table 1 summarizes measured soil conditions at the eight urban sites and two rural reference locations. The average T_s did not vary significantly on an annual basis between urban sites, but soil temperatures were elevated due to the urban heat island (UHI) effect and reduced sky view-factors relative to the rural reference site at WI. On average, θ was higher at sites in Oakridge, where irrigation is more regular, with 61% of homes using automatic irrigation systems, 35% irrigating manually and 5% applying no irrigation at all. Lower average soil moisture conditions were found in the Sunset Neighbourhood, with 1% automatic, 79% manual, and 20% of homes using no irrigation. The effects of irrigation on vegetation

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productivity are evident in contrasting photographs of sites with continuous, automatic irrigation and no irrigation regime from the same date (Figure 1). Soil

organic carbon (SOC) in the upper soil layers at SS1-SS3 and UF exceeded those at OR1-4 by a factor of 2 to 3, while WI had the lowest measured SOC.

Table 1: Soil conditions, vegetation characteristics, and management at 10 sites in the Vancouver region

Site	Annual $T_{s_{ave}}$ (°C)	Annual θ_{ave} (%)	SOC 0-3 cm (%)	SOC 3-6 cm (%)	SOC 6-10 cm (%)	Mid-summer LAI (m ² /m ²)	Average summer grass height (mm)	Irrigation infrastructure	Irrigation frequency	Proximity to large trees
OR1	11.4	42	4.9	5	4.2	6.19	32	manual	sporadic	tall tree cover
OR2	11.2	44.7	5	4.4	4.4	3.75	34	manual	none	no tall trees
OR3	11.2	53.5	4.5	4.1	3.6	5.00	42	automatic	regular	dispersed tall trees
OR4	12.1	44.1	5.9	5.5	4.8	4.68	52	automatic	continuous (2x/week)	tall tree cover
SS1	11.3	29.6	17.9	16.5	9.2	5.90	50	manual	regular	tall tree cover
SS2	11.1	36.4	10.8	8.9	8.4	4.64	35	manual	sporadic	dispersed tall trees
SS3	10.5	23.7	14.1	8.4	6.2	15.41	35	none	none	no tall trees
SS4	10.9	23	7.3	6.1	3.7	6.57	39	manual	sporadic	dispersed tall trees
UF	N/A	N/A	16.9	17.4	10.4	5.9	N/A	none	none	no trees
WI	6.7	36.1	4.8	3.5	3.4	7.03	N/A	none	none	no trees



Figure 1: Grass conditions at frequently irrigated site OR4 (left) and non-irrigated site SS3 (right) on August 22, 2008

2.3. Equipment and Methodology

R_{eco} was measured using a non-steady state portable system equipped with a PVC chamber with a volume of $1.4 \times 10^{-3} \text{ m}^3$, capturing flux from a surface area of $7.9 \times 10^{-3} \text{ m}^2$, and fitted with an opaque cover. Carbon dioxide concentrations within the chamber, sealed to the ground surface with a foam gasket, were

measured with an IRGA (LI-800, LI-COR, Lincoln, USA), and the rate of change was converted to a CO_2 flux rate. Concurrent measurements of T_s at 5 cm and θ integrated over 0-12cm depth were obtained using a copper-constantan thermocouple and a hand held TDR (Hydrosense, CS620, CD620 with 12 cm probe, Campbell Scientific, Logan, USA). Measurements of θ were calibrated based on local soil properties against 4

to 6 samples with gravimetric analysis in the laboratory. Soil cores to 18cm depth at all 50 sampling locations were analyzed using the loss-on-ignition method for Soil Organic Carbon (SOC).

