SURFACE-ATMOSPHERE CO_2 EFFLUXES FROM URBAN TURFGRASS AREAS, SINGAPORE

NG JUN LONG BERNARD
(B.SocSci (Hons), NUS)

A THESIS SUBMITTED FOR THE DEGREE OF
MASTERS OF SOCIAL SCIENCE (RSH)

DEPARTMENT OF GEOGRAPHY
NATIONAL UNIVERSITY OF SINGAPORE
2013/2014

Declaration

I hereby acknowledge that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

____

Ng Jun Long Bernard

15 August 2013

Acknowledgements

O Lord, our Lord, how excellent is thy name in all the earth!

Psalms 8:1

I'm truly thankful to my supervisor, Prof David Higgitt, for giving me this opportunity to embark on and finishing my Masters degree. This thesis would not have been possible without his help and supervision. I'm greatly appreciative of the faith and trust he has in me to finish my tasks, while seeking out opportunities for me to share my work with others.

To the wonderful minds at CENSAM-SMART, Prof Charles Harvey, Dr Alex Cobb, and Dr Kai Fuu-Ming, who were my mentors and supervisors, yet treated me as a colleague and friend. I have benefited immensely from their guidance and support they have provided. Special thanks goes out to Dr Laure Gandois, who introduced me to the project, the team and for being my unofficial supervisor, I'm greatly thankful for the close guidance and academic support she has provided me from formulating my thesis, fieldwork and proof-reading my thesis, always looking out for ways for me to better present my work. To Dr Lucy Hutyra, I'm extremely grateful for the equipment, advice and wanting to bring the little that I have done further. I'm indeed blessed by the opportunity to have met and work with all of them. For such brilliant and busy people, they all have tremendous patience to provide guidance to me.

I would also like to take this opportunity to convey thanks to the administrative staff at the NUS Geography Department. Special thanks go to Ms Pauline Lee for her help with student administrative matters and Mr Tow Fui for his assistance in obtaining equipment and reagents necessary for the running of the experiments, freeing me to concentrate on my work.

Ms Michelle Quak and Mr Cliff Chew, have deserve great respect amongst my peers, for having spent much time and effort assisting me with my laboratory work, statistical analysis and proof-reading; and in doing so challenging my work and thinking. To Ms Betty Chang and Ms Rachael Lee, I'm thankful for helping me read through and improve my early drafts.

To my strongest supporter Ms Teo Sork Chin, who has been an enormous source of encouragement and emotional support, providing aid in both salient and inconspicuous ways. I would also like to thank my family members for the encouragement they have offered, especially my mom and dad who were patient and supportive during my entire candidature.

Ng Jun Long Bernard
10 August 2013

Table of Contents

List of Tables

List of Figures

List of Equations

Summary

Urban green spaces are appreciated for their amenity value; with increasing interest in the ecosystem services they provide (e.g. climate amelioration and increasingly as possible sites for carbon sequestration). In Singapore, turfgrass occupies approximately 20% of the total land area and is readily found on both planned and residual spaces. This project aims to understand carbon fluxes in tropical urban green areas, including controls of soil environmental factors and the effect of urban management techniques. Given the large pool of potentially labile carbon, management regimes are recognised to have an influence on soil environmental factors (temperature and moisture), which in turn affect soil respiration and feedbacks to the greenhouse effect.

A modified closed dynamic chamber method was employed to measure total soil respiration fluxes. In addition to soil respiration rates, environmental factors such as soil moisture and temperature, and ambient air temperature were monitored for the site in to evaluate their control on the observed fluxes. Measurements of soil-atmosphere CO_2 exchanges are reported for four experimental plots within the Singtel-Kranji Radio Transmission Station (103^{o}43'49E, 1^{o}25'53N), an area dominated by *Axonopus compressus* as grass cover. Different treatments such as the removal of turf, and application of clippings were enforced as a means to determine the fluxes from the various components (respiration of soil and turf, and decomposition of clippings), and to explore the effects of human intervention on observed effluxes.

The soil surface CO_2 fluxes observed during the daylight hours ranges from 2.09 ± 0.95 µmol m^{-2} s^{-1} for the bare plot as compared to 8.54 ± 1.80 µmol m^{-2} s^{-1} for the turfed plots; this could be attributed to both autotrophic and heterotrophic respiration. Controls by both soil temperature and soil moisture are observed on measured soil fluxes to varying strengths for the different plots. Turfed plots were more sensitive to temperature increases as compared to bare plots. Effluxes had a polynomial relationship with soil moisture, though it was not possible to identify the possible cause.

Understanding how landscape management strategies and environmental conditions influences the rates of effluxes over urban green areas would allow us to gain appreciation and quantify their carbon sequestration potential; and potentially influence landscape policy in tropical urban areas.

Keywords: CO_2 effluxes, Soil respiration, Closed-Dynamic Chamber, Landscape Management, Environmental influence

1. Introduction

1.1. The Carbon Cycle and Urbanisation

The starting point of the land based carbon (C) cycle begins when plants photosynthesise CO_2 from the air into organic C compounds. These organic compounds are assimilated into plant tissues in the leaves, stems and roots during growth and are also used for metabolic reactions such as respiration. Dead plant materials are broken down by microorganisms to provide energy for microbial growth amongst other activities. Both microbes and the decomposition process releases carbon dioxide which contributes to soil fluxes in the form of heterotrophic respiration (Figure 1).

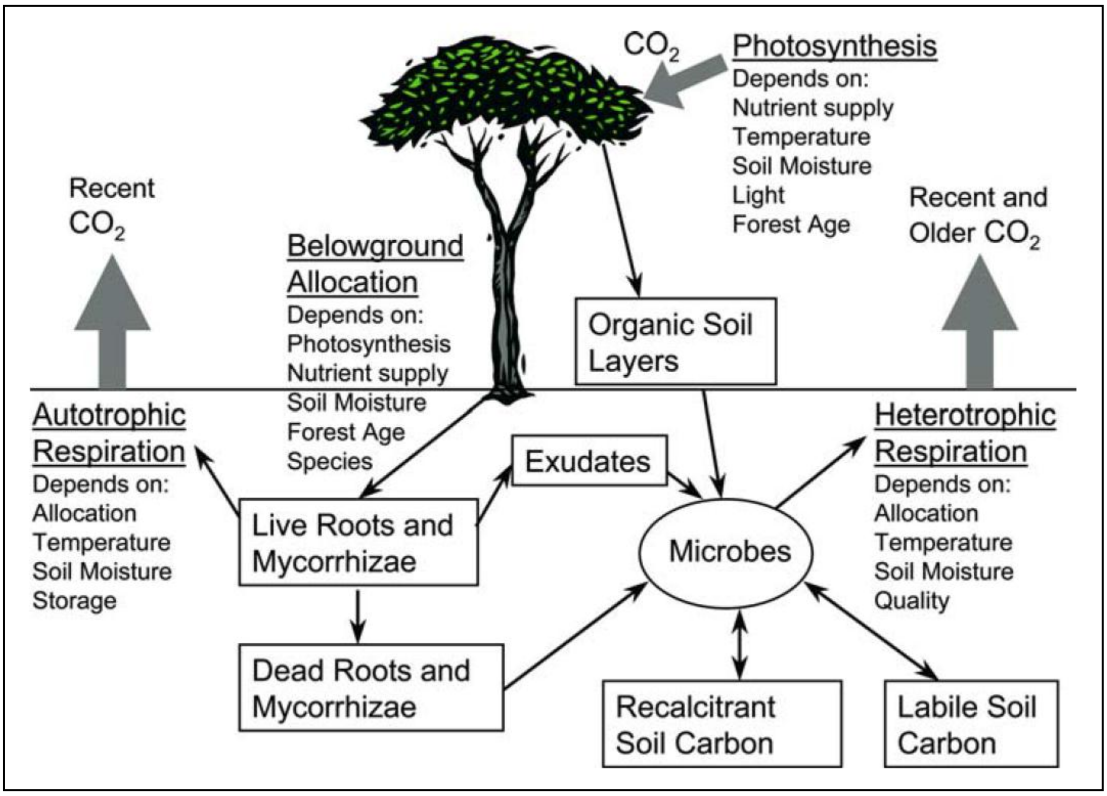

Figure 1: Conceptual model of components and responses of CO_2 efflux from soil (Ryan & Law, 2005)

Current observed trends on the C cycle are associated with the level of urbanisation (Prentice, et al., 2001). The C cycle is influenced by modifications of existing fluxes, which result due to changes in the C stock due to alterations in land use, and increased emissions from anthropogenic activity. Modification of the physical properties of the land surface (Lamptey, et al., 2005; Diffenbaugh, 2009), affects biochemical functions, resulting in feedbacks to the regional and global C cycle. Although urbanization influences many components of the C cycle including the soil carbon content, methane efflux and infiltration, this study will focus on carbon dioxide (CO2) efflux from urban green areas.

Globally, the urban rate of expansion is estimated to be 20 000 km^2 per year (Holmgren, 2006), Southeast Asia has annual urban population growth rate of 1.7-5.6% between 2005 and 2010, which is close to three times of an expected global rate of 1.9% (United Nations, Department of Economic and Social Affairs, 2011). With increasing areal extent and importance of urban areas in economic and social fields of studies, their environmental effects should be considered. Urban areas are able to strongly influence C cycles from local to global scales through their gaseous emissions (Lal, 2012). Thus it is imperative that we consider the effects of the Southeast Asian urban landscape and its associated soil effluxes.

1.1.1. Significance of study to Singapore

Amongst the Southeast Asian cities, Singapore has been highly recognized for its successful urban development and environmental management (Savage & Kong, 1993). Singapore has a land area of 715.8km^2 with a population density of 7422 persons/km^2, making it one of the densest cities in the world. Despite the high population density and urbanized area, Singapore has managed to increase the amount of green cover from 36% to 47% of the total land area (National Parks Board, 2008) – Figure 2Figure 2. Green areas in Singapore includes public parks, golf courses and farms in addition to four Nature Reserves, two National Parks, a network of 100km of park connectors and 24.16km^2 of roadside plantings and 320 public parks (National Parks Board, 2008). Despite the generous definition of what characterises green areas in Singapore, turf remains the dominant vegetation cover of green areas in Singapore.

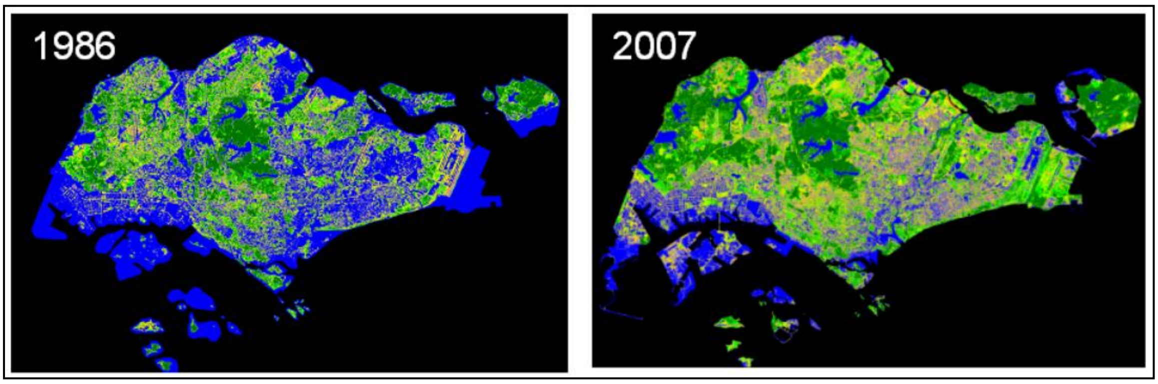

Figure 2: Green Cover in Singapore (CRISP, 2007; in National Parks Board, 2010) Areas in green represent the extent of green cover, yellow the hard/concrete features and blue the areal extent of Singapore.

Singapore's appreciation of the importance of green areas took place early in her development, through campaigns such as Plant-a-Tree day and the Clean-and-Green campaigns. Initially the purpose of these campaigns was not for the ecosystem services that green spaces provides but rather, it was for the aesthetic value it affords (Tan, et al., 2009). With increasing recognition of the ecosystem services which green areas provide, Singapore has taken steps to test existing and new strategies for the adoption of green spaces in tropical urban cities (Singapore Economic Development Board, n.d.). The establishment of green areas in the city-state is in tandem with its approach of tightening its carbon emissions and reducing per capita C intensity. Singapore has attempted to reign in its CO_2 emissions in recent years and will continue to strive to reduce emissions by 7-11% below 2020 business as usual (BAU) levels, this is despite a significant increase in population, economic and other industrial activities (National Climate Change Secretariat, 2012).

Singapore aims to reduce her Green House Gas (GHG) emissions through 1)Increasing energy efficiency; 2)Using less C-intensive fuels and 3)Increasing C ‘sinks’ by planting more trees and conserving large C sink areas such as mangroves and forests (National Climate Change Secretariat, 2008); with a the strong emphasis on increasing energy efficiency. There lies great potential for Singapore and other tropical cities to significantly mitigate anthropogenic CO_2 emissions, as the region is evergreen, providing a substantial C sink (Falge, et al., 2002). Thus urban vegetation could prove to be an effective means of reducing atmospheric C through C sequestration.

Although there have been measurements of the CO_2 emissions, these have been done on a land cover scale, through the use of eddy covariance and a host of other methods. In Singapore, Velasco et al (2013) calculated the contribution of the individual fluxes using bottom up approach and concluded that urban green areas in a suburban setting had a significant uptake of CO_2 and only reduces the total C footprint by 0.4%. This study adds to the existing literature by providing direct measurements for urban turfgrass areas under varying management regimens and also reporting the temperature sensitivity for such area where it has yet to be fully accounted for.

1.2. Soil Respiration: Its Importance and Definition

Soils are defined as the mixture of dead organic matter, air, water and weathered rock that supports plant growth (Buscot, 2005). In an urban context, they include soils which are strongly influenced by human activities (Lehmann, 2006). Soil respiration and soil effluxes are crucial for understanding the earth's systems functions as the two processes play a fundamental role in regulating atmospheric CO_2 concentration and climate dynamics. Soil respiration is the major pathway for the release of C from the soil to the atmosphere; releasing approximately 68-75 Pg C per year globally (Raich & Schlesinger, 1992; Raich & Potter, 1995), accounting for approximately 80% of total ecosystem respiration (Goulden, et al., 1996; Longdoz, et al., 2000). To better understand how climate change would influence and impact the global C cycle and climate system, it is imperative that we comprehend the processes of soil respiration and how it responds to environmental change.

Soil respiration (as defined for this study) is the CO_2 efflux, which is observed from the surface of the soil that does not stem from autotrophic components. On the contrary, Davidson, et al. (2000), Ryan and Law (2005) and Zhao, et al., (2013) have defined soil respiration to include fluxes by root processes. However, soil respiration should be separate from autotrophic components to ensure no complication of terms when analysis is done to calculate the contribution of heterotrophic and autotrophic components as in Chapter 5.1.

The instantaneous rate of CO_2 efflux is controlled by the rate of soil respiration and transport of CO_2 along the soil profile and at the surface. CO_2 transport is influenced by the CO_2 concentration gradient between the soil and the atmosphere, soil porosity, pressure differences and wind speed amongst other variables. At steady state, the CO_2 efflux rate at the soil surface would equal the rate of CO_2 production in soil; as such soil CO_2 efflux is almost equivalent to soil respiration and the two terms are thus employed interchangeably. However, there are situations in which the rate of CO_2 production may not be at steady state with the rate of CO_2 transport as observed CO_2 efflux varies with soil temperature, root activity, and substrate supply (Davidson, et al., 1998) (Chapter 2.2). Due to the complexity involved in accounting for the production of CO_2 beneath the surface of the soil, CO_2 efflux measurements which are made at the surface of the soil are taken to be representative as the rate of production. The measurements are indicative of both the production and transportation of CO_2 through the soil matrix rather than the respiratory flux itself.

In light of the challenge of climate change and the contribution of soil respiration to the global C cycle, efforts dedicated to it should no longer be seen as a purely academic pursuit; rather its study has broad relevance to academics and government officials (Luo & Zhou, 2006). CO_2 emissions from the soil can also be used as an early indicator for C sequestration (Fortin, et al., 1996; Grant, 1997) as it is used in C flux calculations. The possibility of future global carbon-trading markets and the need for better carbon emission models, make it necessary for us to identify and understand the factors which control soil respiration to attain a predictive understanding of soil respiration.

1.3. Aims and Objectives

This study was designed to examine the effects of landscape management practices (such as the presence/absence of turf and turf clippings) and environmental factors (soil temperature and moisture) on respiratory fluxes in a tropical urban turfgrass ecosystem. Measurements of soil effluxes were made using the Closed Dynamic Chamber (CDC) method in the experiments. The experimental manipulation of the site allowed for the accounting of respiratory fluxes from the different components (autotrophic and heterotrophic) and the measurement of soil temperature and moisture, which varies in response to weather conditions. This was done to understand the contributing fluxes of the different components found in turfed areas and test the following hypotheses:

> H1. Landuse and management of urban green areas have a significant influence on soil CO_2 efflux rates.
>
> > H1a. Turfed plots would have significantly higher soil efflux rates compared to bare plots, due to autotrophic respiration.
> >
> > H1b. Addition of clippings would result in a significant increase of soil effluxes, as it would be a source of decomposable material and thus heterotrophic respiration.

H2. Environmental factors would influence the rates of soil CO_2 efflux across all the experimental plots

H2a. There is an exponential relationship between soil temperature and soil CO_2 effluxes as temperature increases is expected to increase both metabolic and chemical reactions.

H2b. There is a polynomial relationship between soil moisture and soil CO_2 effluxes as moisture is necessary for most metabolic and chemical reactions to take place, while in excess would result in anaerobic conditions.

H2bi. Wetting/drying would cause a significant change in the observed rates of soil efflux due to the change in soil moisture conditions which could initiate biochemical responses of the soil and microorganisms.

1.4. Overview of Paper

This paper consisting of six chapters is dedicated to providing an understanding of soil respiration in tropical equatorial urban green areas while taking into consideration the effect of human influence and the environmental factors to soil CO_2 efflux. Chapter 2 gives a literature overview of the importance in accounting for soil-atmosphere CO_2 effluxes in urban green areas, its contributing components, influencing factors and the variations and challenges to accounting for this gaseous transport; thus laying the foundation for understanding the context of the study and the importance of the sampling and experimental method. In Chapter 3, the experimental and sampling methods are described in detail. Chapter 4 describes and discusses the effects of human influences, namely application/removal of turf and clippings and the effect of environmental influences. Chapter 5 draws upon current understandings and draws new conclusions with regards to the data collected. Chapter 6 concludes the thesis by providing policy recommendations in relation to future climate scenarios and how we can better improve policy and climate modelling recommendations.

2. Literature Review

This chapter presents the main concepts behind the motivation for the work, namely 1)the importance of urban areas, 2)soil respiration and its influences, and 3)methods of soil-atmosphere measurements; highlighting the complexity involved in accounting for C effluxes.

2.1. Urban Areas

Anthropogenic driven land use conversion from natural ecosystems to agricultural and urban landforms is a significant component of global change. More than half of the world's current population resides in urban areas and this proportion is expected to increase to approximately 70% by 2030 (United Nations, 2006). Land use conversions are often at the expense of degrading the environment (Foley, 2005). Modifications of the physical properties of the land surface (Lamptey, et al., 2005); result in changes to the energy (Oke, 1988) and water balance (Foley, 2005).

The importance of ecosystem services that urban green spaces provide is witnessed through the incorporation of green measures to counter the urban heat island effect, increase storm water infiltration and restore ecological function (Tzoulas, et al., 2007; James & Bound, 2009). Although turfed landscapes result in milder environmental consequences as compared to tarmac, it still represents a significant change in the energy budget at the surface-atmosphere interface (Savva, et al., 2010), witnessed in the difference of microclimate and hydrology over urban areas (Carlson & Arhur, 2000). With the mounting attention on urban areas being sources of CO_2 emissions (Churkina, 2008), green areas located within urban areas are increasingly being studied for their ability to mitigate anthropogenic C emissions (Dhakal, 2010).

Urban green areas (which include lawns, fields, golfing greens and parks) are increasingly being considered possible sites for C sequestration as atmospheric CO_2 is stored as plant biomass during photosynthesis and parts of the biomass are humified and stored in the soil as soil organic carbon (SOC) during decomposition (Fontaine, et al., 2007). The presence of turf also influences the rate of nutrient, C and N cycling. Consequently, land use, plant and soil management practices influence the rate of C sequestration (Pouyat, et al., 2006), with lawns having shown to sequester C at relatively high rates (Gebhart, et al., 1994; Conant, et al., 2001; Qian & Follett, 2002; Qian, et al., 2010); it appears that green spaces are indeed the panacea for the negative consequences of urban areas. However, there is still much to be understood in relation to the gaseous exchange of urban green areas which have an important role in determining the C budget and subsequently the C sequestration potential of such sites.

In light of this, an understanding of respiratory fluxes in tropical urban areas is vital. Tropical soils are of paramount importance as they could hold the key to short term C fluxes due to their high year-round temperatures and moisture availability (Townsend & Vitousek, 1992; Raich & Potter, 1995). Such knowledge could lead to better climate models and would improve our appreciation of urban green spaces.

2.1.1. Why tropical urban green areas

Tropical vegetation is evergreen and therefore has a larger potential for CO_2 assimilation in comparison to boreal and temperate landscapes (Velasco, et al., 2013). However, most of the C sequestration potential for green spaces has taken place in temperate climates, leaving much potential for similar studies to be conducted in a tropical context. Turf grass has been shown to be a C sink (Milesi, et al., 2005; Golubiewski, 2006) in relation to the high NPP of turfgrass (Wu & Bauer, 2012). In conjunction with studies that elucidate the high C storage of urban trees (Nowak & Crane, 2002); green areas within urban landscapes should be given greater attention.

In comparison with adjacent natural and agricultural areas, urban areas are often found to have higher C densities (Kaye, et al., 2005), as a result of the higher C cycling that is found in urban turfgrass as compared to other vegetation types (Wu & Bauer, 2012). Higher values may also be due to the result of enhanced management practices of irrigation, fertilisation and the stimulating effects of clipping on turfgrass (Wu & Bauer, 2012), and the exposure of modified environmental factors such as elevated air and soil temperatures (Wan, et al., 2002; Klein, et al., 2005) coupled with increased fertilisation and irrigation, which could increase species diversity; modifying rates of sequestration (Nowak & Crane, 2002; Crawford, et al., 2010). Thus, in order to fully appreciate the potential C sequestration potential from turfgrass areas, we would need to assess the magnitude of soil respiration (Pouyat, et al., 2006) and C emissions due to landscape management related activities (Jo & McPherson, 1995; Townsend-Small & Czimczik, 2010a; 2010b).

2.1.2. Evaluation of anthropogenic influence of turf and clippings

The main type of grass cover in Singapore is cowgrass (*Axonopus compressus*) as it does not require high maintenance (National Parks Board, 2009). Land use practice has a profound impact on C cycles (Quested, et al., 2007) in terrestrial ecosystems, and has the ability to significantly modify soil environment factors of temperature and moisture (Wan, et al., 2002; Klein, et al., 2005). Planning decisions for space in urban areas are highly influential and extend beyond having turfed or bare surfaces, it would also influence the management practices that take place when green spaces are adopted and consequently the soil C content (Conant, et al., 2001).

Grass clipping has traditionally been removed from residential lawns and other managed turfgrass areas, bagged and deposited in landfills. There are innovative solutions to dispose of our grass clippings and other organic wastes - such as using them to power boilers for cooling purposes (e.g. Gardens by the Bay conservatory domes) (Halperin, 2012). The simplest method and one often prescribed is to leave them onsite as they provide a source of slow release nitrogen (N) (Kopp & Guillard, 2002). The presence or absence of turf and clippings would result in a change of the biophysical conditions through the modification of substrate supply, N deposition and fertilisation, which directly and indirectly influence the associated soil respiration rates. The rate of CO_2 production by micro and fauna in relation to the immobilisation and/or mineralisation of nutrients are affected by temperature, moisture availability, and the quality and supply of decomposable substrate material.

2.2. Soil Respiration

Soil respiration is an important C flux to be considered as it is an intrinsic part of the C cycle and is associated with nutrient linked processes of decomposition and mineralisation. It may occur at a larger magnitude than anthropogenic C emissions (Raich & Schlesinger, 1992). To model them and make accurate climate predictions would require keen knowledge of the influencing factors. Soil efflux measured at the surface of the soil (Equation 1) can be considered to the respiration of all organisms per unit area, also known as ecosystem respiration (ER), it comprises of both plant (autotrophic) and microbial (heterotrophic) respiration. Plant respiration (R_p) (Equation 2) is differentiated into aboveground respiration (R_a) and belowground respiration (R_b); with belowground plant respiration often assumed to be similar to root respiration.

Equation 1: Efflux Rate on the surface (ER)

$$ER = R_p + R_m$$

Equation 2: Plant Respiration (R_p)

$$R_p = R_a + R_b$$

Due to the difficulty in separating the different components of the flux practically, especially between R_b and R_m, this dissertation adopts the notion that soil respiration is devoid of all autotrophic activity and would thus be equivalent to heterotrophic respiration. Besides the practical difficulty of separating the contributing flux of autotrophic and heterotrophic respiration, a major component of soil respiration is from heterotrophic activity of microbial activity. The importance of CO_2 effluxes from soils has serious implications for climate change scenarios as an increase in temperatures could lead to an increase in soil effluxes regardless of the difference in temperature sensitivity of soils from different climes and vegetation types (Luo & Zhou, 2006). As such, the global climate cycle and C cycle are intimately linked to each other in a positive feedback loop (Cox, et al., 2000; Friedlingstein, et al., 2003). However, acclimatisation of plants could have a balancing effect through increased growth as a result of higher temperatures and CO_2 concentration (Luo, et al., 2001; Taub, 2010)(Figure 3).

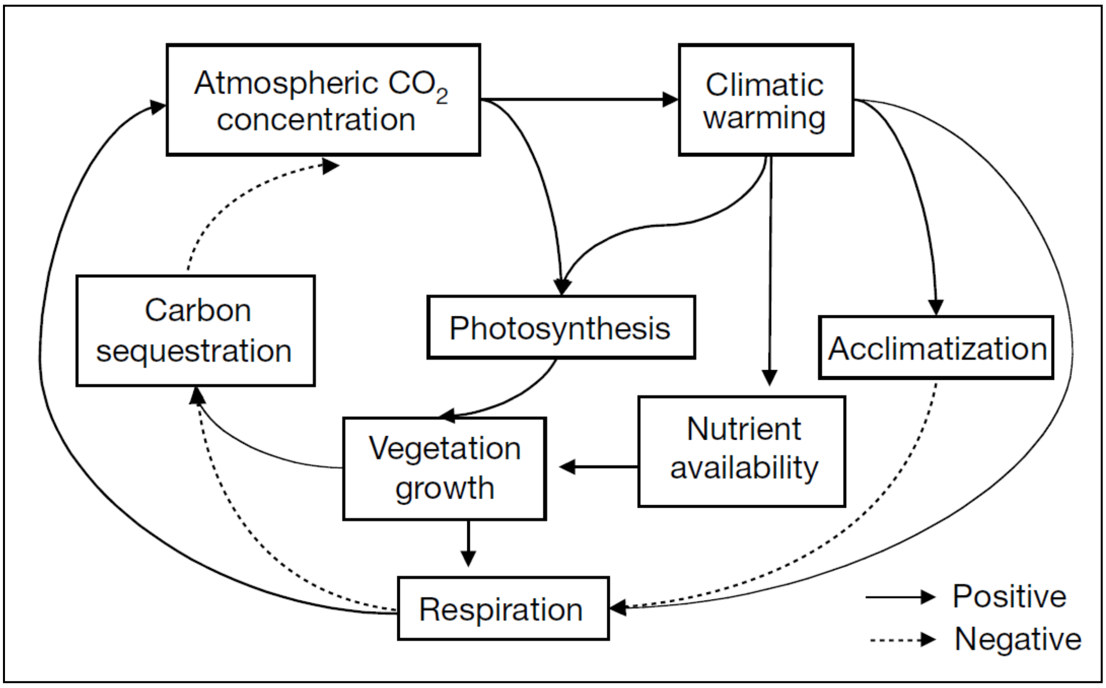

Figure 3: Schematic diagram of possible feedbacks in a coupled-climate carbon cycle system (Luo, et al., 2001)

The effect of soil respiration and other surface-atmosphere effluxes on climate change cannot be understated. Conversely, climate change is able to influence these very effluxes through the modification of temperature and precipitation.

2.2.1. Autotrophic respiration

The autotrophic contribution to soil respiration is approximately 50% (Trumbore, 2006) with root respiration accounting for between 10-90% of the flux (Hanson, et al., 2000). Root respiration rates reflect the diverse energy needs of plants due to a multitude of processes, including 1)biosynthesis of new structural biomass, 2)translocation of phtotosynthate, 3)uptake of ions from soil, 4)assimilation of N and sulphur into organic compounds, 5)protein turnover, and 6)cellular ion-gradient maintenance (Luo & Zhou, 2006). Root respiration is the combination of both vegetation and environmental conditions, with a vast difference in the contribution of root respiration to total soil respiration fluxes as a result of differences in root biomass and specific root respiration rates (Norman, et al., 1992; Dugas, et al., 1999; Bond-Lamberty, et al., 2004). Other than the direct contribution of CO_2 through respiration, plants also temper the temperature and moisture conditions experienced by the ecosystem and consequently play a role in the quantity of the soil efflux.

2.2.2. Heterotrophic respiration

Heterotrophic respiration has a positive relationship with the presence of biomass available for decomposition (Wang, et al., 1999) and is thus closely related to primary productivity of plants. It is affected by the rate of litter production, litter pool sizes and decomposition process. The production of plant detritus is a key mechanism controlling soil respiration rates (Raich & Tufekcioglu, 2000). Root turnover is the other significant source of detritus in numerous ecosystems and contributes between 10-56% of labile material (Gill & Jackson, 2000). Plant growth and microbial activity are co-dependents and are linked processes with soil respiration. Autotrophs control the heterotrophs mainly through the C supply (Zak, et al., 1994) while microbial activity controls plant growth through influence on nutrient availability (Raich, et al., 1997; Reich, et al., 1997). The frequency and decision to remove clippings would also alter the amount of CO_2 produced in and on the surface of the soil as a result of modification to the labile material available.

Landscape management has a sizeable impact on the C pool and flux of terrestrial ecosystems, as they can drastically modify C and N cycles (Quested, et al., 2007), modify Net Primary Productivity (NPP) (Luo, et al., 2009) and soil plant C substrate input (Wan & Luo, 2003). Likewise, the modification of soil environmental factors of temperature and moisture and also affects C effluxes (Wan, et al., 2002; Klein, et al., 2005). While autotrophic and heterotrophic respiration are the two main biological processes which drive CO_2 effluxes on the surface, landscape management practices such as turfing and the removal of mowed clippings would play a significant role in modifying CO_2 effluxes from urban ecosystems.

2.3. Controlling factors

Environmental factors of soil temperature and volumetric water content are significant influencers of both the rates of production and transport of soil respiration (Lambers, et al., 1998). The influence of environmental factors affects both the biochemical and the physical processes, resulting in conflicting conclusions of the effect of climatic variation on the resultant CO_2 efflux.

2.3.1 Temperature

Increases in respiratory fluxes with temperature are the result of enhanced enzymatic reactions and increased cellular (ATP) requirements. The increased rates of biosynthesis, transport and protein turnover occurring as a result of higher temperatures is reflected thorough the temperature response of both plants and soil (Luo & Zhou, 2006). One of the ways to describe the dependency between temperature and biochemical processes is reflected empirically by the exponential Q_{10} function first introduced by Van Hoff (1899) (Equation 3).

Equation 3: Van't Hoff's (1989) biochemical response to temperature

$$R_s = R_{10} Q_{10}^{\frac{(T_S - 10)}{10}}$$

R_{10} is the specific respiration rate at 10°C, Q_{10} is the increase in respiration rate per 10°C increases in temperature, and T_s the soil temperature in degrees Celsius. In the case of ecosystems, the Q_{10} values reflect the response of multiple factors and process to temperature. The estimated values of Q_{10} can vary from 1 (low sensitive) to more than 10 (sensitive), with high Q_{10} values resulting from the confounding effects of temperature on multiple processes and the co-varying variables of light and moisture (Davidson, et al., 1998; Davidson, et al., 2005).

Soil temperatures are able to influence the rate of CO_2 production as the soil is an organo-mineral matrix, responding biophysically to changes in temperature. The temperature-response of biochemical and physiological functions are generally defined exponentially till it reaches a maximum temperature of 45-50°C (Luo & Zhou, 2006) following which it would decline sharply. An example of the physiological processes depending on temperature is seen in the protoplast system of cool season plants, where at temperatures higher than 35°C, it starts to denature. However, the temperatures for root growth and thus responses vary widely according to taxa, temperature regimes (Kaspar & Bland, 1992), and age of roots (Palta & Nobel, 1989). Temperature also indirectly affects CO_2 effluxes from soils as it influences the diffusion of gases within the soil and across the soil-atmosphere interface. Rates of diffusion are determined by both soil water content and soil diffusivity. It has been found that at any given soil water content, diffusivity increases with temperature (Davidson & Trumbore, 1995).

Rising atmospheric CO_2 concentrations results in elevated temperatures, stimulating soil respiration, and contributing to an enhanced greenhouse effect, resulting in a positive feedback loop in the global C cycle (Cox, et al., 2000; Friedlingstein, et al., 2003). However, the effects of temperature rarely occur independently of other environmental factors under field conditions and co-vary with other factors such as soil moisture content and solar radiation, which also influences the photosynthetic and microbial activity.

2.3.2 Soil Moisture

Soil moisture is the second major factor influencing soil respiration. Moisture is necessary for most biochemical processes to take place as it alters the rate of transportation of CO_2 through the physical process of solution and diffusion of gases in soils. The optimum water content for soil effluxes occurs when moisture levels are near field capacity. This implies that the macropores are air filled, facilitating the gaseous diffusion, whilst the micropores are water filled, allowing diffusion of soluble substrates (Liu, et al., 2002; Xu, et al., 2004). Soil microbial activity or processes of litter decomposition, N mineralisation, nitrification and denitrification are also dependent on soil moisture (Jackson, et al., 1989; Schimel, et al., 1989; Burke, et al., 1997). While laboratory experiments identify the possibility of an optimal water content to soil respiration (Bowden, et al., 1998), there may be a plateau of optimal soil moisture responses to a broad range of soil moisture with steep decreases at either very low or very high moisture content (Figure 4) (Liu, et al., 2002; Xu, et al., 2004).

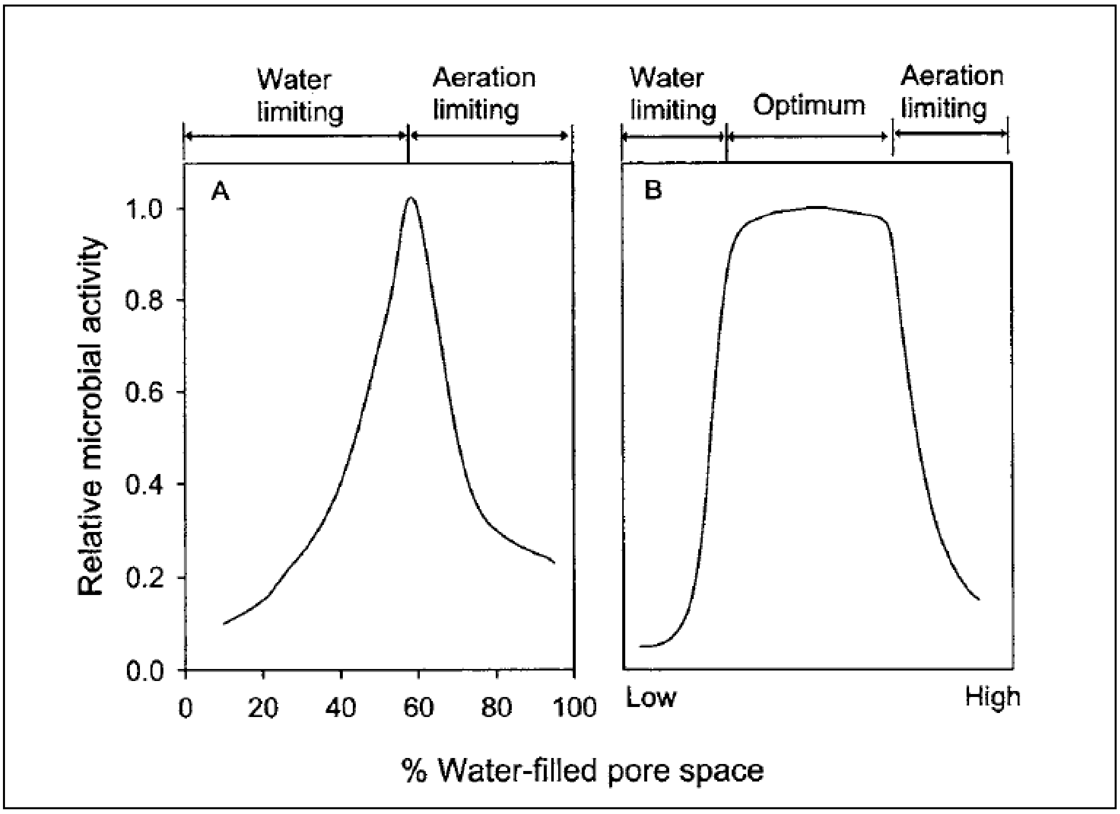

Figure 4: Idealised relationship between soil moisture and microbial respiration, where A represents a possible optimal moisture point and B showing that there is a plateau of optimal soil moisture responses (Luo & Zhou, 2006).

In the absence of human intervention, soil water content depends on rainfall amounts and frequency, as well as soil drainage capacity. During extended periods of drought conditions, microorganisms would reduce metabolic activity, resulting in significantly reduced soil CO_2 effluxes. Rhizosphere activity (autotrophic respiration) which is shown to contribute significantly to total ecosystem respiration would also be affected by low moisture content. Following such dry periods, any addition of water can result in a sudden increase of CO_2 released from the soil as a result of microbial activation (Glinski & Stepniewski, 1985; Liu, et al., 2002; Xu, et al., 2004) and/or increased exposure and availability of organic substrates (Fierer & Schimel, 2003). In contrast, high water content reduces respiratory fluxes as it results in anaerobic conditions which limit the respiratory process of microbial activity. Furthermore, it reduces the diffusion of gases within and out of the soil as the difference between diffusivity of gases between air and water is approximately 10,000 times (Luo & Zhou, 2006), thus inhibiting movement of gases within water-saturated soils.

Due to the complications and the covariance of numerous environmental factors, simultaneous consideration of multiple factors that influence soil respiration and consequently ecosystem respiration are limited. In recognition that factors such as nutrient availability (Raich & Tufekcioglu, 2000), photosynthetic rates (Hogberg, et al., 2001), and the rates of C inputs (Davidson & Trumbore, 1995) are important and covaries with both soil temperature and soil moisture, this study’s experimental method allows for the observation of the effects of these variables as they vary with environmental change.

2.4 Evaluation of Soil-Surface CO_2 Measurement Techniques

Studies accounting for CO_2 fluxes from soils have started from as early as 1926 with Lundegaardh (1926) employing a static closed chamber setup in addition to alkali absorption. Since then, methods for accounting for soil fluxes have evolved rapidly taking into account the challenging nature of CO_2 transport within the porous medium of soil and between the soil-atmosphere interface. Movement of CO_2 within the soil matrix and soil-atmosphere interface is affected by both diffusion and pressure gradients. As such measurement methods have attempted to account for all the possibilities and disturbances which would alter either or both gradients;

acknowledging that distortions to either gradients would result in significant errors (Davidson, et al., 2002).

While there are many limitations of chamber-based systems, they are developed to allow for the direct account of CO_2 efflux from soils (Meyer, et al., 1987; Norman, et al., 1992). The main complications associated with the use of such methods are related to pressure and temperature artefacts (Rochette & Eriksen-Hamel, 2008), a lack of spatial integration and discontinuity of measurement (Flechard, et al., 2007). Furthermore, when used as part of ecosystem measurements, they are limited to low stature vegetation (Ham, et al., 1995; Drake, et al., 1996; Stocker, et al., 1997). Despite the known disadvantages of chamber methods in comparison to eddy covariance (EC) methods, they are able to obtain a high level of agreement between the measurements when landscape and management influence are taken into account (Zha, et al., 2007; Schrier-Uijl, et al., 2010).

Micrometeorological techniques, particularly those involving the use of EC methods offer significant advantages for the quantification of net gas exchange rates such as the continuous quantification of landscape-scale temporal variability (Aubinet, et al., 2000). However, due to their dependence on turbulence, they are less accurate during periods of low wind speed and turbulence (Dore, et al., 2003). They are best employed in areas of homogeneity or when net measurements of ecosystem fluxes are of importance to the study.

2.4.1 Comparison between different measurement techniques

To cope with the difficulties in accounting for effluxes from soils, numerous chamber measurement methods have been developed to overcome the challenges, thus resulting in less biased measurements. The main considerations with regards to the use of chamber techniques are 1)soil disturbance and compaction due to chamber placement (Matthias, et al., 1980); 2)modification of moisture and temperatures under the chamber; 3)modification of CO_2 concentration gradients under chamber headspace (Healy, et al., 1996); 4)modification of soil-atmosphere pressure differences (Rayment & Jarvis, 1997); and 5)pressure difference within and outside the chamber (Matthias, et al., 1980; Rochette, et al., 1997).

As a result of the numerous concerns regarding the use of the chamber methods, commercial and off-the-shelf solutions attempt to address most of these concerns in one way or another. Despite the many possible features that different users and producers of chamber systems may use, they vary only slightly across the different operating principles, namely the Closed Dynamic Chamber (CDC), Closed Static Chamber (CSC) and Open Dynamic Chamber (ODC). Dynamic chambers allow for the circulation of air between the chamber and the measurement sensor in comparison to static chambers where circulation is absent. Open and closed chambers differ in that the ODC methods are continuously ventilated as compared to allowing CO_2 concentrations to rise without ventilation in the case of CDC chambers (Figure 5).