3. RESULTS AND DISCUSSION

3.1 Observed Respiration

Measured CO₂ flux from urban lawns ranged from 0.5 μmol m⁻² s⁻¹ to 14.59 μmol m⁻² s⁻¹. Temperature affects many aspects of the respiration process, including acting as a control on the activity of respiratory enzymes (Luo and Zhou 2006). Past studies in a range of settings have established positive correlations between soil temperature and respiration (Lloyd and Taylor 1994). The expected exponential increasing relationship held for the observed data (Figure 2). Low temperatures clearly restricted the magnitude of observed respiration, and also the variability imposed by other controls on R_{eco} . At temperatures higher than 15°C, far more scatter appeared in the data set for all sites, most likely as a result of lower θ associated with higher T_s as has been reported by Jassal et al. (2008).

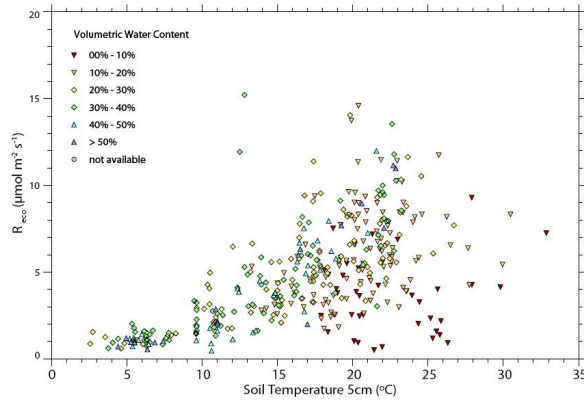


Figure 2: Soil temperature response of R_{eco} for all data sorted by soil volumetric water content.

The optimal water content to facilitate respiration is expected to be near field capacity (Luo and Zhou 2006). Koerner and Klopatek (2002) have established that when θ is limited the influence of this factor is enhanced. The limitation on R_{eco} imposed by low values of θ was clearer when examining the trend in respiration with increasing soil volumetric water content (Figure 3). Respiration was restricted below 5 μmol m⁻² s⁻¹ for $\theta < 8\%$, and declined sharply towards zero as θ approached 5%. At values of θ between 10 and 20%, R_{eco} increased steadily, and attained a maximum value before slightly declining at $\theta > 32\%$ owing to lower T_s associated with wetter soil conditions. There was no indication of oxygen limitation restricting respiration.

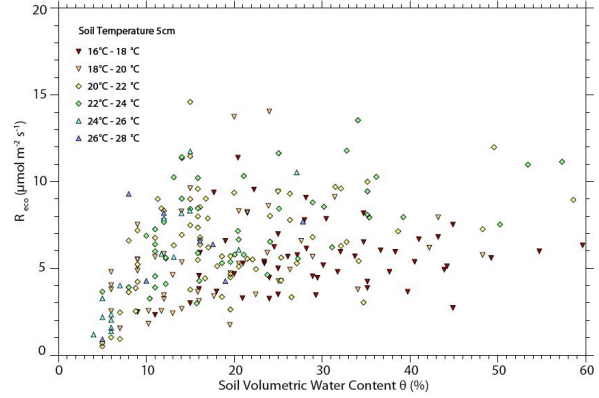


Figure 3: Soil volumetric water content response of R_{eco} for all data sorted by soil temperature at 5 cm

3.2 Empirical Model to Determine R_{eco} From Urban Soils

Based on the observed respiration results, recognizing the accelerating rate of respiration with temperature and the limitations imposed by low soil moisture, we developed an empirical model to describe R_{eco} as a function of T_s and θ for all urban sites.

The temperature dependence was based on the Arrhenius equation, which accounts for decreasing activation energy for enzymatic activity with increasing temperature, and was expressed as an exponential equation using a formulation based on Lloyd and Taylor (1994).

$$R_{eco}(T) = R_{ref}(T_{ref}) \exp \left[E_0 \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0} \right) \right] \quad (1)$$

Inputs of T_{ref} , the reference temperature and T_0 , the low-temperature limit for respiration were fixed at 10°C and -46°C respectively, following Lloyd and Taylor (1994). The sensitivity of the temperature response was represented by E_0 . Figure 4 shows a curve fit to the data from all urban sites.