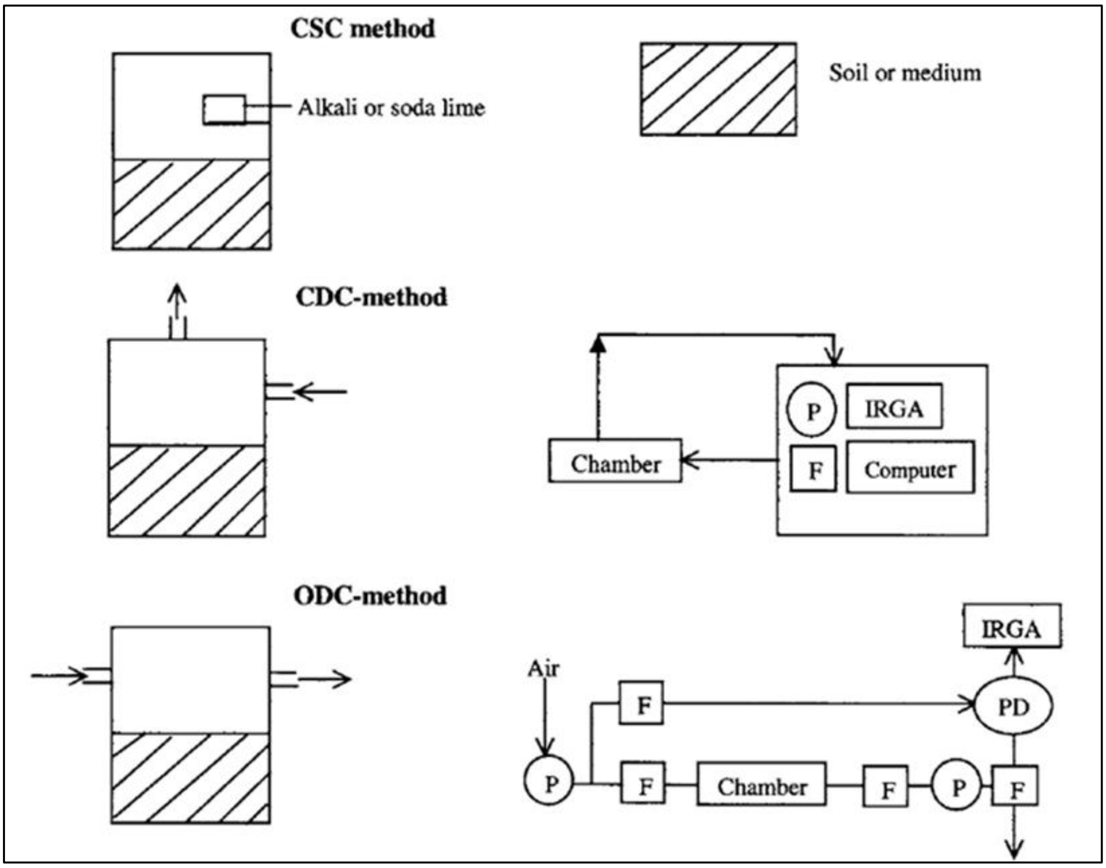

Figure 5: Conceptual model showing the differences between the three methods of measuring CO_2 efflux (Luo & Zhou, 2006)

2.4.1.1. Closed Static Chamber (CSC) Method

Closed static chamber techniques were the first systems to be utilised in attempting to account for soil fluxes. It involves enclosing an area of soil within a chamber utilising a chemical absorbent to absorb CO_2 molecules within a fixed period of time. This method is known as the non-flow through chamber technique, since the chamber is closed with no air flow, except CO_2 releases from the soil. The driving concept behind the methodology is Fick's law of diffusion, and relies on chambers being installed for a significantly long period of time such that the rate of diffusive transport from the soil is equivalent to the rate of production (Rayment & Jarvis, 2000).

The rate of CO_2 absorption is rarely in equilibrium with the surface efflux rates, leading to many potential errors in measurements. The CSC method tends to overestimate the soil CO_2 efflux during low effluxes and underestimates during high effluxes (Nay, et al., 1994). The use of chemical absorption could also be a contributing factor in the alteration of concentration and pressure gradients known to be present with the CDC system. However, when CSCs are well designed and installed it is possible for CSC methods to produce results quantitatively similar to a CDC (Davidson, et al., 2002; Keith & Wong, 2006). Despite the obvious issues associated with pressure difference, soil-atmosphere gradients, effectiveness of alkali absorption over time and the introduction of microclimate changes due to long incubation period, CSC continues to be utilised (Bowden, et al., 1993) in view of its ease of use and relatively low cost (Raich, et al., 1990).

2.4.1.2. Closed Dynamic Chamber (CDC) Method

The CDC method is able to account for soil effluxes through the enclosing of an area of interest, circulating air between the chamber and an Infrared Gas Analyser (IRGA) during measurement periods. The rate of CO_2 efflux is calculated through the rate of increase in CO_2 concentration in the chamber; it is assumed that the rate of increase is proportional to the rate of efflux, *ceteris paribus*. The rate of increase is measured from the linear of the slope of the concentration measured at the starting and ending points.

As CO_2 builds up within the chamber, it acts to modify both diffusion (Gao & Yates, 1998; Davidson, et al., 2002) and pressure gradients (Healy, et al., 1996; Gao & Yates, 1998) between the soil and atmosphere. Pressure equilibrium between the air in the chamber and the surrounding air could be maintained by a tube or relief vent (Bain, et al., 2005) as seen with the LiCor 6400-09 chamber system. To reduce the problems associated with diffusion gradients, chamber CO_2 concentration should not be allowed to rise too far above ambient CO_2 concentration, otherwise the flux would be underestimated due to a reduction of the diffusion gradient (Welks, et al., 2001). Soil CO_2 efflux can be obtained in about 1-5minutes (Luo & Zhou, 2006). Air within the chamber system is mixed in the chamber using a diaphragm air sampling pump which circulates air through the chamber at a certain flow rate, depending on the chamber design. Air is usually withdrawn from the top of the soil chamber, passes through the IRGA and re-enters from the bottom.

2.4.1.3. Open Dynamic Chamber (ODC) Method

In contrast to the CDC, which uses the increase in concentration gradients within a chamber to account for soil efflux, the ODC method uses the difference in CO_2 concentration of ambient air entering the chamber and enriched air exiting the chamber to calculate the rates of respiration, under the assumptions that rates of respiration and air flow through the chamber are constant.

One of the advantages of the open system is that it allows for continuous measurements to be made over an extended period of time, allowing for temporal observation and records of temperature responses amongst others (Norman, et al., 1997). However, ODC methods are highly susceptible to pressure differences inside and outside of the chamber, resulting in mass flow of CO_2 from the soil which would cause errors in CO_2 efflux measurements (Lund, et al., 1999). Ideal flow rates for such systems are difficult to determine, as flow rates would influence the altered diffusion gradient or pressure differences (Davidson, et al., 2002).

This chapter has presented the need to account for CO_2 effluxes over tropical urban areas and the importance for having an understanding of the environmental influences to these effluxes, and this is followed by a brief overview of current chamber techniques employed so as gain an appreciation of the methodology of the study, which has adopted the CDC chamber method for measuring soil effluxes.

3. Methodology

This chapter presents the approach taken in determining soil CO_2 efflux and the surrounding ancillary measurements; to 1) understand the system in question, and 2) test the hypothesis that environmental factors and anthropogenic influences play a critical role in influencing soil efflux. The field study was conducted from July-December 2012 at the Singtel-Kranji Radio Transmission Station, located in the Northern tip of Singapore (103^{o}43’49E, 1^{o}25’53N). The climate in Singapore is classified as tropical rainforest (A*f*) under the Koppen climate classification; characterised by uniform temperature and pressure with no distinct wet or dry seasons, though the monsoons are accompanied by more frequent rain (Figure 11). The surface under observation was relatively flat with a homogenous soil cover and dominated by *Axonopus compressus* a C4 plant, representative of the majority of turf in Singapore.

3.1. Experimental Design

Four experimental plots (5m x 5m) of bare and grass covers in varying combinations were established on 22 March 2012 (Figure 6). The treatments were bare no clipping (BNC); bare with clippings (BWC); turf no clippings (TNC); and turf with clippings (TWC). The TWC plot was established in order to obtain the effluxes from decomposing clipping material. Located adjacent to each other, each contained five permanent collars for replicate measurements and were distributed to ensure a minimum 1.5m distance between collars and the edge of the plot (Figure 7). In order to retard the growth of vegetation on the bare plots, weeding and the use of herbicide (Roundup, Monsanto (Malaysia) Sdn. Bhd.) was applied on the bare plots fortnightly.

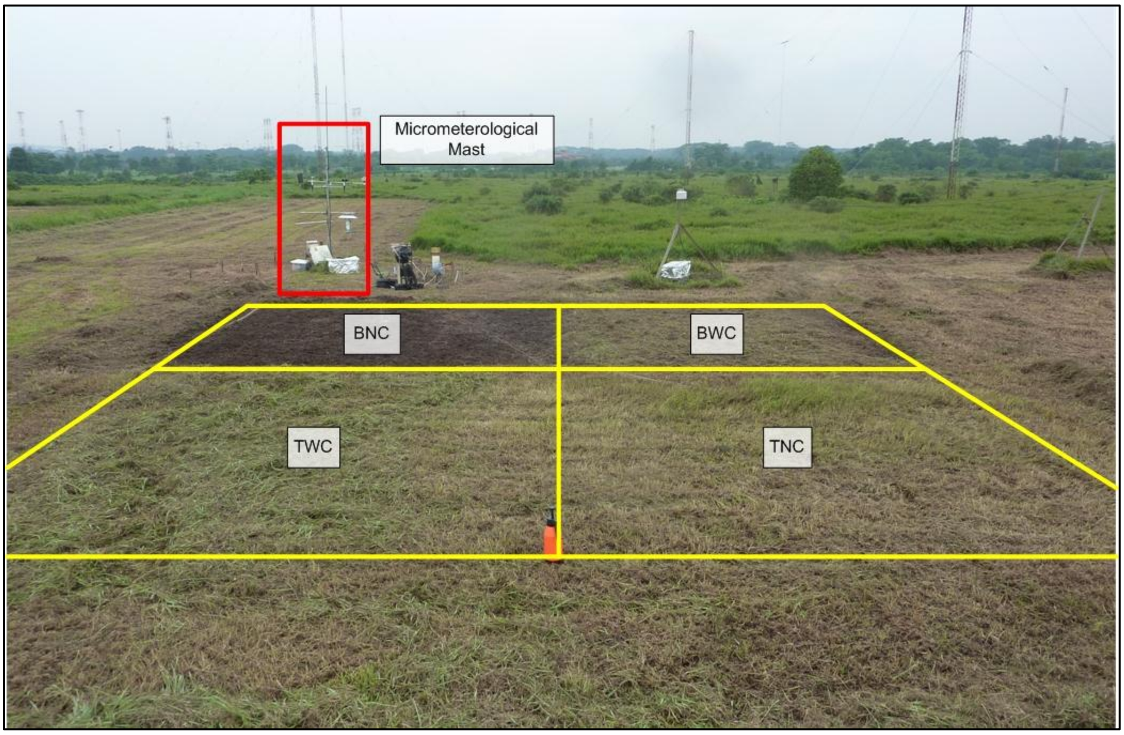

Figure 6: Plot layout of the experimental site

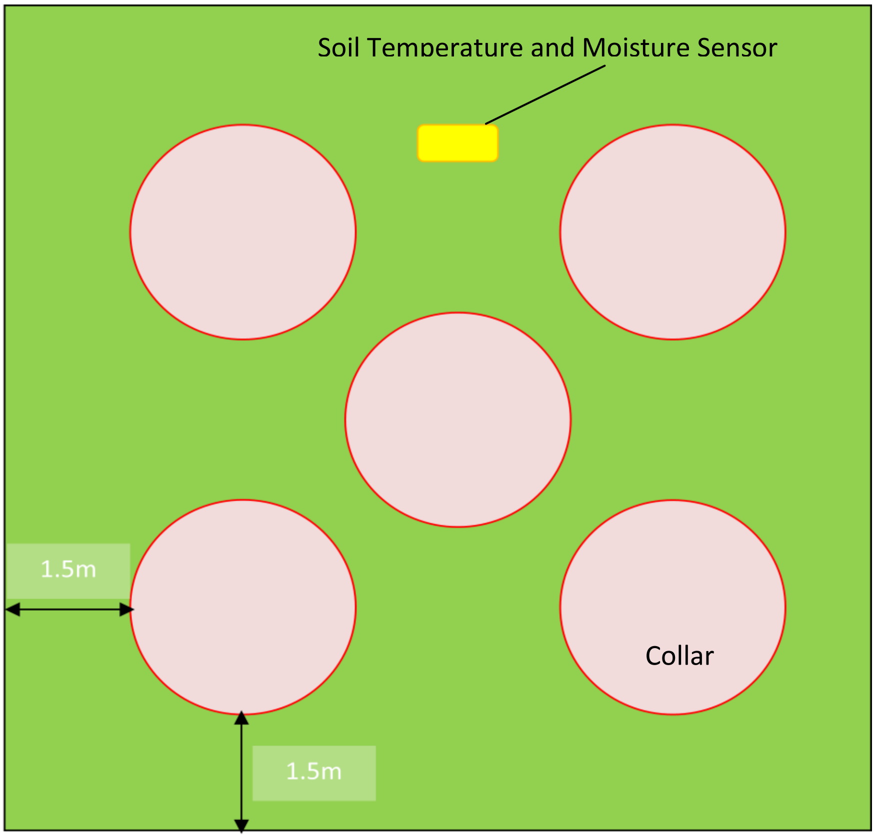

Figure 7: Layout of Collars, soil moisture and soil temperature sensors within plot

3.2. Measurements of CO_2 fluxes

Soil-surface CO_2 fluxes were measured with a modified closed dynamic chamber system based on Bain et al. (2005) designs. Soil efflux was measured approximately twice a week, throughout the daylight hours (between 0900hrs and 1830hrs) where weather conditions allowed. CO_2 fluxes in ($\mu mol^{-1} m^{-2} s^{-1}$) were subsequently calculated from the slopes of the concentration versus time curves, the system volume, and the surface area covered by the chamber and ambient temperature. Soil Surface CO_2 efflux (F_c, $\mu mol m^{-2} s^{-1}$) was calculated with the following equation:

Equation 4: Calculation of soil efflux (Davidson, et al., 1994)

$$F_{CO_2} = \frac{PV}{RTS} \cdot \frac{dC_{CO_2}}{dt}$$

where P is the atmospheric pressure (Pa); V is the volume of the system (m^3); R is the ideal gas constant; T is the ambient temperature (k); S is the surface area under observation (m^2) and dc/dt is the rate of change of CO_2 concentration in the chamber headspace between the 100 and 200 seconds after putting the chamber in place. Concentration gradients were only calculated when the data was stable (Figure 8). The values from F_c were averaged from five collars for subsequent analysis.

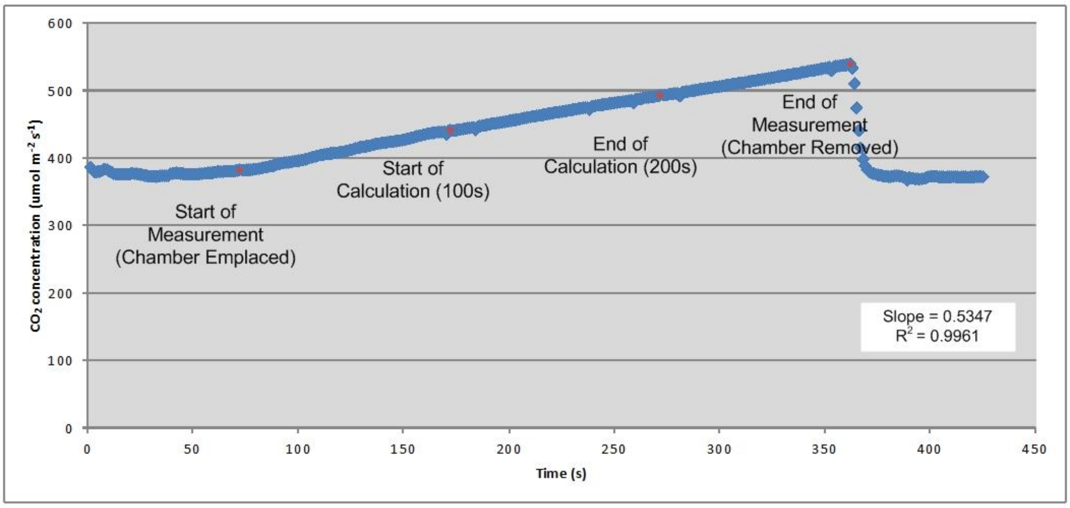

Figure 8: Determination of concentration gradient on a stable observation graph

3.2.1. Chamber design and construction

The portable chamber system designed and used for this study (Figure 9) is based upon Closed Dynamic Chamber principles (Parkinson 1981), measuring F_{CO2} through the calculation of the change in C concentration over time. The chamber design attempted to address most of the major concerns surrounding the use of Closed Dynamic Chamber systems, namely the altered diffusion gradient, environmental disturbance, pressure inequalities and thorough mixing.

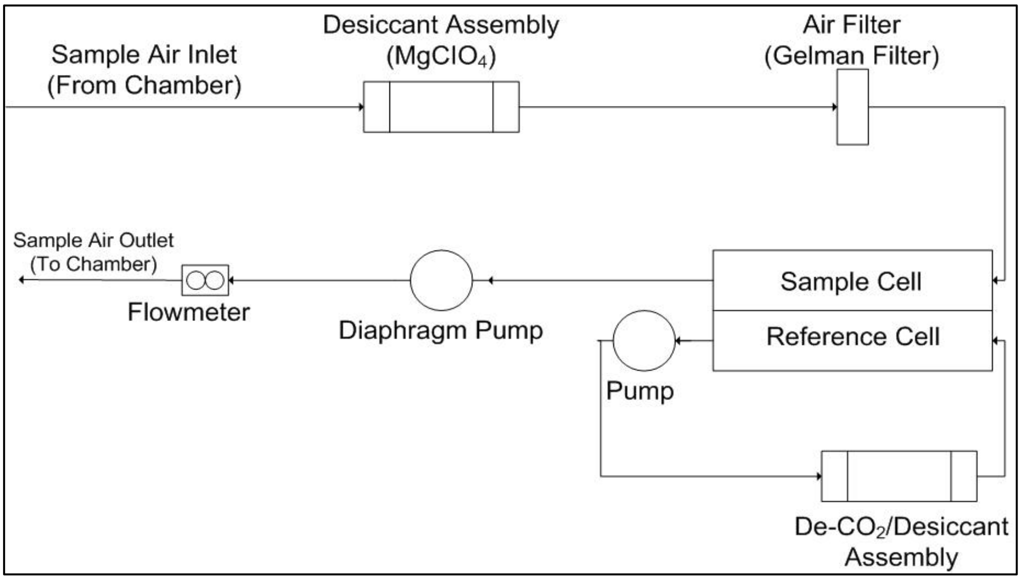

Figure 9: Analyser setup

Mixed chamber air was fed from the top of the chamber to a $Mg(ClO)_4$ desiccant chamber prior to entering the differential, non-dispersive, infrared (NDIR) gas analyser (IRGA, LI-6252m LiCor Industries, Lincoln, NE) to avoid possible dilution due to endogenous humidity of the soil air circulating in the closed system. The inclusion of the desiccant assembly, which is usually absent from systems in other studies and Bain et al's (2005) design, is necessary for studies in tropical areas due to the high humidity and condensation occurring in the connecting hoses and the system during incubation, which would affect flow rates and have a possible dilution effect on the CO_2 concentration. Air was circulated back to the chamber via a diaphragm pump (~0.5*l*/min) in a closed loop.

In order to reduce the anomalous pressure effects resulting from high pressure differences between the atmosphere and the chamber, the addition of a 'pigtail' extension vent was installed in the chamber top through a Swagelok fitting to reduce the problems with pressure difference due to high speed winds (Hutchinson & Livingston, 2001; Salimon, et al., 2004). The IRGA reference air was scrubbed both with soda lime and $Mg(ClO)_4$. The chamber sampled an area of $0.0531m^2$ (ø: 0.23m), with a height of 0.125m for a system volume of $0.00682m^3$. A measurement cycle of approximately 5 minutes was employed with C gradients calculated between 100-200s of measurement to allow for adequate and steady mixing within the chamber (Figure 8).

3.2.2. Collars

Semi-permanent collars that exactly matches the size of the chamber 0.05m^2 (ø: 0.23m) were deployed to reduce CO_2 leakage during measurement and ensure that there was minimal site disturbance; reducing possible errors due to constant chamber insertion and removal which would lead a reduction in the observed fluxes. Collars were inserted approximately 5-7 cm into the ground to ensure that there was a firm fit and that it reached into the B horizon of the soil (Figure 10). The collars were undisturbed for five months (March - July 2013) to allow the site to equilibrate to the installation. Five collars were installed in each plot to allow for replicates to obtain more accurate measurements. A soil depth of 5-7 cm was considered for the CO_2 respiration observations. Soil at this layer has the most labile organic C and accessible nutrients, with the highest microbial activity and correspondingly high GHG production/consumption (Risk, et al., 2008)

3.2.3. Calibration

Calibration of the LiCor 6252 system was conducted at the end of every month using a two-point calibration method to ensure the accuracy of the measurements and to detect the drift in the instruments. This was done through the use of 2 known standard gases of zero air, 348ppm and tested against a known standard of 389ppm at the flow rate of ~0.5l/min, which is similar to the pump rate. The effectiveness of the scrubber unit for the reference was tested by passing a known gas through it and testing it against zero air; no known change was observed over the testing period. The scrubber unit for the reference cell was also checked for efficiency monthly. Any changes that had to be made were done through adjustment of the potentiometers located on the instrument. No significant drift was noted in the instruments during the period of August to December 2012.

3.3. Clipping application

To account for the contribution of clippings to CO_2 effluxes, clippings were placed in leaf litter bags prior to leaving them on site. This was necessary as clippings that were spread across the field were transported away from the collars and site by wind and rain. The application of grass clippings followed the same frequency and schedule of mowing for the site. The total weight of the clippings were weighed and collected from plot TNC and divided by the total area to approximate the mass of clippings generated per area. Clippings were then placed in a commercially available leaf litter bag (dimensions: 30x20cm, mesh size: 0.5cm), and left onsite between clippings.

3.4. Ancillary Measurements

The environmental factors of soil temperature (T_S) and soil moisture (VW) which were hypothesised to influence the rate of CO_2 efflux, were measured between two collars in each plot, whilst air temperature was measured at the mast.

3.4.1. Soil characteristics and parameters

Due to the nature and location of the study area, the soils found within could be classified as Technosols under the World Reference Base for Soil Resources (2006) with the mineral horizon containing clay and iron oxides. The A1 (10YR 3/1), A2 (10YR 5/3) and B (10YR 7/6) horizons are easily distinguished in the top 10 cm of the soil profile, due to the distinct colour difference between the horizons (Figure 10). The depths of the different horizons are different between the Bare (BNC and BWC) and the Turfed (TNC and TWC) plots as a result of the removal of vegetation from the Bare plots. Most of the roots could be located within the first 5cm of the soil profile (Figure 10), within the A horizon.

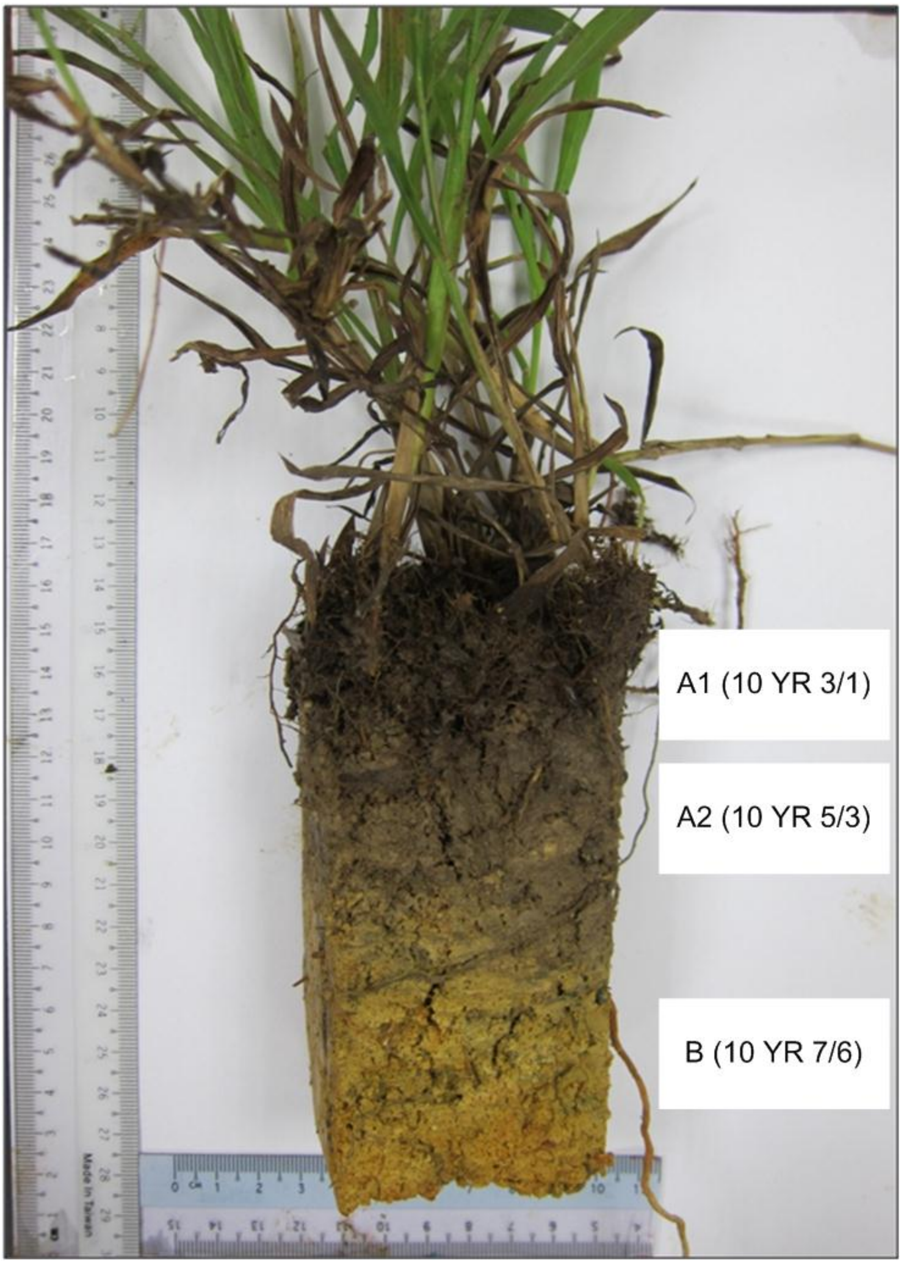

Figure 10: Soil Profile

3.4.2. Site parameters (temperature, moisture and bulk density)

Soil temperature, soil moisture were measured for each plot to evaluate their relationship with CO_2 emissions. Soil temperature was measured with thermistors (107, Campbell Scientific Inc., Logan, UT, USA) and soil moisture was measured with time domain reflectometers (CS616, Campbell Scientific, Logan, UT, USA) inserted in the soil at a low angle to obtain a composite measurement of the soil temperature and moisture for the first 0-7cm depth of the soil. All soil environment factors were measured from the surface to a depth of 5-7cm of the A layer and were recorded every minute with a datalogger (CR 1000 and AM16/32, Campbell Scientific Inc., Logan, UT, USA).

Soil cores were extracted to determine the bulk density for depths of 0-5cm and 5-10cm. Samples were oven dried at 105°C for 48 hours and bulk density was determined volumetrically as the mass of oven dried divided by the volume of the core (ø: 5cm, ht:5cm, vol:98.175cm^3). Percentage soil C content was accounted for on oven dried (70°C for 72 hours or until constant weight) samples sieved through a 2mm screen (to remove rocks, coarse rocks, coarse roots and organic material). The sample was subsequently ball-milled to fine powder and analysed for total C content with an elemental analyser (varioTOC cube, Hanau, Germany). Total C content for the aboveground biomass was estimated every 6-8 weeks to the height of approximately 3-4cm, at the same time when the area outside the plots were mowed by the management with three replicates.

3.4.3. Air temperature

In order for the calculation of C flux from the ecosystem, air temperature was obtained from the site via a humidity and temperature probe (HMP 155, Vaisala, Helsinki, Finland) situated within an aspirated radiation shield located at approximately 1.2m above ground level.

3.5. Statistical analysis

Means of soil respiration rate, and soil temperature were calculated through the average of 3-5 readings for the time period in question. One-way ANOVA, accompanied by Games-Howell post-hoc analysis, was performed to test the significance of difference in soil effluxes rates, soil temperature and soil moisture according to the different experimental treatments. Pearson product-moment correlation and regression (exponential and polynomial) models was utilised to understand possible relationships between CO_2 efflux rates and environmental variables. Significant effects were determined at $p<0.05$. Statistical analysis was performed with SPSS Version 16.0 (2007). The missing environmental data were due to various instrumental errors such as power outages and damage by wild animals.

4. Results

This chapter reports the findings to provide insights into the C dynamics of an urban turfgrass ecosystem, which was subjected to management regimes and environmental factors. Direct respiratory measurements of respiratory fluxes and all available ancillary measurements are reported. As there is a lack of studies on urban turfgrass ecosystems, the results of this study is compared with respiratory fluxes in the geographic tropics.

4.1. Site Description

The carbon content of the system in question was quantified to be able to understand the stores of carbon within the system (Table 1). Table 1 elucidates the total amount of carbon within the soil profile (up to 1m), with the calculations being made. Carbon content concentration was highest in the A1 and A2 horizons of the soil, with a sharp distinction with the B horizon which reflects the composition of the material in the lower parts of the profile with organic matter and roots being largely absent. The carbon pool estimates were made on the start of the experimental period, and thus most representative of the treatment TWC.

Table 1: Carbon pool analysis of experimental site

Soil Profile	Profile	Colour	Biomass (turf and roots)	Bulk density (soil)	Depth (soil)	Total % Carbon Concentration (as of mass)	Mass of Carbon (C Conc x Bulk Density x depth)	Carbon Density	Proportionate composition of profile
			g/m2	T/m3	m	%	gC/m2	kgC/m2	%
	Clippings & Verdure	N.A	98.16	N.A	N.A	42.20	67.52	0.04	1.4
	Roots (>2mm)	N.A	139	N.A	N.A	20.83	28.95	0.03	0.98
	A1 & A2 Horizon (inc. Roots <2mm)	10 YR 3/1 & 10YR 5/3	N.A	0.8	0.06	5.45	2616	2.62	88.9
	B Horizon (inc. Roots <2mm)	10 YR 7/6	N.A	2	0.04	0.32	256	0.26	8.7

The soil bulk density values were 0.8 ± 0.05 and 2.0 ± 0.63 g cm^{-3} for the A and B soil horizons respectively, with C content values of 5.5 and 0.3% respectively. This is a reflection of the composition of the material in the lower parts of the profile where, there is high mineral content and an absence of fine and course roots. The grass and clippings had a mean mass of 160 g m^{-2} with a 42.6% C content, with an estimated productivity of $2.39 gm^{-2} day^{-1}$.

4.2. Soil Environment Indicators (Temperature & Moisture)

The climatic conditions of the experimental plots were consistent with that experienced over the rest of the island state. Experimental manipulation through the removal of turf altered soil conditions in the bare soil plots and temperature and moisture were significantly different between bare (BNC and BWC) and turfed plots (TNC and TWC) (Table 2). Over the course of the measurement period, there was an increased frequency of rainfall from November 2012 onwards (Figure 11).

BNC and BWC had statistically higher soil temperatures ($31.9 \pm 2.45^{o}C$), as compared to TWC and TNC ($29.6 \pm 1.14^{o}C$), $t(185.55) = 9.695$, $p<0.001$. The presence of plants has an ameliorating effect on soil temperatures and consequently urban temperatures. This could be due to the effect of shading, soil structure, and increased average soil moisture, all of which would influence the specific heat capacity of the surface. The difference in soil temperatures could thus be partially explained through the presence or lack of turf, and is similarly described by Wan et al. (2003) and Klen et al. (2005).

Unlike soil temperature, soil moisture was not significantly modified by the presence or absence of turfgrass. BNC and BWC experienced higher moisture contents (67.07 ± 26.36%) compared to TNC and TWC (63.99 ± 19.62%), *t*(242)=1.074, p=0.284. Despite the non-statistically significant difference in moisture, a larger range of values is observed for the bare plots as compared to the turfed plots (Table 2).

Table 2: Soil Environment Indicators at the Kranji Experimental Site during flux measurements (September to December 2012)

	BNC Bare, No clippings	**BWC** Bare, With clippings	**TNC** Turfed, No clippings	**TWC** Turfed, With clippings
Average Soil Temperature	32.72	31.09	29.53	29.71
Temperature Range	27.55 – 38.74	27.40 – 34.71	27.50 – 31.08	26.80 – 32.52
Average Soil Moisture Content	73.29	90.85	64.04	63.95
Moisture content Range	33.21 – 100.00	57.91 – 100.00	33.61 – 86.10	25.49 – 89.37

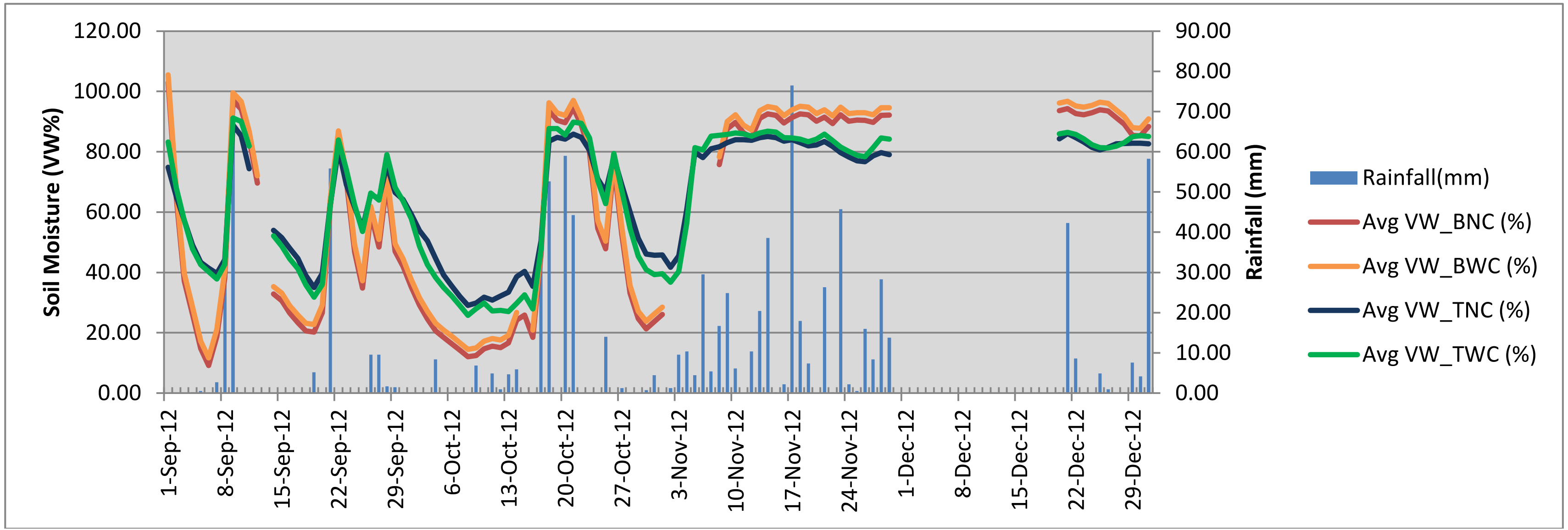

Figure 11: Rainfall and soil volumetric water content

4.3. Soil-Atmosphere Effluxes

Soil fluxes were hypothesised to be influenced not only by human intervention of clipping application and the presence of turf; but also by environmental factors of temperature and moisture. Approximately 1200 efflux readings were recorded, values reported in this study refer to the average of 3-5 readings per treatment per half hour period.

Table 3: Descriptive Statistics CO_2 fluxes of the different plots.

Plot	N	Mean ($\mu molm^{-2}s^{-1}$)	S.D	Std. Error	95% Confidence Interval for Mean		Min	Max	Range
					Lower Bound	Upper Bound			
BNC (Bare)	66	2.09	0.95	0.12	1.86	2.33	0.23	4.87	4.64
BWC (Bare, Clippings)	66	3.18	0.93	0.11	2.95	3.41	1.20	5.65	4.45
TNC (Turfed)	66	8.54	1.80	0.22	8.10	8.99	3.49	13.19	9.70
TWC(Turfed, Clippings)	66	7.05	1.76	0.22	6.62	7.48	2.98	11.64	8.97
Total	264	5.22	3.02	0.19	4.85	5.58	0.23	13.19	12.96

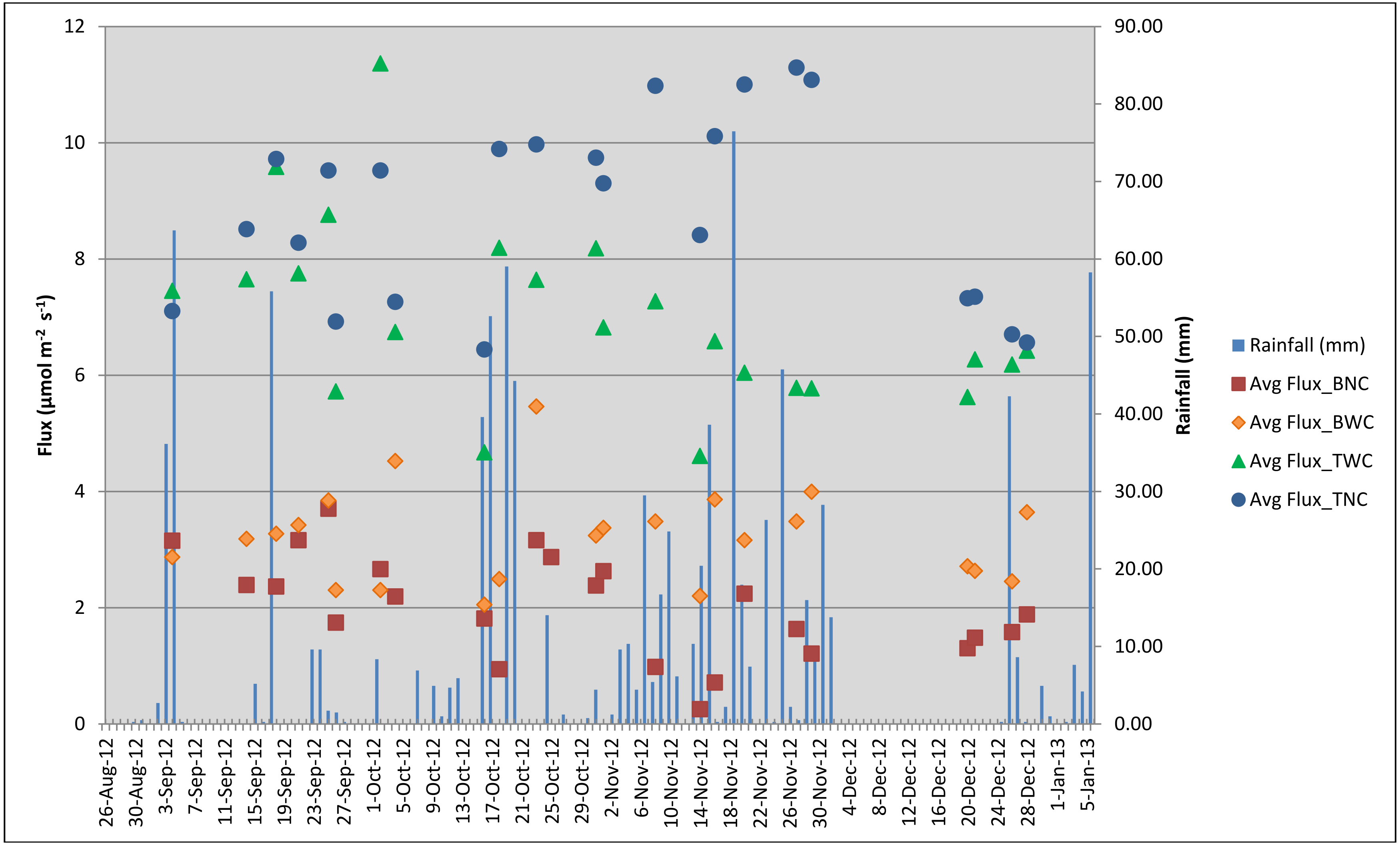

Figure 12: Rate of soil efflux and rainfall

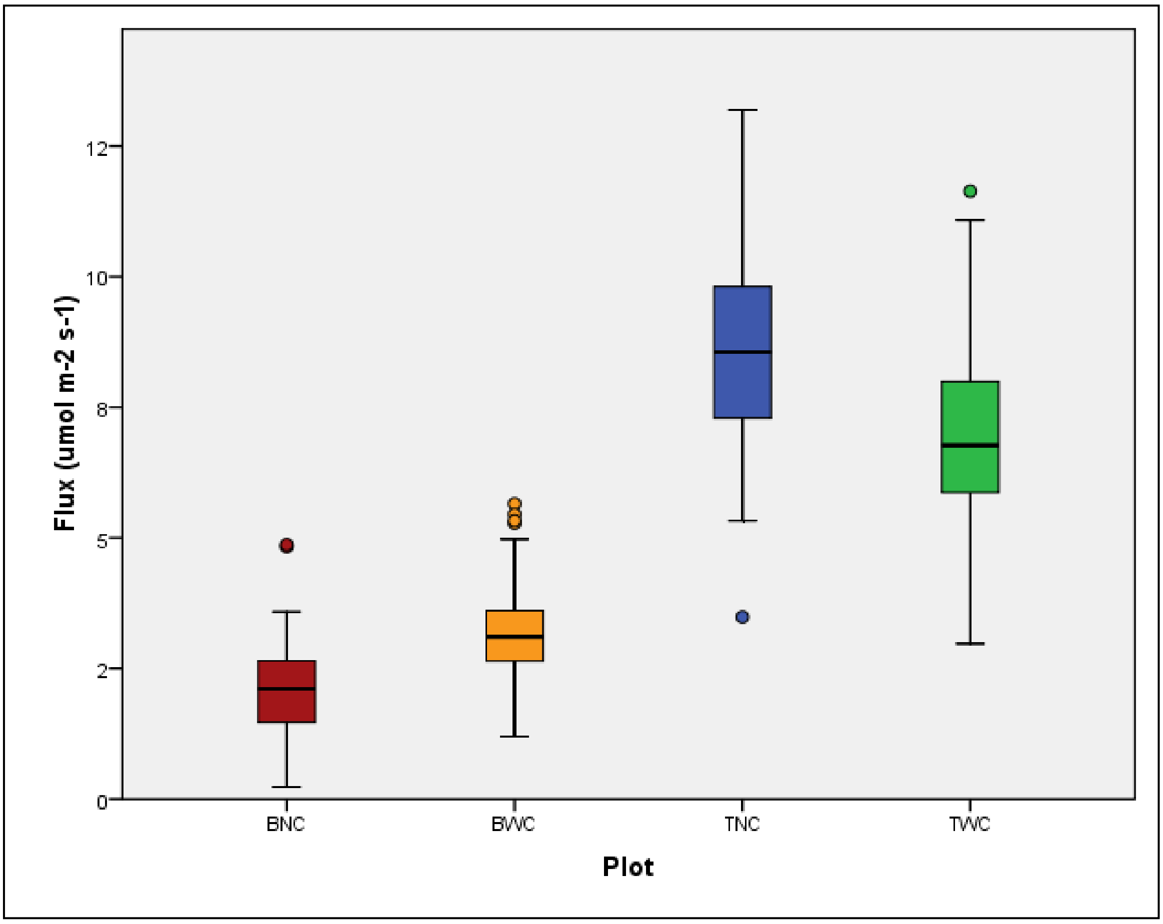

Figure 13: Boxplots of the different plots (treatments).