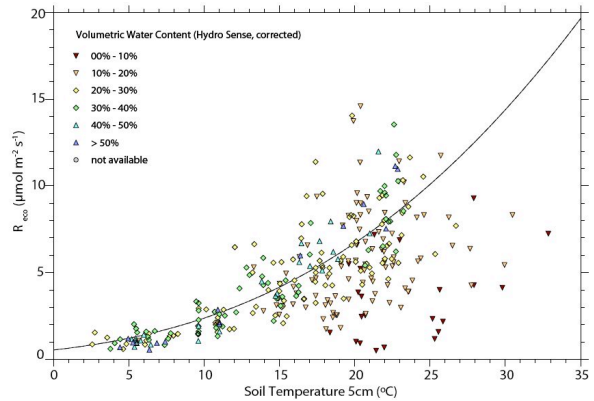


Figure 4: Data from all urban sites, sorted by volumetric water content. The black line is the best fit with $R_{ref} = 2.4$ and $E_0 = 383$ for all classes between 20% and 40%. Note the significant reduction of respiration below 20%.

E_0 and R_{ref} were determined for each site for $20\% < \theta < 40\%$. This range was selected recognizing the reduction of respiration at low moisture conditions. Table 2 summarizes the empirical parameters established for modeling the temperature response. We use the individual parameters derived for each site for further analysis of R_{eco} .

Table 2: Site specific and global parameters for modeling the temperature response of R_{eco}

Site	R_{ref} ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	E_0 (K)
OR1	2.5	325
OR2	3.3	347
OR3	2.2	436
OR4	2.2	405
SS1	No useful reg.	No useful reg.
SS2	1.8	402
SS3	2.1	249
SS4	2.4	287
All urban	2.4	383
UF	No useful reg.	No useful reg.
WI	3.4	265
All rural	3.0	329
All sites	2.5	369

Soil moisture dependence was incorporated into the model using an empirical function based on the response of R_{eco} below field capacity.

$$R_{eco}(T, \theta) = R_{eco}(T, \theta_{ref}) \frac{(\theta - \theta_0)^b}{(\theta_{ref} - \theta_0)^b} \quad (2)$$

Through optimization, we established the coefficient b to be 0.33 for all urban data, with θ_0 set to 4%, and θ_{ref} at 30%. Figure 5 shows this equation fit to data from all urban sites.

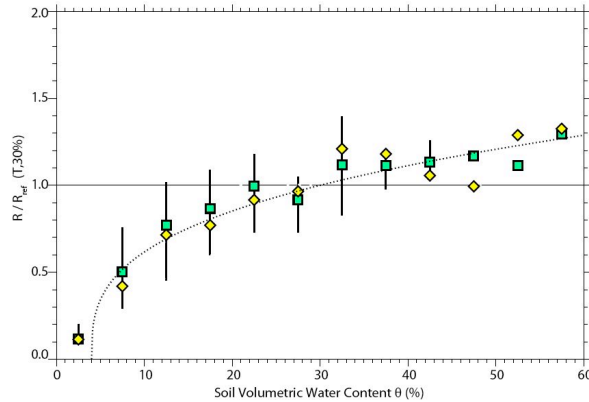


Figure 5: Measured respiration as a fraction of calculated respiration R_{ref} based on the Lloyd and Taylor (1994) model at reference soil volumetric water content vs. volumetric water content. Diamonds indicate class median values, squares are class averages, and vertical lines include the 1st and 3rd quartile. The dotted line is the regression with $b = 0.33$ and $\theta_0 = 4\%$.

Combining equations (1) and (2) to incorporate the temperature and moisture dependence of R_{eco} , ecosystem respiration for the urban sites was modeled as follows:

$$R_{ref}(T_{ref}, \theta_{ref}) \exp \left[E_0 \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0} \right) \right] \frac{(\theta - \theta_0)^b}{(\theta_{ref} - \theta_0)^b} \quad (3)$$

Figure 6 shows a visualization of the response surface of R_{eco} as a function of T_s and θ .