To examine the effect of treatments (presence or absence of turf and/or clippings) on observed CO_2 effluxes, a one-way ANOVA was conducted (Table 4). Visual inspection of the boxplot (Figure 13) does not show that a statistical difference between plots especially between plots TNC and TWC (Figure 15). However, the Games-Howell post-hoc test for difference shows a significant difference in the amount of CO_2 efflux being observed between all the plots ($p < 0.001$) (Table 3).

Table 4: Comparison of approaches based on different experimental plots based on presence or absence of turf and/or clippings, using Games-Howell post-hoc test

(I) p	(J) p	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
BNC	BWC	-1.09*	0.164	0.001	-1.52	-0.663
	TWC	-4.96*	0.246	0.001	-5.60	-4.31
	TNC	-6.45*	0.251	0.001	-7.11	-5.80
BWC	BNC	1.09*	0.164	0.001	0.663	1.52
	TWC	-3.87*	0.245	0.001	-4.51	-3.23
	TNC	-5.36*	0.249	0.001	-6.01	-4.71
TNC	BNC	6.45*	0.251	0.001	5.80	7.11
	BWC	5.36*	0.250	0.001	4.71	6.01
	TWC	1.50*	0.310	0.001	0.691	2.30
TWC	BNC	4.96*	0.246	0.001	4.31	5.60
	BWC	3.87*	0.245	0.001	3.23	4.51
	TNC	-1.50*	0.310	0.001	-2.30	-0.691

*. The mean difference is significant at the 0.05 level.

4.4. Comparison to Existing Literature

This study is unique in its attempt to account for soil effluxes using chamber measurements in an urban area in the geographic tropics; there is a dearth of literature that would allow for direct comparison of measurements. Comparisons with other studies are based on published data on grasslands or agricultural lands in tropical areas (Table 5). Criterion for comparison includes the use of chamber methods to account for fluxes to reduce possible difference due to differing methods.

A literature analysis done by Lloyd and Taylor (1994) approximates that the rate of respiration taking place at between 30-40^{o}C ranges between 6-11 µmolm^{-2}s^{-1}. From a list of 11 studies, soil respiration values obtained through observation ranged from 0.96-23.74 µmolm^{-2}s^{-1} with a mean value of 5.22 µmolm^{-2}s^{-1} (Table 5). It indicates the possible range of values of respiratory fluxes in the tropics.

The range of values (0.23-13.19 μmolm^{-2}s^{-1}) obtained in this study lies within the reported range of values for tropical areas.

Table 5: Soil Efflux values from tropical (23^{o}N - 23^{o}S) studies

Landcover	Latitude	Country, State	Landuse	Measurement	Treatment/Presence of Vegetation in chamber	Flux (µmolm^{-2}s^{-1})	Soil Type	Author
Turfgrass (this study)	1.03	Singapore	Turfed	Soil and Ecosystem Respiration	Cleared and Uncleared	0.23-13.19	Ferric acisols	
Agriculture	13.31	USA, Guam		Soil and Ecosystem respiration	Cleared and Uncleared	9.5-23.74	Rendzic Leptosols	(Motavalli, et al., 2000)
	5.29	Micronesia	Taro	Soil Respiration	Not mentioned	1.15	Peat	(Chimner, 2004)
	-21.15	Brazil	Maize	Soil Respiration	Tilled	0.96-1.59	Ferrasol	(La Scala, et al., 2005)
	-1.5	Indonesia	Plantation agriculture	Soil Respiration	Not mentioned	7.27	Peat	(Ali, et al., 2006)
	2.5	Malaysia	Oil palm & Rubber plantations	Soil Respiration	Not mentioned	2.8	Sandy Clay Loam	(Adachi, et al., 2005)
	-1.07	Brazil	A.mangium & I. edulis	Soil Respiration	Fallow Period / Not mentioned	5.40-6.82	Entisol	(Verchot, et al., 2008)
	-21.17 to -21.18	Brazil	Sugarcane	Soil Respiration	Not mentioned	2.40-2.84	Typic Eutrustox	(Brito, et al., 2009)
	-21.24	Brazil	Sugarcane	Soil Respiration	Not mentioned	2.06-2.8	Oxisol	(Panosso, et al., 2009)
Grassland	-2.59	Brazil	Cattle Pasture	Soil Respiration	Not mentioned	2.74-4.11	Haplustox (usda)	(Davidson, et al., 2000)
	-9.77 to -9.94	Brazil	Pasture	Soil Respiration	Uncleared	5.04 - 7.53	Ultisols	(Salimon, et al., 2004)
	9.19	Central Panama	Plantation, Pasture, Grassland	CO2 efflux	Grass was cut prior to measurement	5.1-8.1	Not mentioned	(Schwendenmann, et al., 2007)

4.5. Fluxes and Temperature Sensitivity

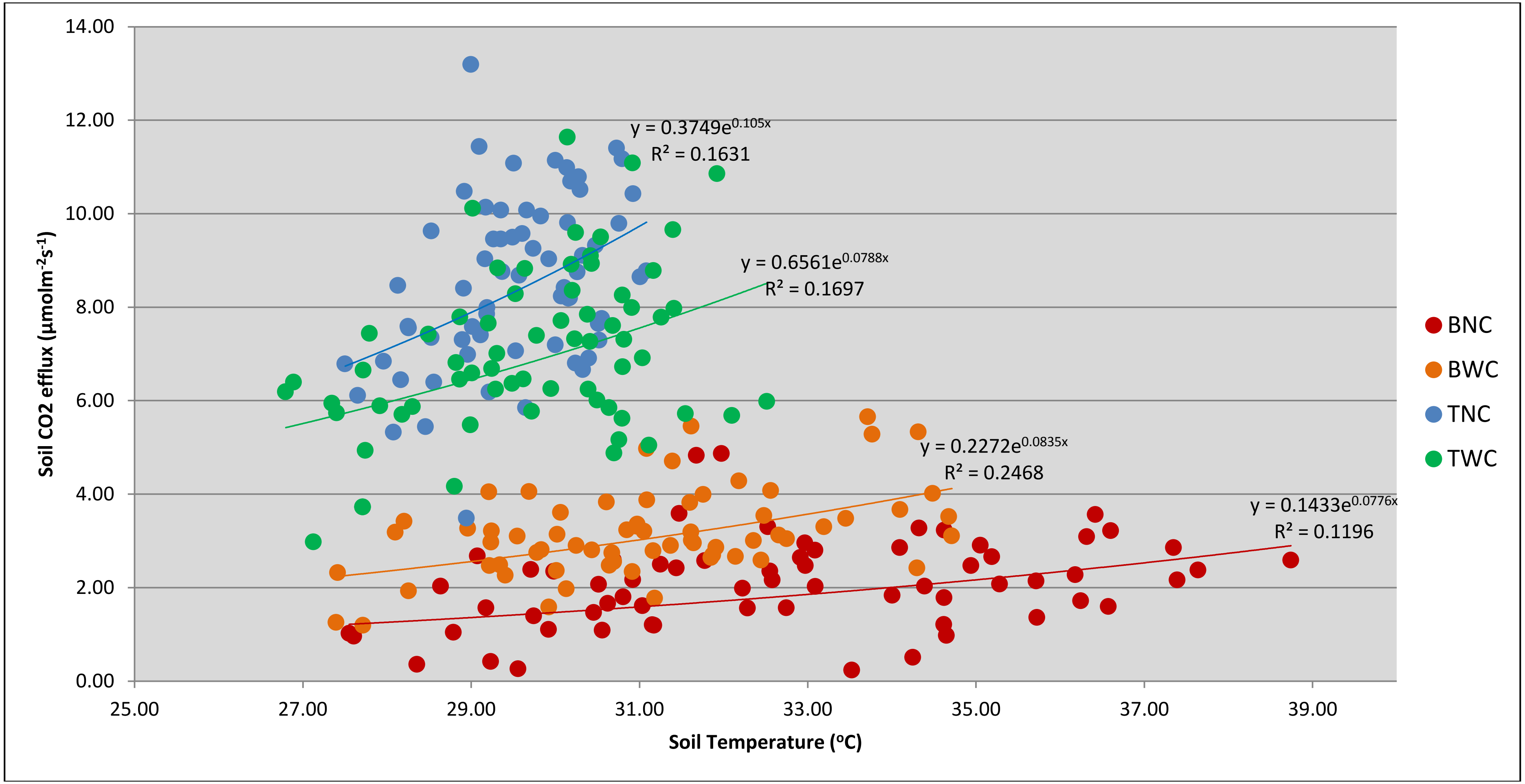

Figure 14: Sensitivity of ecosystem respiration to temperature

The relationships between soil respiration and temperature are mainly drawn from experimental data in the lab or through observations in temperate climates. Although soil respiration is known to vary with temperature, observations within the range of temperature in this study (26-48°C) has not been well researched into as publications on similar studies usually cover a larger range of temperatures at lower extents (0-30°C).

Table 6: Exponential Fit between Temperature and Flux

Plot	R	R Square	df (Regression)	df (Residual)	Mean Square	F	Sig f
BNC	0.346	0.12	1	64	2.915	8.697	0.004
BWC	0.480	0.25	2	63	6.435	9.417	0.001
TNC	0.404	0.16	1	64	0.546	12.473	0.001
TWC	0.412	0.17	1	64	0.750	13.084	0.001

Regression analysis based on an exponential fit between temperature and fluxes were conducted. Temperature does not appear to be a good predictor of observed fluxes from its low R^2 values (0.12-0.23), however, it does appear that there is a correlation between the two factors from its R values (0.35-0.48) (Figure 14 and Table 6).

Table 7: Site Specific Q_{10}, R_{10} values with Expected and Observed Respiration

Plot	Q_{10}	R_{10}	$R_{simulated}$ (mean)	$R_{observed}$ (mean)
BNC	2.173	0.311	1.85	2.09
BWC	2.305	0.524	3.08	3.18
TNC	2.859	1.072	8.37	8.54
TWC	2.199	1.443	6.34	7.05

The Q_{10} and R_{10} values were calculated using Van't Hoff's equation after soil CO 2 values were determined to be log-normally distributed. Soil CO2 values which follows one of the fundamental laws of geochemistry (Ahrens, 1954), are usually log-normally distributed (Lewicki et al 2005). The temperature sensitivity observed through the Q_{10} values, are in close agreement to the values that are found within Bond-Lamberty & Thomson's (2010) database, which has tropical values for agricultural and grassland areas between 1.68-4.58 $\mu molm^{-2}s^{-1}$ with a mean value of 2.17 $\mu molm^{-2}s^{-1}$.

4.6. Fluxes and Moisture Dependence

Moisture was hypothesised to be the second major factor after temperature in influencing soil effluxes. Though it is less studied than temperature dependence on soil effluxes, it is accepted that it plays a significant role in determining soil effluxes. Unlike temperature which is generally assumed follow an exponential relationship; a quadratic relationship exists between soil moisture and fluxes. Certain authors have managed to draw a relationship between the wettings and/or drying of the soil and resultant fluxes of a plot of soil moisture and fluxes (Figure 15). However this study was unable to discern such relationships from the observed data possibly due to the close to instantaneous change in fluxes which were not detected due to the methods. Additionally, due to the nature of the soil horizons, percolation to the deeper layers of the soil takes place at a very slow rate or is largely absent, as such there is water stagnation on the soil surface during periods of high rainfall such as from November onwards (Figure 11).

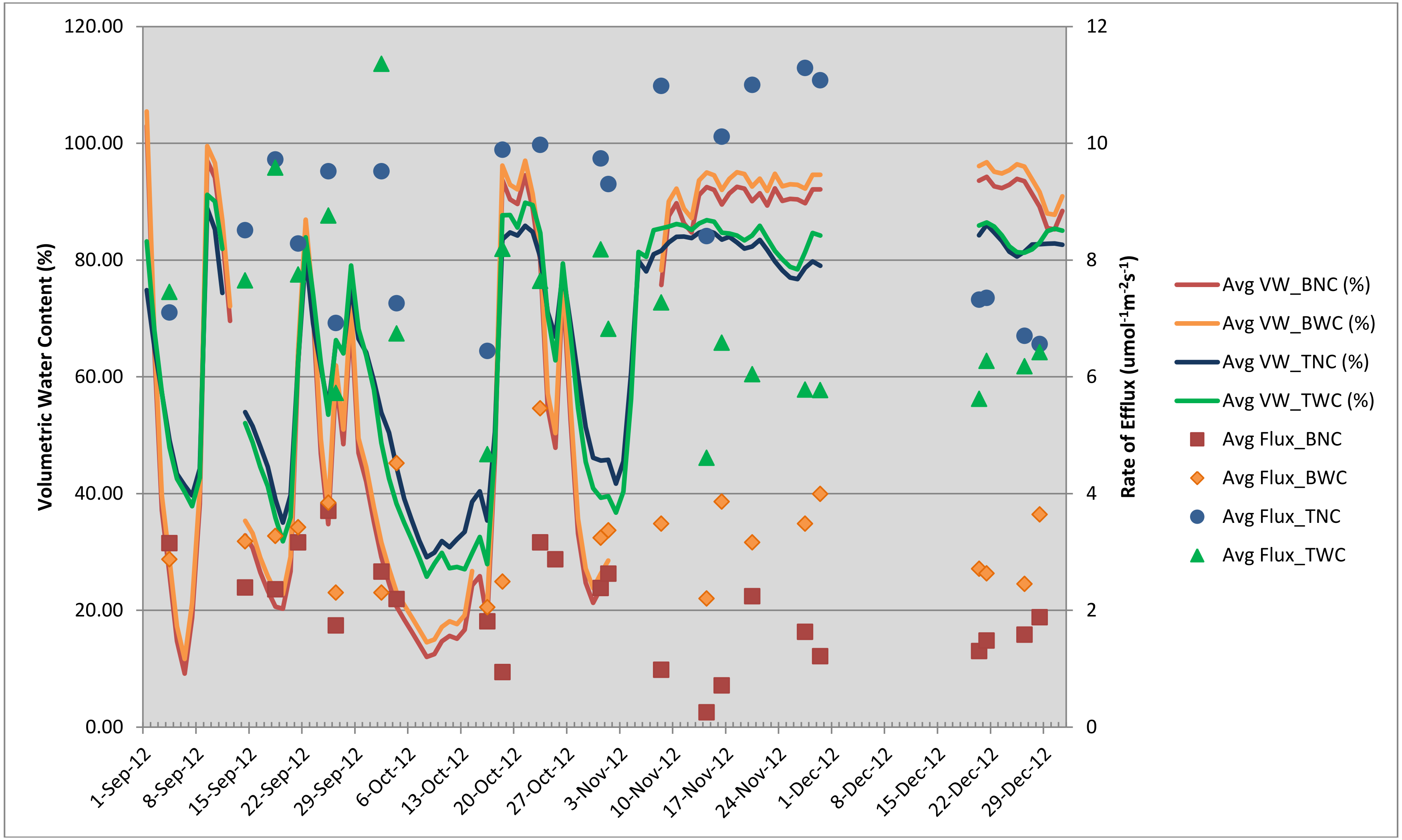

Figure 15: Daily averaged water moisture content with corresponding efflux measurements

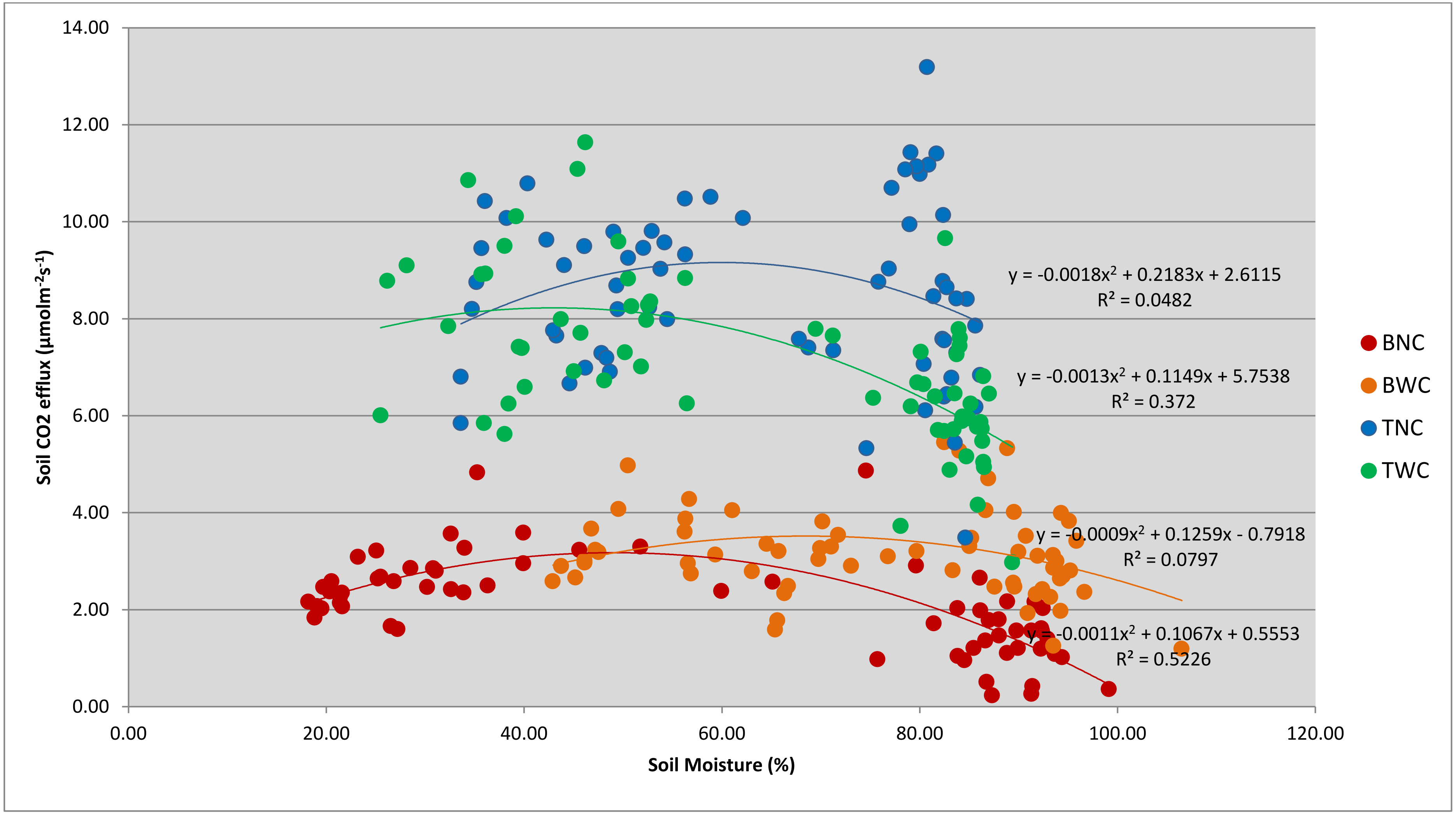

Figure 16: Ecosystem respiration and soil moisture dependence

Table 8: Quadratic fit between soil moisture and fluxes

Plot	R	R Square	df (Regression)	df (Residual)	Mean Square	F	Sig f
BNC	0.723	0.523	2	63	15.482	34.476	0.001
BWC	0.08	0.05	2	63	2.227	2.726	0.073
TNC	0.220	0.048	2	63	5.072	1.595	0.211
TWC	0.610	0.372	2	63	37.308	18.662	0.001

A regression analysis based on a hypothesised quadratic fit has mixed results with a weak or lack of relationship between moisture and fluxes for plots BWC and TNC. There is a stronger relationship between the factors for plots BNC and TWC, as seen from both the relatively higher R and R^2 values (Figure 16 and Table 8). Thus it is not possible to directly pinpoint the factor (autotrophic or heterotrophic respiration) which is the key agent in fluxes.

4.7. Effects of Temperature and Moisture on Fluxes

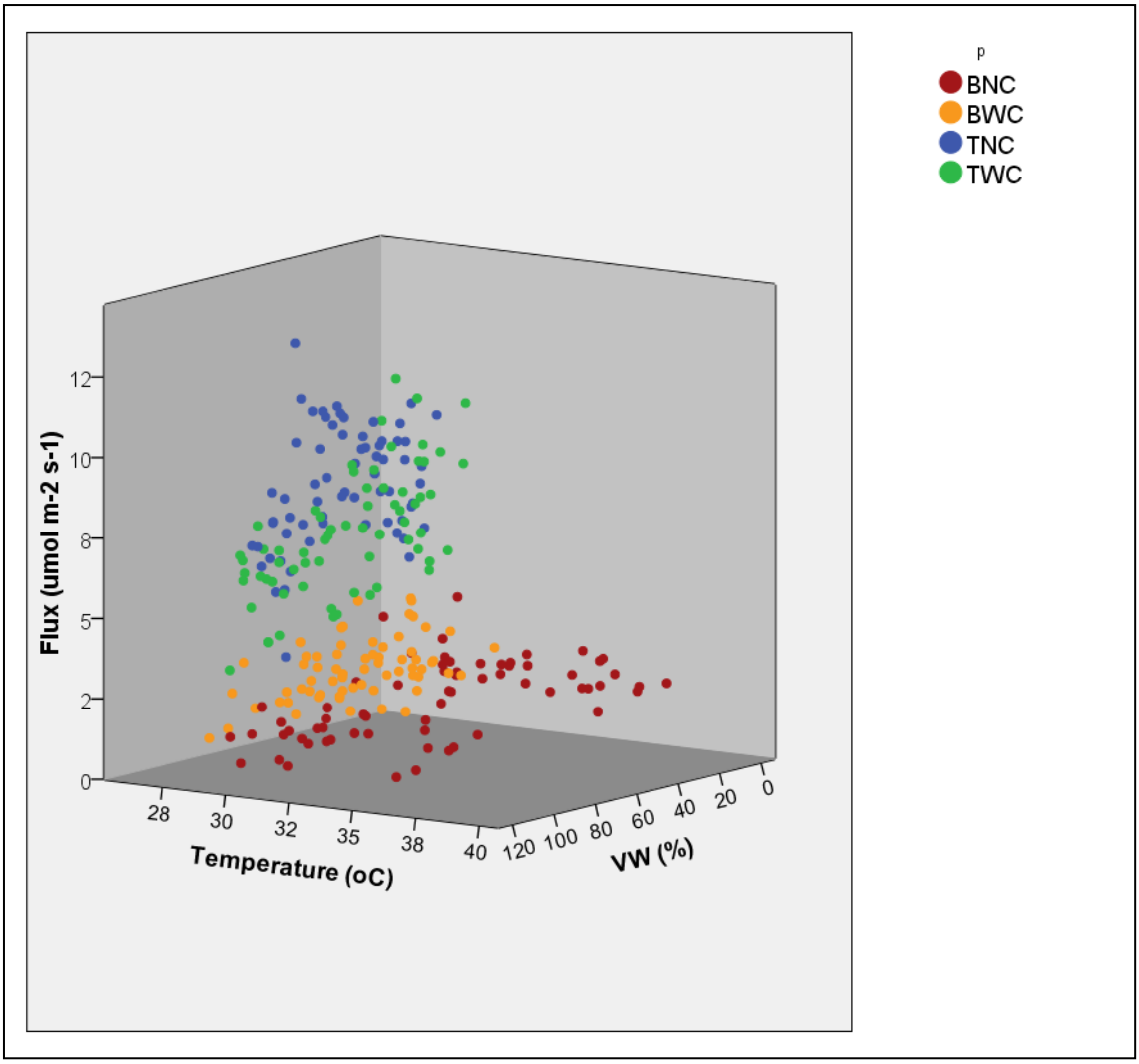

Figure 17: Relationship between environmental factors and observed CO_2 efflux

The relationship between soil temperature, soil moisture and soil effluxes are clustered according to the plots (Figure 17). This is to be expected due to the distinct nature of the ground cover as a result of the experimental methodology, modifying soil temperature and soil moisture (Table 2). The modification of the soil factors of temperature and moistures results in changes in other factors noted earlier (Section 2.2 and 2.3) but not accounted for in this study. Although there are significant differences in the environmental factors and resultant fluxes, it should be noted that there is less differentiation between the plots TNC and TWC. BWC has the widest range of temperature values in comparison to the other plots. In recognition that temperature and moisture are known to co-vary with each other, regression analysis would not be suitable for understanding the relationship among the three variables as doing so would result in large standard error.

5. Discussions

This chapter discusses the findings of the data reported in the previous chapter and attempts to provide new insights into the C dynamics of a tropical urban turfgrass ecosystem. Special attention is paid to the influence of management regimes (presence and/or absence of turf) and environmental factors (soil temperature and moisture).

5.1. Contribution of soil respiration to Ecosystem Respiration

The fluxes measured for BNC are considered as soil respiration as the vegetation from the area has been removed and germination of new plants kept to a minimum. A mass balance/component integration approach was used to calculate the fluxes from turf and clippings. The aim of such approaches measures the respiration rates of spatially separable contributors to CO_2 fluxes so as to estimate the relative importance of each component to the total flux (Trumbore, 2006). The mass balance approach adopted by this study has been used by numerous other studies (Wan & Luo, 2003; Bond-Lamberty, et al., 2004; Zhou, et al., 2007) and is based upon the assumption that the total mass and rate of respiration of CO_2 remains constant across the treatments for the components. Thus for this study, TWC (turfed, with clippings) is considered representative of complete ecosystem respiration and BNC (bare, no clippings) as representative of soil respiration, following these assumptions the subsequent equations were deduced,

Equation 5: Heterotrophic Respiration from decomposing clippings

Fluxes from BWC ($R_{clippings}$) – Fluxes from BNC (R_{soil})

Equation 6: Autotrophic Respiration from turfgrass biomass

Fluxes from TNC (R_{turf}) – Fluxes from BNC (R_{soil})

Table 9: Respiratory Fluxes from the different components in a turfgrass ecosystem

Components	Plots used in calculation	Type of respiration	Respiratory Flux (μmol m^{-2} s^{-1})	Percentage of total (%)
Turfgrass (roots and leaf)	TWC–BWC	Autotrophic	3.87	54.9
Soil	BNC	Soil & Heterotrophic	2.09	29.6
Clippings	BWC-BNC	Heterotrophic	1.09	15.5
Total	TWC		7.05	100

The adoption of the mass balance approach to understanding respiratory fluxes allows for the possible calculation of fluxes from each component found in the turfgrass ecosystem. The calculated contributions of each factor (autotrophic and heterotrophic respiration) are similar to values being adopted by the scientific community for ecosystem understanding, that approximately 50% of ecosystem respiration (Trumbore, 2006).

5.2. Comparison between management regimes

The difference in management regimes resulting in the presence or absence of turf and/or clippings led to a statistical difference in the observed CO_2 effluxes (Table 4) and soil environmental conditions (Table 2). It is hypothesised that the difference was the result of 1) contribution of both above and belowground respiratory fluxes, and 2)the availability and abundance of organic material favourable for microbial activity.

5.2.1. Comparing effects of presence or absence of turfgrass

Turfgrass significantly impacts the amount of fluxes as they represented respiring biomass that is present both above and below the surface of the soil. The leaf blade and the roots would contribute to autotrophic respiration and encourage heterotrophic respiration. The effect of turfgrass has a significant impact on ecosystem respiration as observed from both Figure 8 and Table 4. Through the use of the mass balance approach, the difference in fluxes between BNC and TNC and BWC and TWC would give us an idea of the possible contribution of autotrophic respiration to ecosystem respiration.

Table 10: Possible contribution of respiratory fluxes from aboveground vegetation respiration

Mean CO_2 efflux (μmol m^{-2} s^{-1})		Difference between Plots (Contribution from Turf)	Possible % Contribution of Respiration by Turf (Autotrophic)
TNC 8.54	**BNC** 2.09	6.45	75.5
TWC 7.05	**BWC** 3.18	3.87	54.9

The fluxes that are influenced by the presence of turf ranges from 3.87-6.45 $\mu molm^{-2}s^{-1}$, which consists of 55-76% of ecosystem respiratory fluxes (Table 10). While the arithmetic mass balance approach is highly simplistic due to the multiple assumptions, the results are coherent with reviews conducted by Hanson et al., (2000), Hogberg et al (2001) and Zhou et al., (2007) who estimates that the relative contribution of autotrophic respiration used during metabolic activity for the growth of roots and associated mycorrhizae generally accounts for approximately half of total soil CO_2 efflux from soils.

The difference between plots may differ by a large margin, as a result of a multiplicity of factors, which are not accounted for when taking a simple mass balance approach to account for autotrophic respiration. The presence or absence of clippings would possibly change the quantity and activity of microbial activity found on the plots (Holland & Coleman, 1987; Billings & Ballantyne, 2013). BWC represents an extreme scenario and a highly unlikely one for urban green areas as plots are rarely kept intentionally bare through application of herbicides and weeding. In contrast, bare plots in urban areas are the result of trampling and compaction and thus would result in a dearth of organic matter. Although BWC is barren it continues to have a very shallow A horizon, as the site does not experience the same degree of disturbance. Thus it would be critical to view fluxes over BWC as the maximum possible flux that could be observed over bare areas in an urban complex.

Understanding that the contributing fraction of the heterotrophic component of respiration accounts for approximately half that of total respiration values but account for 63% of the total C pool, allows us to better appreciate the importance and role of vegetation in urban green areas. The role of vegetation can thus be appreciated in terms of their C storage potential.

5.2.2. The effect of clippings

The effect of clippings was expected to make a significant difference in the amount of fluxes observed as they represented readily decomposable material, which would lead to higher fluxes in plots BWC and TWC comparison to plots BNC and TNC which do not have them. This is increasingly significant, especially if fluxes are found to significantly increase the observed effluxes found over green areas, as horticultural groups and researchers advocate the application of clipping on site to increase the organic N and C on site. While studies have been made into the N (Qian, et al., 2003) and C (Takahashi, et al., 2008) contribution of clippings to the soil profile , fewer have accounted for the possible difference in C fluxes resulting from application of clippings.

Table 11: Contributing fluxes by clippings to Ecosystem Respiration

Mean CO_2 efflux (μmol m^{-2} s^{-1})		Difference between Plots (Contribution from clippings)	Possible % Contribution of Clippings (Heterotrophic)
BWC 3.18	**BNC** 2.09	1.09	34.27
TWC 7.05	**TNC** 8.54	-1.49	-21.13

Trumbore (2000) and Giardina et al., (2004) have noted that heterotrophic respiration associated with the utilisation of recently produced organic material as a substrate accounts for approximately 40% of soil efflux. In comparison the percentage contribution by clippings when comparing BNC and BWC appears to be approximately 34% (Table 11).

While it is not readily observed from Figure 13, a one-way ANOVA test (Table 4) shows that the fluxes observed from the plots are significantly different from each other. There is a slight increase in the mean CO_2 flux observed between BNC and BWC, it should be noted that the converse is observed in comparison between plots TNC & TWC, which was not hypothesised/expected. The presence of clippings within the litter bags appeared to restrict/prohibit the growth grass and thus reduced the amount of the CO_2 observed. The contributing fluxes of the clippings are much lower than that of the aboveground leaf biomass, in addition to the quick decomposition rates (and thus contributing fluxes), resulting in mean fluxes for TWC being lower than TNC (Table 11).

It is also observed that the difference between the fluxes for TWC and TNC are negative with TNC having lower average fluxes (Table 11). This was not expected, since clippings are a source of organic material promoting heterotrophic respiration, increasing fluxes as seen through the difference between plots BWC and BNC. It is put forth that the less than expected contribution to CO_2 fluxes by clippings could be due to the rapid decomposition of labile material of the recently clipped turf. It was found in an incubation study by Cleveland et al (2004) that more than 70% of the organic matter compounds from leaf litter decomposed within 10 days. This pattern could not be readily discerned from the data (Figure 18).

Other than the quick decomposition of labile material which could have resulted in a less than expected rise in observed effluxes, it also results in a suppression of effluxes in TWC as compared to TNC (Figure 12). It is hypothesised that the lower fluxes of TWC in comparison to TNC could be as a result of the interference of CO_2

production and transport due to the presence of clippings on the surface of the turf, which would be water saturated during periods where rainfall occurs. Another possibility could be the inhibition of photosynthesis due to shading effects as a result of the presence of the litter bags being placed on the surface of the turf in TWC.

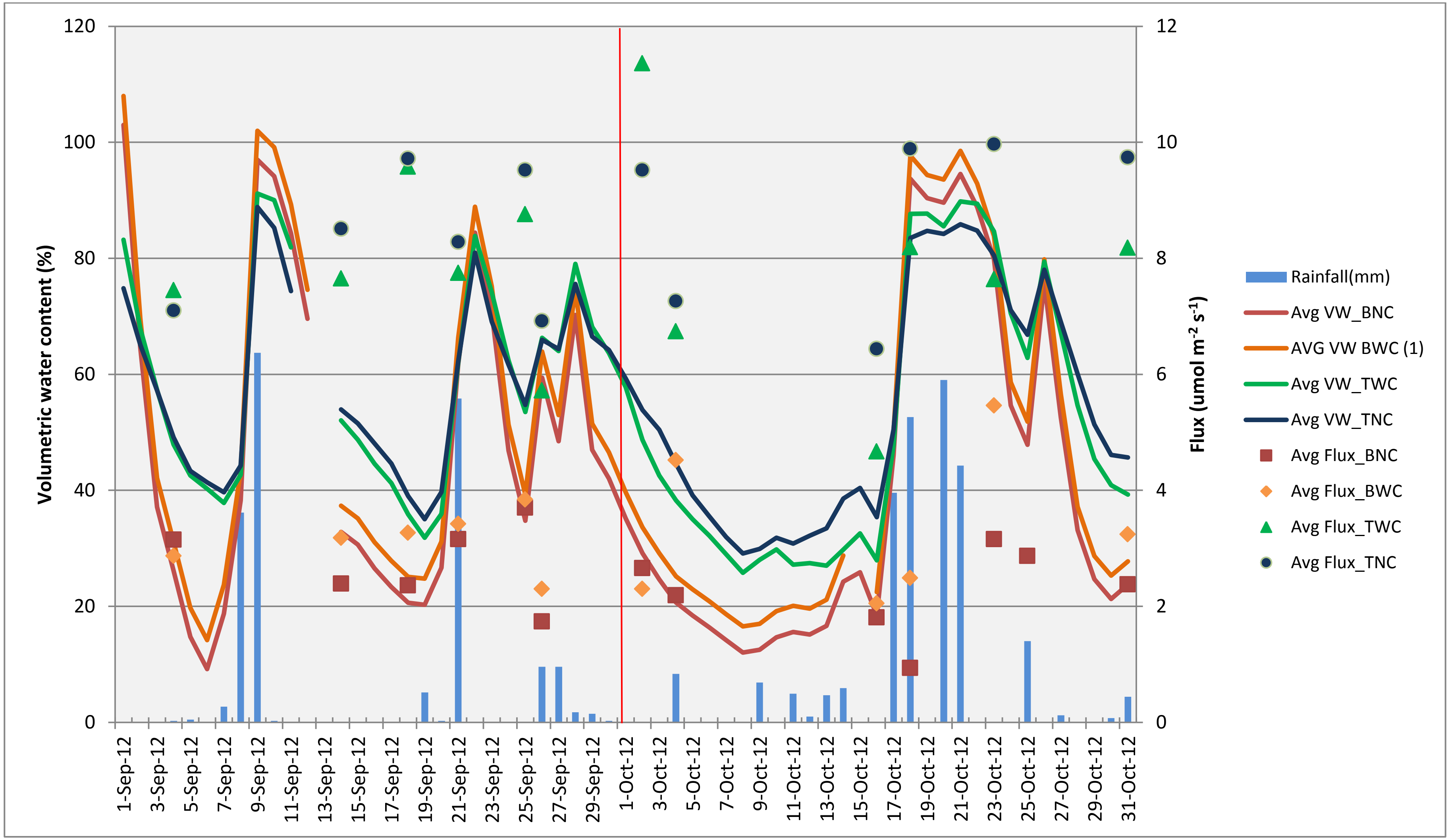

Figure 18: Soil moisture content and fluxes (1 month before and after clipping)

5.2.3. Initial carbon budget estimates

The data reveals that the different fluxes of autotrophic and heterotrophic respiration at the site are influenced by human management techniques. To approximate the effectiveness of turf to sequester C from the atmosphere, the primary productivity and thus the NEP of the site was approximated through the mass of clippings obtained between mowing events. The mass of clippings would be representative of the net C accumulation rate, as gross primary productivity (GPP) exceeds ER. On short time scales, net ecosystem production (NEP) is the difference between gross primary production (GPP) and ER (Equation 7).

Equation 7: Net Ecosystem Production (Chapin, et al., 2006; Lovett, et al., 2006)

NEP = GPP - ER

Equation 8: Rate of C uptake through primary production

Mass of clippings collected between clippings / days between clippings / area x C concentration

Equation 9: Carbon balance between photosynthesis and respiration

Rate of C uptake – Rate of C respired

Table 12: C Capture and Loss from TWC

C captured in the aboveground biomass (gC/m^2/day)		**C loss through respiration (TWC) (gC/m^2/day)**		**C loss through respiration (BNC) (gC/m^2/day)**	
Mass of clippings (dry)	2454g	µmol →mol	10^6	µmol →mol	10^6
Days bet. clippings	41	S → day	86 400	S → day	86 400
Area	25m^2	mol → g	12	mol → g	12
C concentration	42.6%				
C =	1.02	C =	7.31	C =	2.17

The GPP of the site can thus be approximated to be 6.29 gC m^{-2} day^{-1}, given the relationship between NEP, GPP and ER (Equation 7). It should be noted that the given GPP and NEP values proposed in this section is an underestimate as it does not account for the increase in biomass below that of the mowing height, such as the increase in root density. Conversely the ER respiration values would be an overestimate considering that the C efflux rates observed are based upon dark respiration which generally results in a negative Net Ecosystem Production (NEP) (Chapin, et al., 2006).

The absence of turf over bare ground (BNC and BWC), represents a net loss of C from exposed soil (Table 12). The presence of turf is not only a means of sequestering atmospheric carbon, but also as a means of maintain and possibly increasing the soil C stock, within the A1 and A2 horizons where a significant portion of the C stocks are held in the urban turfgrass C pool (Table 1).

5.3. Environmental Influences

The influence of temperature (Jenkinson, et al., 1991; Katterer, et al., 1998) and soil moisture (Parker, et al., 1984; Davidson, et al., 2000) has been well documented. However, the relationship between soil respiration and these two environmental factors are found to vary between ecosystems (Mosier, 1998; Rustad, et al., 2000). As such this research responds to the call for more measurements and contributes to the existing body of work, owing to its unique nature of it being one of the pioneering studies to be conducted in the geographic tropics, looking specifically at urban turf as an ecosystem. While the previous chapter focused on how management techniques and consequently how experimental methodology allowed insights into the C dynamics of the urban green ecosystem. This chapter focuses on the influences of soil temperature and moisture on observed effluxes taking into account the differences in experimental treatments. As neither temperature nor moisture is able to fully account for respiratory fluxes, their confounding influences were analysed with the widely used multiplicative model in addition to the simplistic multivariate analysis.

5.3.1. Temperature influences

The sensitivity of respiratory fluxes to temperature is of concern especially since global warming is acknowledged to be a reality. The increase in temperatures, results in the increase of fluxes through the increase of both biological (microbial, plant, fungal or animal) activity and changes physical properties in the soil which results in an increase of CO_2 fluxes from the soil surface, consequently temperature was expected to have a positive relationship with effluxes.

Temperature dependence of soil fluxes has been well studied for some time, however, with site specificity of temperature dependence on soil respiration (Tang, et al., 2006) it would be prudent to study and understand the relationship between temperature and soil effluxes from a tropical urban green area in order to test if the same relationships exist. The soil temperature regime of green areas in the urban complex is vastly different from that of the urban forest, much less that of comparable tropical grasslands. This is due not only to the difference in species and soil types but also the urban morphology and resulting climatic and anthropogenic inputs (Klein, et al., 2005). Most studies recognise the site-specificity of their data and thus it would be prudent to do the same.

For data analysis, an exponential relationship was assumed between temperature and soil effluxes following the works of (Davidson, et al., 1998; Bekku, et al., 2003). The assumptions behind an exponential relationship between temperature and fluxes were based on both field and laboratory observations. However, it would be prudent to note that the temperature range (0-35°C) at which the relationship was observed for are not representative of those found in tropical climates (Table 2). Regression analysis (Table 6) for the various plots show R^2 values ranging from 0.14 to 0.23. This could due to the higher temperatures and the relatively small range of observed temperatures (26-39°C) as compared to those studies. As noted by Lellei-Kovacs et al. (2011), the goodness of fit for temperature-ecosystem respiration functions is strongly dependent on the temperature range, in which the data were obtained. Thus in the tropical temperature regime, it is unlikely that there will exist a large range of temperatures in comparison to both laboratory tests and data collected from temperate climates.

Unlike boreal and temperate regions, where a wide range of temperatures are experienced, respiratory flux values exhibited large seasonality. A study by Hashimoto et al (2004), in Thailand where the range of temperatures observed was fairly constant; a similar lack of distinct relationship between soil respiration and soil temperature was noted. They hypothesised that soil moisture played a greater role in governing soil respiration than soil temperature does. In addition, they put forth that seasonality limited by soil moisture is small in the tropics. In addition, the optimal temperature for soil respiration may only be detected in the presence of severe environmental constraint, such as large temperature fluctuations, serious water shortage or low quantities of soil organic matter (Lellei-Kovacs, et al., 2011), which was not present at our site. It should be noted in light of the shallow depth of observation, temperature sensitivity of soil respiration rates to temperature changes are lower in surface soils compared to subsurface soils (Fierer, et al., 2003). The low convergence of temperature to fluxes as demonstrated through the low R^2 values calls for the consideration of alternative and confounding effects of temperature and soil moisture.