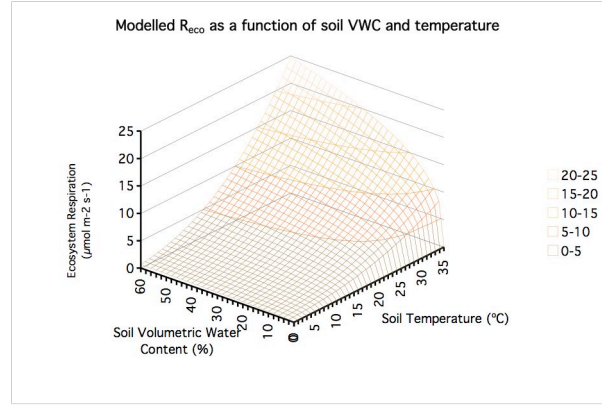


Figure 6: A visualization of the empirical model for R_{eco} (equation 3), based on the parameters for all urban data: $R_{ref} = 2.37 \mu\text{mol m}^{-2} \text{s}^{-1}$, $E_0 = 383.9 \text{ K}$, and $b = 0.33$.

3.3 Major Controls on R_{eco} for Urban Lawns

Evaluating the modeled value of R_{eco} against measured respiration under the same climatic conditions (T_s and θ) shows the dominant environmental controls explaining the variability of ecosystem respiration of urban lawn surfaces (Table 3)

Table 3: R^2 of measured vs. modeled R_{eco} and partitioning into effects of T_s and θ

	Variation accounted for by model (R^2)	Variation accounted for by	
		T_s attributable	θ attributable
OR1	0.468	0.435	0.033
OR2	0.413	0.398	0.015
OR3	0.794	0.684	0.110
OR4	0.847	0.804	0.043
SS1	0.668	0.557	0.111
SS2	0.668	0.395	0.274
SS3	0.238	0.038	0.199
SS4	0.636	0.587	0.049
All urban	0.633	0.558	0.075

For the data from all urban sites, a significant proportion of variability in R_{eco} was accounted for by the environmental controls ($R^2 = 0.63$), suggesting that with knowledge of T_s and θ , R_{eco} can be explained reasonably. The majority of this was attributable to changes in soil temperature (56%), with θ acting as a secondary control (8%). In general, T_s changes explained significantly more variation in modeled R_{eco} than θ at nearly all locations, accounting for between 5 and 20 times more variability at individual sites.

3.3.1 Inter-site Variability

Some differences in the strength of environmental controls were evident. The average proportion of variability accounted for with changes in T_s was 46%, while that attributable to θ was 12%.

OR3 and OR4 showed especially high values for both total variability accounted for by the model, and the proportion attributable to changes in T_s . This may be related to the absence of moisture limitations at these sites; θ remained above 15% at both sites throughout the six-month measurement period.

At SS3, we found the lowest correlation for the combined effects of T_s and θ . Further, this was the only location where soil moisture was established as a stronger control (19%) than temperature (4%). Measurements taken at this site were under low soil moisture conditions ($4\% < \theta < 32\%$) and this location, with no regular irrigation schedule, was characterized by one of the lowest average annual moisture values ($\theta_{ave} = 23.7\%$). Where soil moisture is consistently limited, it becomes a more important control on R_{eco} , and modeling using these environmental conditions explains lesser variance.

3.3.2 Unexplained Variability

37% of the variability in R_{eco} remained unexplained for the data from all urban sites, with this value ranging from 15% to 76% when individual sites were considered. A variety of factors not included in this model have been addressed as possible controls on R_{eco} including lawn management and substrate supply. Allaire et al. assessed lawn management strategies and the resulting influence on CO_2 emissions, or net ecosystem exchange (NEE) for urban turfgrass in Quebec City (2008). This study found that frequently mowed lawns produced the highest emissions, with mowing frequency having a higher impact than fertilization on NEE.