5.3.1.1. Q_{10} Empirical Model

Empirical models are favoured over process based models to simulate soil respiration due to the complexity of the soil environment (Janssens & Pilegaard, 2003). There have been numerous temperature response functions being introduced, however none seems to be particularly better than the others (Janssens, et al., 2003). The use of Q_{10} values has been used extensively as witnessed through the wide adoption of Van't Hoff's (1899) equation and its variants; however it should be noted that annual Q_{10} values are only reflective and accurate when there is an absence of simultaneously co-varying variables. The Q_{10} and the R_{10} functions calculated for the site (Table 7) are similar with incubation experiments by Bekku et al. (2003), who found Q_{10} values ranging from 2.1-2.7. As noted by Janssens and Pilegaard (2003), the fluxes of most Q_{10} values do not represent only the temperature response of soil effluxes; rather it is the combined influence of temperature on root biomass activity, moisture conditions and other lesser known variables. However, there is no clear indication as to how Q_{10} is affected by factors other than temperature (Fang & Moncrieff, 2001; Tjoelker, et al., 2001). A site specific Q_{10} and R_{10} was computed for the various plots (Table 7) in contrast, Velasco, et al. (2013) used the works of Machecha et al. (2010) and Bond-

Lamberty and Thomson (2010) for his Q_{10} (1.4) and R_{10} (2.07) values respectively. As a result his calculated value of 4.08µmolm^{-2}s^{-1} for soil respiration at his urban residential site is not similar to our observations.

The temperature response of respiration has recently been in question (Luo, et al., 2001; Tjoelker, et al., 2001); with Cox et al. (2000) suggesting that models have largely overestimated terrestrial ecosystem respiration cycles. With moisture being acknowledged to be the second most influential factor of soil fluxes, the next chapter aims to investigate the independent role of moisture with respect to observed fluxes.

5.3.2. Moisture Dependence

While the relationship between temperature and soil effluxes has been extensively studied and accepted by the scientific community, there have been studies that have shown that respiration is negatively correlated with temperature and positively related to soil water (Xu & Qi, 2001; Qi, et al., 2002; Reichstein, et al., 2002) over a limited range of soil water content. This demonstrates the relative importance of moisture and its influence on fluxes. The varying effects of soil water content have been attributed (through laboratory investigations to be due) to mechanistic factors such as; the limitation of diffusion of substrate in water films, to stresses resulting from moisture deficit (Orchard & Cook, 1983; Linn & Doran, 1984; Skopp, et al., 1990), and to the reduction of diffusion through pore spaces at high water contents (Linn & Doran, 1984; Skopp, et al., 1990). Acknowledging that soil contains biological organisms, the presence or absence of moisture in the soil influences microbial activity such as litter decomposition, N mineralisation, nitrification and de-nitrification (Jackson, et al., 1989; Schimel, et al., 1989; Burke, et al., 1997). Under most natural conditions, water content are not in their optimal ranges as such consideration of soil water effects in the relationships between respiration and environmental elements is critical for accurate prediction of global climate change scenarios.

Howard and Howard (1993) put forth that a parabolic relationship between soil respiration and soil moisture exists; in addition Davidson et al. (2000) showed that soil respiration is highest at intermediate water content and that respiration decreases at moisture contents below or above the optimal range. As such, a polynomial relationship was hypothesised between soil moisture and soil effluxes. Unlike soil temperature, soil moisture ranges were not significantly modified by the presence or absence of turfgrass, though it is noticeable that the range of experienced moisture is less in the turfed plots compared to the bare plots. A regression between temperature and fluxes (Table 8), shows mixed results with regards to the effect of the different treatments with low correlation (R) and predictive (R^2) relations for plots BWC and TNC. However, the high correlation between moisture and fluxes are higher for the remaining 2 plots as compared to (Table 6)

It has been suggested that the rewetting of dry soil due to irrigation or rainfall, increases CO_2 effluxes by increasing microbial activities, C mineralisation, and respiration (Sparling & Ross, 1988; Van Gestel, et al., 1993; Calderon & Jackson, 2002). This relationship was not observed from the data collected (Figure 15). This could be due to the lack of observations made under all soil moisture ranges due to the experimental methodology and sampling frequency. Furthermore, the lack of an extreme dry spell, where there was a moisture deficit was not experienced at the site (Figure 15). As such any possible increase of fluxes would be less drastic. However as noted by Lellei-Kovacs, et al. (2011), that the intermediate optimal range of moisture levels which results in the higher possible soil effluxes, is seldom observed under environmental conditions. This is confounded by the shallow A horizons, followed by a sharp change to high sand and clay contents, resulting in sharp changes in soil moisture values.

Inhibition of soil respiration in drier soils is an effect of desiccation stress while inhibition in more moist areas is a result of the development of anaerobic conditions (Healy, et al., 1996; Davidson, et al., 1998). It could be observed that during the month of November (Figure 15), the rate of soil respiration from BNC is lower than the months that preceded it. However a similar observation could not be made for the other plots and this could be due to the presence of clippings and turf, which confounds the relationship. Increased CO_2 flux after irrigation or after a heavy rain in dry soil increasing C mineralisation has been observed (Howard & Howard, 1993; Curtin, et al., 2000). This could be due to a large proportion of soil CO_2 flux being contributed by respiration from plant roots, rhizosphere, and microbial flora and fauna (Rochette & Flanagan, 1997; Curtin, et al., 2000); it is likely that irrigation of dry soil would increase microbial activities and CO2 emissions. It was also found that initial rainfall leading to rewetting of the soil resulted in high effluxes. However, over subsequent rewetting events efflux gradually decreased (Sotta, et al., 2004).

The influence of moisture on respiration should not be understated as mentioned by Flanagan and Johnson (2005) that soil moisture was the dominant environmental factor that controlled seasonal and inter-annual variation in respiration, when variation in temperature is constant. In consideration that single varying factors are usually absent in the natural environment, increasing emphasis should be placed on understanding the combined effects of multiple important factors.

5.4. Other considerations/Combined effects of soil temperature and soil moisture

Studies attempting to identify the independent relationship between CO_2 fluxes and soil temperature or soil moisture are both well tested and established as described in the above sections, however it is often based on the assumption that it is there exists no other influences. Since it is widely understood that soil temperature and moisture co-vary with each other, it would be prudent to understand the possible relationship(s) they have in combination on observed respiratory fluxes.

Combined or multiple factor analysis is less common in literature and practice, though some studies have sought to establish a relationship of soil respiration rate with soil moisture and temperature simultaneously (Lloyd & Taylor, 1994; Davidson, et al., 1998; Davidson, et al., 2000; Xu & Qi, 2001; Reichstein, et al., 2002). Studies attempting to understand the influence of multiple factors largely assume that the effects are additive (Mielnick & Dugas, 2000; Reichstein, et al., 2002; Zhou, et al., 2007). One which is considered to be restrictive and inaccurate (Wen, et al., 2006), it continues to be the most adopted approach due to its straight forward nature (Fang & Moncrieff, 1999; Armacher & Mackowiak, 2011). As a result of these shortcomings in the understanding of the environmental dynamics of respiratory process, models today are limited in their utility.

It is increasingly being recognised that the factors of soil temperature and soil moisture alter the parameters of each other (Qi, et al., 2002; Reichstein, et al., 2002; Xu, et al., 2004). This is not a straight forward process and requires much consideration beyond assuming the independent nature of each of the variables and employing simple regression analysis. As noted by (Cheng, et al., 2010), the counteracting effects of temperature and moisture are difficult to differentiate as the loss of moisture could depress decomposition and thus offset the potential increases coming about from warming. Although increased temperature under a warming climate may accelerate microbial activity at a given soil moisture (Hobbie, 1996; Shaw & Harte, 2001), warming also decreases soil moisture, which strongly depresses soil microbial activity (Shaw & Harte, 2001). Current models, which work to elucidate simultaneous relationships between the two factors and more, are highly site specific due to the unique relationships.

The distinct clustering of flux values following plot treatments (Figure 17) is expected due to the distinct nature of the ground cover as a result of the experimental setup, which modifies both soil temperature and soil moisture (Table 2). The different treatments also modify the soil environment conditions, such that the mean and range of soil temperature and moisture are different for the different plots, though there is less differentiation between TNC and TWC. BWC has the widest range of temperature and soil moisture values in comparison to the other plots.

Temperature and moisture influences the rates of ecosystem respiration in an urban grassland, though the correlations between each might not be strong individually, however when considered in tandem better results should be apparent (Figure 17). Understanding the bulk system responses of respiration to factors like temperature and moisture; while useful for filling data gaps are ultimately like to be misleading as they integrate responses of a number of different process, and co-vary with other processes, such as photosynthesis (Davidson, et al., 2005).

6. Conclusion

Urban green areas in tropical cities hold great potential for C sequestration and storage given the established relationships in temperate climates and the favourable conditions found in tropical areas. However, the C potential of green areas is dependent not only on their current pools, but also the rate of C uptake and release. This study has shown that the rates of efflux (in the dark) are influenced by both landscape management strategies and environmental factors. The magnitude of the efflux would thus determine both the rates of sequestration and the size of the pool. The identification of the influence of factors goes towards determining the strength of the C source/sink of urban green areas.

6.1. Effects of Management and Policy Implications

This study has shown that landscape management practices, especially through the inclusion of turfgrass on a landscape significantly modifies the observed CO_2 efflux ($p<0.05$) thus, proving hypothesis H1a to be true that urban landscape management practices of turfing areas has a significant impact on observed effluxes. The presence of autotrophic material during measurement would consist of the presence and contribution of autotrophic respiration by the above and belowground plant parts in addition to heterotrophic activity. This is a contribution to atmospheric CO_2 which C sequestration programmes attempt to mitigate. While green areas absorb a significant amount of CO_2 as a result of photosynthetic activity, this study finds that there is a net loss of C from turfed areas to the atmosphere (Section 5.2.3).

The effect of clippings to total efflux is less pronounced than first hypothesised, although it still significantly modifies the fluxes ($p<0.05$) as compared to the rest of the treatments, possibly due to the rapid decomposition of labile material. This study did not account for the contribution of clippings to SOM/SOC; the inclusion of clippings onsite would increase C sequestration potential and also serve as a source of N fertilisation (Kopp & Guillard, 2002).

Singapore is well positioned within the region to significantly influence the development of sustainable cities. Asian cities can improve their C footprint by prioritising and incorporating green areas as part of their landscape. Some other important considerations include the use of improved building design to incorporate green spaces (e.g. green roofs), hybrid green measures (e.g. bio-swales that act as flood water retention and green areas) and enhancing awareness of the biophysical environment. This is in combination to manage the intensity of landscape management which would include less frequent clippings to allow increased C sequestration potential.

6.2. Effects of Environmental Factors on Soil Effluxes

From the calculated Q_{10} and R_{10} results, we can see that turfed plots (Q_{10}: 2.2-2.9; R_{10}: 1.1-1.4) are more susceptible to changes in temperature as compared to bare plots (Q_{10}: 2.1-2.3; R_{10}: 0.3-0.5). Regression analysis based on the exponential relationship between temperature and fluxes has demonstrated a moderate correlation (R=0.34-0.48, $p<0.05$) between observed temperatures and fluxes. This is a cause for concern in light of climate change where higher temperatures of 2.0-5.4^{o}C in the year 2090-2099 based on the IPCC A2 estimates. Increases in temperature would result in higher soil CO_2 effluxes, implying that the effectiveness of green areas in mitigating urban atmospheric C would be reduced.

Unlike the temperature response to effluxes, moisture dependency of fluxes is more complicated. All the plots appeared to follow the quadratic relationship as in Davidson et al. (2000), with varying strengths of correlation (R=0.08-0.723, $p>0.05$), thus lending some support to the H2a hypothesis Due to the mixed results between the treatments (bare vs. turfed and presence vs. absence of clippings), this study was unable to determine with certainty the key factor (autotrophic or heterotrophic respiration) which controls effluxes under such a relationship. While it is qualitatively observed that fluxes in November, are lower especially for the BNC, we were unable to prove the wetting/drying hypothesis with regards to the in-situ soil moisture content (H2bi)

The soil-atmosphere C efflux response to environmental factors that is presented in this study is relevant to future climate scenarios of increased temperatures and soil moisture conditions. Gaining insights into such responses of C effluxes with varying temperature and moisture would allow us to better assess the C sequestration potential of green areas. However, the impact of climate change on soil respiratory fluxes is more complicated than a modified response due to environmental factors. Rather, it has the ability to change species composition of both autotrophic and heterotrophic organisms (Castro, et al., 2010). Total amount of C store in urban ecosystems depends on a multiplicity of factors such as the build-up density of a city, dominant vegetation types, rates of C uptake and release by vegetation, C release by soil, as well as management of vegetation and soils (Churkina, 2012).

6.3. Final Remarks

While the enhancement of the living environment and the improvement in the quality of life as a result of inclusion of green features such as turf and trees should be acknowledged, increasing recognition should be given to such features for the ecosystem services they play, such as the amelioration of temperature and the improvement of water quality. Turfgrass can play an important role in helping reduce atmospheric CO_2, especially since it a dominant vegetation type in urban cities.

The results from this study indicate that depending on vegetative conditions and management intensity, the CO_2 effluxes of turfgrass was high and with large variability. The provide an insight into C dynamics of turf covered areas in the city, though the values should not be taken as universal, given that such studies are highly site specific. Despite the specificity, this study offers insights into the possible patterns we may observe for other tropical grass species and soil surfaces in urban areas.

Due to the limitations of time and resources associated with this study, it was not possible to have a longer observation period, which might have allowed us to capture other significant patterns in relation to environmental factors and also increased the data set to allow greater insight to the relationships between effluxes and soil temperature and moisture. In order for us to obtain a better understanding of the respiratory values, it would be necessary for us to obtain ecosystem respiration values in the light. This could be achieved through the employment of clear chambers which do not interfere with photosynthesis processes of the plants.

Additionally, to close account for the NPP of the system, the use of EC systems could be introduced. For this and other studies to make a plausible policy recommendation on urban green areas, specifically to turfgrass, future works would have to consider the rate of accumulation in both the aboveground and belowground biomass, and the CO_2 emissions related with landscape management strategies, in relation to observed CO_2 effluxes.

It is also acknowledged that a myriad of factors also influence the rate of surface-atmosphere effluxes and that the measurements of soil moisture and soil temperature captured would not be able to account for all the variables which influence fluxes. Other environmental factors which should be considered include that of the wind(speed) which would influence the readings as mentioned in Section 3.2.1. The variables of cloud cover and solar radiation should also be considered given that they influence the rate of evaporation, transpiration and photosynthesis. In order to make an accurate judgment as to the effectiveness of green areas as a means to mitigate CO_2 emissions in urban areas, CO_2 is not the only agent that should be considered. Consequently we would need to consider the effects of other GHG and their response to the different management and environmental conditions, such as nitrous oxide and methane which are the result of both clippings and high water moisture respectively, as they could hold the key into determining the true effectiveness of green areas as sites of C sequestration. To obtain a more wholesome understanding of C sequestration rates, we would need to quantify the C cost of mowing, irrigation, fertilization and remove it from the calculated SOC sequestration (Zirkle, et al., 2011).

Bibliography

Armacher, M. C. & Mackowiak, C. L., 2011. Seasonal Soil CO2 Flux Under Big Sagebrush (Artemisia tridentata Nutt.). *Natural Resources and Environmental Issues,* Volume 17.

Aubinet, M. et al., 2000. Estimates of the Annual Net Carbon and Water Exchange of Forests: The EUROFLUX Methodology. *Advances in Ecological Research,* Volume 30, pp. 113-175.

Bain, W. G. et al., 2005. Wind-induced error in the measurement of soil respiration using closed dynamic chambers. *Agricultural and Forest Meteorology,* Volume 131, pp. 225-232.

Bekku, Y. S. et al., 2003. Effect of warming on the temperature dependence of soil respiration rate in arctic, temperate and tropical soils. *Applied Soil Ecology,* Volume 22, pp. 205-210.

Billings, S. A. & Ballantyne, F., 2013. How interactions between microbial resource demands, soil organic matter stoichiometry,and substrate reactivity determine the direction and magnitude of soil respiratory responses to warming. *Global Change Biology,* Volume 19, pp. 90-102.

Bond-Lamberty, B. & Thomson, A., 2010. A global database of soil respiration data. *Biogeosciences,* Volume 7, pp. 1915-1926.

Bond-Lamberty, B., Wang, C. & Gower, S. T., 2004. Contribution of root respiration to soil surface CO2 flux in a boreal black spruce chronosequence. *Tree Physiology,* Volume 24, pp. 1387-1395.

Boone, R. D., Nadelhoffer, K. J., Canary, J. D. & Kaye, J. P., 1998. Roots exert a strong influence on the temperature sensitivity of soil respiration. *Nture,* Volume 396, pp. 570-572.

Bowden, R. D. et al., 1993. Contributions of aboveground litter, belowground litter, and root respiration to total soil respiration in a temperate mixed hardwood forest. *Canadian Journal of Forest Research,* Volume 23, pp. 1402-1407.

Bowden, R. D., Newkirk, K. M. & Rullo, G. M., 1998. Carbon dioxide and methane fluxes by a forest soil under laboratory controlled moisture and temperature conditions. *Soil Biology and Biochemistry,* 30(12), pp. 1591-1597.

Burke, I. C., Lauenroth, W. K. & Parton, W. J., 1997. Regional and Temporal Variation in Net Primary Production and Nitrogen Mineralization in Grasslands. *Ecological Society of America,* 78(5), pp. 1330-1340.

Buscot, F., 2005. What are soils?. In: F. Buscot & V. Ajit, eds. *Microorganisms in Soils: Roles in Genesis and Functions.* Berlin: Springer, pp. 3-17.

Calderon, F. J. & Jackson, L. E., 2002. Rototillage, disking, and subsequent irrigation: effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. *Journal of Environmental Quality,* 31(3), pp. 752-758.

Carlson, T. N. & Arhur, T. S., 2000. The impact of land use - land cover changes due to urbanisation on surface microclimate and hydrology: a satelite perspective. *Global and Planetary Change,* Volume 25, pp. 49-65.

Castro, H. F. et al., 2010. Soil microbial community responses to multiple experimental climate change drivers. *Applied and Environmental Microbiology,* 76(4), p. 999=1007.

Chapin, F. I. et al., 2006. Reconcilling carbon-cycle concepts, terminology, and methods. *Ecosystems,* Volume 9, pp. 1041-1050.

Cheng, X. et al., 2010. Experimental warming and clipping altered litter carbon and nitrogen dynamics in a tallgrass prairie. *Agriculture, Ecosystems and Environment,* Volume 138, pp. 206-213.

Churkina, G., 2008. Modelling the carbon cycle of urban systems. *Ecological Modelling,* Volume 216, pp. 107-113.

Churkina, G., 2012. Carbon Cycle of Urban Ecosystems. In: R. Lal & B. Agustin, eds. *Urban Ecosystems.* Neatherlands: Springer, pp. 315-330.

Cleveland, C. C., Neff, J. C., Townsend, A. R. & Hood, E., 2004. Composition, Dynamics, and Fate of Leached Dissolved Organic Matter in Terrestrial Ecosystems: Results from a Decomposition Experiment. *Ecosystems,* pp. 275-285.

Coleman, M. D., Friend, A. L. & Kern, C. C., 2004. Carbon allocation and nitrogen acquisition in a developing Populas deltoides plantation. *Tree Physiology,* Volume 24, pp. 1347-1357.

Conant, R. T., Paustain, K. & Elliott, E. T., 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications,* 11(2), pp. 343-355.

Cox, P. M. et al., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Letters to Nature,* Volume 408, pp. 184-187.

Crawford, B., Grimmond, C. B. & Christen, A., 2010. Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area. *Atmospheric Environment,* Volume 45, pp. 896-905.

Curtin, D. et al., 2000. Tillage Effects on Carbon Fluxes in Continuous Wheat and Fallow - Wheat Rotations. *Soil Science Soiciety of America Journal,* 64(6), pp. 2080-2086.

Davidson, E. A., Belk, E. & Boone, R. D., 1994. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology,* Volume 4, pp. 217-227.

Davidson, E. A., Jassens, I. A. & Luo, Y., 2005. On the variability of respiration in terrestrial ecosystems: moving beyond Q10. *Global Change Biology,* 12(2), pp. 154-164.

Davidson, E. A., Savage, K., Verchot, L. V. & Navarro, R., 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agriculture and Forest Meteorology,* Volume 113, pp. 21-37.

Davidson, E. A. & Trumbore, S., 1995. Gas diffusivity and production of CO2 in deep soils of the eastern Amazon. *Tellus,* Volume 47B, pp. 550-565.

Davidson, E. A. et al., 2000. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. *Biogeochemistry,* Volume 48, pp. 53-69.

Dhakal, S., 2010. GHG emissions from urbanization and opportunities for urban carbon mitigation. *Current Opinion in Environmental Sustainability,* Volume 2, pp. 277-283.

Diffenbaugh, N. S., 2009. Influence of modern land cover on the climate of the United States. *Climate Dynamics,* 33(7/8), p. 945.

Dore, S. et al., 2003. Cross validation of open-top chamber and eddy covariance measurements of ecosystem CO2 exchange in a Florida scrub-oak ecosystem. *Global Change Biology,* Volume 9, pp. 84-95.

Drake, B. G. et al., 1996. Acclimation of photosynthesis, respiration and ecosystme carbon flux of a wetland on Chesapeake Bay, Maryland to elevated atmospheric CO2 concentration. *Plant and Soil,* Volume 187, pp. 111-118.

Dugas, W. A., Heuer, M. L. & Mayeux, H. S., 1999. Carbon dioxide fluxes over bermudagrass, native prairie, and sorfhum. *Agricultural and Forest Meterology,* Volume 93, pp. 121-139.