Golubiewski et al. (2006) address the changes in soil organic carbon pools following urbanization, suggesting that pools increase following an initial loss with conversion to types of urban land. Varying proportions of C pools at each site can moderate T_s and θ effects. Further, respiration in grassland soils has been demonstrated to be closely related to the component of substrate supply controlled by

aboveground photosynthesis, e.g. clipping of grasses reduced CO_2 flux from grasslands by reducing canopy photosynthesis (Bremer et al. 1998). The management regime and mowing frequency may also contribute to respiration rates by reducing the supply of carbon from photosynthesis to the root system

Mature trees were established on many of the urban lawns under study. Respiration from large roots may have influenced measurements of R_{eco} , but the magnitude of the flux produced may have responded differently to environmental changes than soil microorganism and grass-leaf and root respiration.

This model was based on a direct response of R_{eco} to θ , but the history of soil moisture makes this relationship a complex function of time. The time required for a stressed soil microbe population to recover to a healthy state after wetting of a soil that has been subject to drought conditions will cause a different R_{eco} response than that in a consistently moist soil (Reichstein et al. 2003).

4. ANNUAL TOTALS OF R_{eco}

Based on time series of T_s and θ measured at long term soil hydrology stations installed at the study sites, the total annual R_{eco} for one year was modeled and calculated for a unit area at each site. Time series data of environmental conditions at five-minute intervals were input into the empirical model for R_{eco} and the resulting fluxes were summed for the year (Figure 7, Table 4)

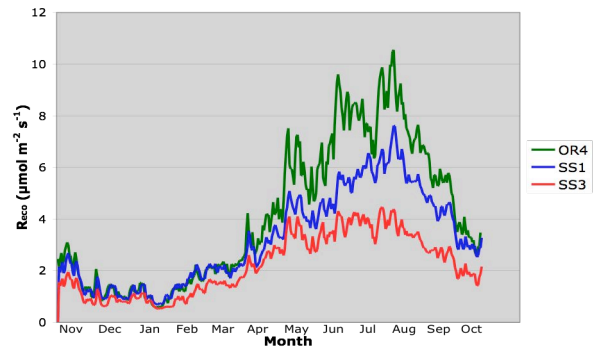


Figure 7: Time trace of modeled R_{eco} at OR4 (frequent, automatic irrigation), SS1 (regular, manual irrigation) and SS3 (no irrigation) at 5-minute intervals from November 1, 2007 to October 31, 2008.

Table 4: Total Annual R_{eco} (Nov 1/07-Oct 31/08)

Site	Total Annual R_{eco} (g C m ⁻² yr ⁻¹)
OR1	1302
OR2	1790
OR3	1467
OR4	1498
SS1	1177
SS2	968
SS3	810
SS4	949
WI	1131

The average total for R_{eco} at urban sites was $1286 \text{ g C m}^{-2} \text{ yr}^{-1}$, with sites in the 'Oakridge-Vancouver' neighbourhood producing an average of $1423 \text{ g C m}^{-2} \text{ yr}^{-1}$ and 'Sunset-Vancouver' locations having average totals of $1149 \text{ g C m}^{-2} \text{ yr}^{-1}$. A similar magnitude of soil CO_2 efflux ($1113 \text{ g C m}^{-2} \text{ yr}^{-1}$) was established by Koerner and Klopatek for residential land use in the Phoenix metropolitan region (2002). As expected, with similar average annual soil temperatures across all urban sites (see Table 1), the more intense irrigation and management in the Oakridge neighbourhood produced greater total flux from the lawns. When site-specific parameters for E_0 and R_{ref} are used for modeling, the differences in θ produced in summer by management dominates inter-site differences in response to environmental conditions (Figure 8).

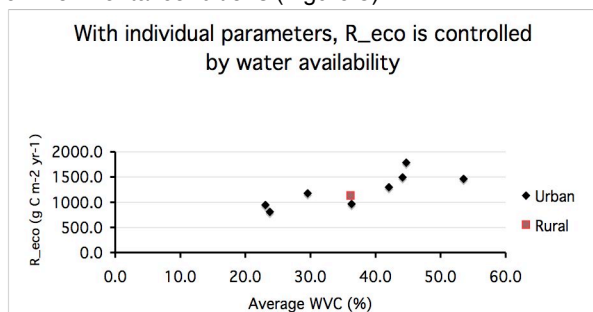


Figure 8: Annual total of R_{eco} for a unit area. Note the increased respiration as a response to higher average θ .

5. CONTRIBUTION OF R_{ECO} TO TOTAL URBAN NEE

All urban R_{eco} measurement sites were within the footprint of eddy covariance towers measuring neighbourhood-scale flux densities of CO_2 . Nighttime CO_2 flux densities in summer are expected to reflect a primary contribution from soil respiration, due to minimal anthropogenic contributions from traffic and/or space heating and the absence of photosynthesis at night. The average diurnal course of both Urban NEE (based on eddy covariance measurements) and flux of CO_2 from lawns over a 10-day clear-sky period from July 15-24, 2008 is shown in Figure 9.

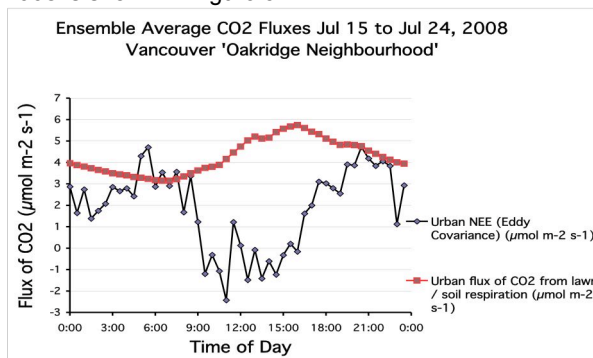


Figure 9: Ensemble averages of Urban NEE and R_{eco} contribution for a 10-day period in July 2008.

Based on a calculated fraction of land cover in the Oakridge Neighbourhood classified as lawn surface (56%), the modeled efflux of R_{eco} based on measured traces of T_s and θ was scaled to produce the total contribution to urban carbon fluxes. The average contribution of R_{eco} ($\sim 3\text{-}6 \mu\text{mol m}^{-2} \text{ s}^{-1}$) was indeed consistent with the measured nighttime tower fluxes. This suggests that lawn respiration can be identified as a dominant process in controlling CO_2 fluxes in this setting during summer.

6. CONCLUSION

Management of urban lawns leads to a unique set of environmental conditions that affect the efflux of CO_2 by grass, roots and soil microorganisms into the urban atmosphere. Analysis of measurements of ecosystem respiration on residential lawns in two suburban neighborhoods in Vancouver, Canada showed that soil temperature and moisture are major controls on the magnitude of CO_2 efflux, and that this relationship can be modeled reasonably when these factors are known. T_s was established as a dominant control on R_{eco} from urban lawns, especially in the absence of soil moisture limitations due to irrigation, exceeding the influence of θ by 5 to 20 times. Certainly, the elevated soil temperatures associated with the urban heat island effect enhance the efflux of biogenic CO_2 , which is established to be significant in regulating urban CO_2 fluxes in the summer.

While the low-moisture limitation imposed on R_{eco} may suggest that restricting irrigation may be an effective strategy to minimize contribution of biogenic CO_2 to the urban carbon balance, it is important to recognize the role of water availability in supporting photosynthesis, and the potential importance of sequestration by urban turfgrass in determining CO_2 fluxes. Further investigations of the relationship between environmental factors and urban biogenic carbon fluxes will improve understanding of how urban greenspace can be optimally managed to improve carbon sequestration. Measuring and modeling Net Ecosystem Exchange can give a more complete picture of the effects of management regimes, while incorporating the effects of time changes in Leaf Area Index will likely improve the performance of this empirical model.

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