Falge, E. et al., 2002. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. *Agricultural and Forest Meteorology,* Volume 113, pp. 75-95.

Fang, C. & Moncrieff, J. B., 1999. A model for soil CO2 production and transport 1:: Model development. *Agriculture and Forest Meteorology,* 95(4), pp. 225-236.

Fang, C. & Moncrieff, J. B., 2001. The dependence os oil CO2 efflux on temperature. *Soil Biology and Biochemistry,* 33(2), pp. 155-165.

Fierer, N., Allen, A. S., Schimel, J. P. & Holden, P. A., 2003. Controls on microbial CO2 production: a comparison of surface and subsurface soil horizons. *Global Change Biology,* Volume 9, pp. 1322-1332.

Fierer, N. & Schimel, J. P., 2003. A proposed mechanism for the pulse in carbon dioxide production commonly observed following the rapid rewetting of a dry soil. *Soil Science Society of America Journal,* Volume 67, pp. 798-805.

Flanagan, L. B. & Johnson, B. G., 2005. Interacting effects of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. *Agricultural and Forest Meteorology,* Volume 130, pp. 237-253.

Flechard, C. R. et al., 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. *Agriculture Ecosystems and Environment,* Volume 121, pp. 135-152.

Foley, J., 2005. Global Consequence of Land Use. *Science,* Volume 309, pp. 570-574.

Fontaine, S. et al., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature,* Volume 450, pp. 277-280.

Fortin, M. C., Rochette, P. & Pattey, E., 1996. Soil carbon dioxide fluxes from conventional and no-tillage small-grain cropping systems. *Soil Science Society of America Journal,* Volume 60, pp. 1541-1547.

Friedlingstein, P., Dufresne, J. -L., Cox, P. M. & Rayner, P., 2003. How positive is the feedback between climate change and the carbon cycle?. *Tellus ,* Volume 55B, pp. 692-700.

Gao, F. & Yates, S. R., 1998. Laboratory study of closed and dynamic flux chambers: Experimental results and implications for field application. *Journal of Geophysical Research Atmospheres,* 103(D20), pp. 26115-26125.

Gebhart, D. L., Johnson, H. B., Mayeux, H. S. & Polley, H. W., 1994. The CRP increases soil organic carbon. *Journal of Soil and Water Conservation,* 49(5), pp. 488-192.

Giardina, C. P. et al., 2004. Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Ecosystem Ecology,* Volume 139, pp. 545-550.

Gill, R. A. & Jackson, R. B., 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytologist,* Volume 147, pp. 13-31.

Glinski, J. & Stepniewski, W., 1985. *Soil aeration and its role for plants.* Boca Raton: CRC Press.

Golubiewski, N. E., 2006. Urbanisation increases grassland carbon pools: effects of landscaping in Colorado's front range. *Ecological Application,* 16(2), pp. 555-571.

Goulden, M. L. et al., 1996. Exchange of carbon dioxide by deciduous forest: response of interannual climate variability. *Science,* Volume 271, pp. 1576-1578.

Grant, R. F., 1997. Changes in soil organic matter under different tillage and rotation: Mathematical modeling in ecosys. *Soil Science Society of America,* 61(4), pp. 1159-1175.

Groffman, P. M. et al., 2009. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. *Journal of Environmental Quality,* Volume 38, pp. 1848-1860.

Halperin, C., 2012. *Changing Cities: Singapore, the Garden City.* [Online] Available at: http://abcnews.go.com/blogs/technology/2012/07/changing-cities-singapore-the-garden-city/
[Accessed 15 July 2013].

Ham, J. M., Owensby, C. E., Coyne, P. I. & Bremer, D. J., 1995. Fluxes of CO2 and water vapour from a prairie ecosystem exposed to ambient and elevated atmosphere CO2. *Agricultural and Forest Meteorology,* 77(1-2), pp. 73-93.

Hanson, P. J., Edwards, N. T., Garten, C. T. & Andrews, J. A., 2000. Separating root and soil microbial contributions to soil respiration: A review of methods and observations. *Biogeochemistry,* Volume 48, pp. 115-146.

Hanson, P. J., Wullschleger, S. D., Bohlman, S. A. & Todd, D. E., 2000. Separating root and soil microbial contributions to soil respiration. *Tree Physiology,* Volume 48, pp. 15-146.

Hashimoto, S. et al., 2004. Soil respiration and soil CO2 concentration in a tropical forest, Thailand. *Journal of Forest Research,* 9(1), pp. 75-79.

Healy, R. W. et al., 1996. Numerical evaluation of static-chamber measurements of soil-atmosphere gas exchange: identification of physical processes. *Soil Science Society of America Journal,* Volume 60, pp. 740-747.

Hobbie, S. E., 1996. Temperature and plant species control over litter decomposition in Alaskan Tundra. *Ecological Monographs,* 66(4), pp. 503-522.

Hoff, V. J. H., 1899. *Lectures on theoretical and physical chemistry.* s.l.:London, E.Arnold.

Hogberg, P. et al., 2001. Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature,* Volume 411, pp. 789-792.

Holland, E. A. & Coleman, D. C., 1987. Litter placement effects on microbial and organic matter dynamics in an agroecosystem. *Ecological Society of America,* 68(2), pp. 425-433.

Holmgren, P., 2006. *Global land use area change matrix: Input to the fourth global environmental outlook (GEO-4),* Rome: Food and Agriculture Organisation (FAO) of the United Nations, Forestry Department,.

Howard, D. M. & Howard, P. J., 1993. Relationships between CO2 evolution, moisture content and temperature for a range of soil types. *Soil Biology and Biochemistry,* Volume 25, pp. 1537-1546.

Hutchinson, G. L. & Livingston, G. P., 2001. Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. *European Journal of Soil Science,* Volume 52, pp. 675-682.

Jackson, L. E., Schimel, J. P. & Firestone, M. K., 1989. Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil Biology and Biochemistry,* 21(3), pp. 409-415.

James, P. & Bound, D., 2009. Urban morphology types and open space distribution in urban core areas. *Urban Ecosystems,* Volume 12, pp. 417-424.

Janssens, I. A. et al., 2003. Climatic influences on seasonal and spatial difference in soil CO2 efflux. In: R. Valentini, ed. *Fluxes of Carbon, Water and Energy of European Forests.* Berlin: Springer-Verlag, pp. 233-253.

Janssens, I. A. & Pilegaard, K., 2003. Large seasonal changes in Q10 of soil respiration in a beech forest. *Global Change Biology,* 9(6), pp. 911-918.

Jenkinson, D. S., Adams, D. E. & Wild, A., 1991. Model estimates of CO2 emissions from soil in response to global warming. *Nature,* Volume 351, pp. 304-306.

Jo, H.-K. & McPherson, G. E., 1995. Carbon storage and flux in urban residential greenspace. *Journal of Environmental Managment,* Volume 45, pp. 109-133.

Kaspar, T. C. & Bland, W. L., 1992. Soil temperature and root growth. *Soil Science,* 154(4), pp. 290-300.

Katterer, T., Reichstein, M., Andren, O. & Lomander, A., 1998. Temperature dependence of organic matter decomposition: a critical review using literature data analysed with different models. *Biology and Fertility of Soils,* Volume 27, pp. 258-262.

Kaye, J. P., Mcculley, R. L. & Burke, I. C., 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. *Global Change Biology,* Volume 11, pp. 575-587.

Keith, H. & Wong, S. C., 2006. Measurement of soil CO2 efflux using soda lime adsorption: both quantitative and reliable. *Soil Biology and Biochemistry,* 38(5), pp. 1121-1131.

Klein, J. A., Harte, J. & Zhao, X.-Q., 2005. Dynamic and complex microclimate responses to warming and grazing manipulations. *Global Change Biology,* 11(9), pp. 1440-1451.

Kopp, K. & Guillard, K., 2002. Clipping Mangement and Nitrogen Fertilization of Turfgrass: Growth, Nitrogen Utilization, and Quality. *Plant Science Articles,* Volume 1, pp. 1225-1231.

Lal, R., 2012. Urban ecosystems and climate change. In: R. Lal & B. Augustin, eds. *Carbon Sequestration in Urban Ecosystems.* New York: Springer, pp. 3-9.

Lambers, H., Chapin III, S. F. & Pons, T. L., 1998. *Plant Physiology Ecology.* 2nd ed. Berlin: Springer-Verlag.

Lamptey, B. L., Barron, E. J. & Pollard, D., 2005. Impacts of agriculture and urbanisation on the climate of the Northeastern United States. *Global and Planetary Change,* 49(3-4), pp. 203-221.

Lehmann, A., 2006. Technosols and other proposals on urban soils for the WRB. *International Agrophysics,* Issue 20, pp. 129-134.

Lellei-Kovacs, E., Kovacs-Lang, E., Botta-Dukat, Z. & Kalapos, T., 2011. Thresholds and interactive effect of soil moisture on the temperature response of soil respiration. *European Journal of Soil Biology,* Volume 47, pp. 247-255.

Linn, D. M. & Doran, J. W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal,* Volume 48, pp. 1267-1272.

Liu, X. et al., 2002. Response of soil CO2 efflux to water manipulation in a tallgrass prairie ecosystem. *Plant and Soil,* Volume 240, pp. 213-223.

Lloyd, J. & Taylor, J. A., 1994. On the temperature dependence of soil respiration. *Functional Ecology,* Volume 8, pp. 315-323.

Longdoz, B., Yernaux, M. & Aubinet, M., 2000. Soil CO2 efflux measurements in a mixed forest: impact of chamber distances, spatial variability and seasonal evolution. *Global Change Biology,* Volume 6, pp. 907-917.

Lovett, G. M., Cole, J. J. & Pace, M. L., 2006. Is net ecosystem production equal to ecosystem carbon accumulation?. *Ecosystems,* Volume 9, pp. 152-155.

Lund, C. P., Riley, W. J., Pierce, L. L. & Field, C. B., 1999. The effects of chamber pressurisation on soil-surface CO2 flux and the implications for NEE measurements under elevated CO2. *Global Change Biology,* Volume 5, pp. 269-281.

Luo, Y., Sherry, R., Zhou, X. & Wan, S., 2009. Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest. *GCB Bioenergy,* 1(1), pp. 62-74.

Luo, Y., Wan, S., Hui, D. & Wallace, L. L., 2001. Acclimation of soil respiration to warming in a tall grass prairie. *Nature,* Volume 413, pp. 622-625.

Luo, Y. & Zhou, X., 2006. *Soil Respiration and the Environment.* Norman: Academic Press.

Mahecha, M. D. et al., 2010. Global Convergence in the Temperature Sensitivity of Respiration at Ecosystem Level. *Science,* Volume 329, pp. 838-840.

Matthias, A. D., Blackmer, A. M. & Bremner, J. M., 1980. A simple chamber technique for field measurment of emissions of nitrous oxide from soils. *Journal of Environmental Quality,* 9(2), pp. 251-256.

Meyer, W. S., Reicosky, D. C., Varrs, H. D. & Shell, G. G., 1987. A portable chamber for measuring canopy gas exchange of crops subject to different root zone conditions. *Agronomy Journal,* Volume 73, pp. 181-184.

Mielnick, P. C. & Dugas, W. A., 2000. Soil CO2 flux in a tallgrass prairie. *Soil Biology and Biochemistry,* 32(1), pp. 221-228.

Milesi, C. et al., 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. *Enivronmental Managment,* Volume 36, pp. 426-438.

Mosier, A. R., 1998. Soil processes and global change. *Biology and Fertility of Soils,* 27(3), pp. 221-229.

National Climate Change Secretariat, 2008. *Singapore's National Climate Change Strategy,* Singapore: National Climate Change Secretariat.

National Climate Change Secretariat, 2012. *Climate Change and Singapore: Challenges. Opportunities. Partnerships.,* Singapore: National Climate Change Secretariat.

National Parks Board, 2008. *Annual Report 07-08: My Green City. Singapore,* Singapore: National Parks Board.

National Parks Board, 2009. *News: Greener, lusher species of turfgrasses being tested - NParks sets up new turfgrass research facility at Hort Park.* [Online] Available at: http://www.nparks.gov.sg/cms/index.php?option=com_news&task=view&id=179&Itemid=50
[Accessed 15 July 2013].

Nay, M. S., Mattson, K. G. & Bormann, B. T., 1994. Biases of chamber methods for measuring soil CO2 efflux demonstrated with a laboratory apparatus. *Ecological Society of America,* 75(8), pp. 2460-2463.

Norman, J. M., Garcia, R. & Verma, S. B., 1992. Soil surface CO2 fluxes and the carbon budget of a grassland. *Journal of Geophysical Research,* Volume 97, pp. 18845-18853.

Norman, J. M. et al., 1997. A comparison of six methods for measuring soil-surface carbon dioxide fluxes. *Journal of Geophysical Research,* 102(D24), pp. 28771-28777.

Nowak, D. J. & Crane, D. E., 2002. Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution,* Volume 116, pp. 381-389.

Oke, T. R., 1988. The urban energy balance. *Progess in Physical Geography,* Volume 12, pp. 471-508.

Olson, J. S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology,* Volume 44, pp. 322-331.

Orchard, V. A. & Cook, F., 1983. Relationship between soil respiration and soil moisture. *Soil Biology and Biochemistry,* Volume 15, pp. 447-453.

Palta, J. A. & Nobel, P. S., 1989. Root respiration for Agave deserti: Influence of temperature, water status and root age on daily pattersn. *Journal of Experimental Botany,* 40(2), pp. 181-186.

Parker, L. W. et al., 1984. Effects of simulated rainfall and litter quantities on desert soil biota: soil respiration, microflora and protozoa. *Pedobiologia,* Volume 27, pp. 185-195.

Pouyat, R. V., Yesilonis, I. D. & Nowak, D. J., 2006. Carbon storage by urban soils in the United States. *Journal of Environmental Quality,* Volume 35, pp. 1566-1575.

Prentice, I. C. et al., 2001. The Carbon Cycle and Atmospheric Carbon Dioxide. In: J. T. Houghton, et al. eds. *Climate Change 2001: The Scientific Basis.* New York: Cambridge University Press, pp. 185-225.

Qian, Y. L. et al., 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics. *Journal of Environmental Quality,* Volume 32, pp. 1694-1700.

Qian, Y. L. & Follett, R., 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. *Agronomy Journal,* Volume 94, pp. 930-935.

Qian, Y. L., Follett, R. F. & Kimble, J. M., 2010. Soil organic carbon input from urban turfgrass. *Soil Science Society of America Journal,* Volume 74, pp. 366-371.

Qi, Y., Xu, M. & Wu, J., 2002. Temperature sensitivity of soil respiration and its effects on ecosystem carbon budget: nonlinearity begets surprises. *Ecological Modelling,* Volume 153, pp. 131-142.

Quested, H., Eriksson, O., Fortunel, C. & Garnier, E., 2007. Plant traits relate to whole community litter quality and decoposition following land use change. *Functional Ecology,* Volume 21, pp. 1016-1026.

Quested, H., Eriksson, O., Fortunel, C. & Garnier, E., 2007. Plant traits relate to whole-community litter qulaity and decomposition following land use change. *Functional Ecology,* 21(6), pp. 1016-1026.

Raich, J. W., Bowden, R. D. & Steudler, P. A., 1990. Comparision of two static chamber techniques for determining carbon dioxide effluxes from forest soils. *Soil Science Society of America Journal,* Volume 54, pp. 1754-1757.

Raich, J. W. & Potter, C. S., 1995. Global patterns of carbon dioxide emissions from soils. *Global Biogeochemical Cycles,* 9(1), pp. 23-36.

Raich, J. W., Russell, A. E. & Vitousek, P. M., 1997. Primary productivity and ecosystem development alon an elevational gradient on Mauna Loa, Hawai'i. *Ecology,* 78(3), pp. 707-720.

Raich, J. W. & Schlesinger, W. H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B,* 44(2), pp. 81-99.

Raich, W. J. & Tufekcioglu, A., 2000. Vegetation and soil respiration: correlations and controls. *Biogeochemistry,* Volume 48, pp. 71-90.

Rayment, M. B. & Jarvis, P. G., 1997. An improved open chamber system for measuring soil CO2 effluxes in the field. *Journal for Geophysical Research,* 102(24), pp. 28779-28784.

Rayment, M. B. & Jarvis, P. G., 2000. Temporal and spatial variation of soil CO2 efflux in a Canadian boreal forest. *Soil Biology and Biochemistry,* 32(1), pp. 35-45.

Reich, P. B., Grigal, D. F., Aber, J. D. & Gower, S. T., 1997. Nitrogen Mineralisation and Productivity in 50 Hardwood and Conifer Stands on Diverse Soils. *Ecology,* 78(2), pp. 335-347.

Reichstein, M. et al., 2002. Ecosystem respiration in two Mediterranean evergreen Holm Oak forests: drought effects and decomposition dynamics. *Functional Ecology,* 16(1), pp. 27-39.

Risk, D., Kellman, L., Beltrami, H. & Diochon, A., 2008. In situ incubations highlight the environmental constraints on soil organic carbon decomposition. *Environmental Research Letters,* Volume 3.

Rochette, P. et al., 1997. Description of dynamic closed chamber for measuring soil respiration and its comparison with other techniques. *Canadian Journal of Soil Science,* Volume 77, pp. 195-203.

Rochette, P. & Eriksen-Hamel, N. S., 2008. Chamber measurments. *Soil Science Society of America Journal,* 72(2), pp. 331-342.

Rochette, P. & Flanagan, L. B., 1997. Quantifying rhizosphere respiration in a corn crop under field conditions. *Soil Science Society of America Journal,* Volume 61, pp. 466-474.

Rustad, L. E., Huntington, T. G. & Boone, R. D., 2000. Controls on soil respiration: Implications for climate change. *Biogeochemistry,* Volume 48, pp. 1-6.

Ryan, M. G. & Law, B. E., 2005. Interpreting, measuring, and modeling soil respiration. *Biogeochemistry,* Volume 73, pp. 3-27.

Salimon, C. I., Davidson, E. A., Victoria, R. L. & Melo, A. W. F., 2004. CO2 flux from soil in pastures and forests in southwestern Amazonia. *Global Change Biology,* 10(5), pp. 833-843.

Savage, V. R. & Kong, L., 1993. Urban constraints, policicitical imperatives: environmental 'design' in Singapore. *Landscape and Urban Planning,* Volume 25, pp. 37-52.

Savva, Y. et al., 2010. Effects of land use and vegetation cover on soil temperature in an urban ecosystem. *Soil Science Society of America Journal,* Volume 74, pp. 469-480.

Schimel, J. P., Jackson, L. E. & Firestone, M. K., 1989. Spatial and temporal effects on plant-microbial competition for inorganic nitrogen in a california annual grassland. *Soil Biology and Biochemistry,* 21(8), pp. 1059-1066.

Schimel, J. P., Jackson, L. E. & Firestone, M. K., 1989. Spatial and temporal effects on plant-microbial competition for inorganic nitrogen in a california annual grassland. *Soil Biology and Biochemistry,* 21(8), pp. 1059-1066.

Schlesinger, W. H., 1977. Carbon balance in terrestrial detritus. *Annual Review of Ecology and Systematics,* Volume 8, pp. 51-81.

Schrier-Uijl, A. P. et al., 2010. Comparison of chamber and eddy covariance-based CO2 and CH4 emission estimates in a heterogeneous grass ecosystem on peat. *Agricultural and Forest Meteorology,* Volume 150, pp. 825-831.

Shaw, M. R. & Harte, J., 2001. Control of litter decomposition in a subalpine meadow-sagebrush steppe ecotone under climate change. *Ecological Applications,* 11(4), pp. 1205-1223.

Singapore Economic Development Board, n.d. *Urban Solutions,* Singapore: Singapore Economic Development Board.

Skopp, J., Jawson, M. D. & Doran, D. W., 1990. Steady-state aerobic microbial activity as a function of soil water content. *Soil Science Society of America Journal,* Volume 54, pp. 1619-1625.

Sotta, E. D. et al., 2004. Soil CO2 efflux in a tropical forest in the central Amazon. *Global Change Biology,* Volume 10, pp. 601-617.

Sparling, G. P. & Ross, D. J., 1988. Microbial contributions to the increased mineralisation after air-drying of soils. *Plant and Soil,* Volume 105, pp. 163-167.

Stocker, R., Leadley, P. W. & Korner, C. H., 1997. Carbon and water fluxes in a calcareous grassland under elevated CO2. *Functional Ecology,* 11(2), pp. 222-230.

Takahashi, T., Amano, Y., Kuchimura, K. & Kobayashi, T., 2008. Carbon content of soil in urban parks in Tokyo, Japan. *Landscape and Ecological Engineering,* Volume 4, pp. 139-142.

Tang, X.-L.et al., 2006. Dependence of soil respiration on soil temperature and soil moisture in successional forests in Southern China. *Jounal of Integrative Plant Biology,* 48(6), pp. 654-663.

Tan, Y. S., Lee, T. J. & Tan, K., 2009. *Clean, green and blue: Singapore's journey towards environmental and water sustainability.* 1st ed. Singapore: ISEAS.

Taub, D. R., 2010. Effects of rising atmospheric concentrations of carbon dioxide on plants. *Nature Education Knowledge,* 3(10).

Tjoelker, M. G., Oleksyn, J. & Reich, P. B., 2001. Modeling respiration of vegetation: evidence for a general temperature-dependent Q10. *Global Change Biology,* Volume 7, pp. 223-230.

Townsend, A. R. & Vitousek, P. M., 1992. Tropical soils could dominate the short-term carbon cycle feedbacks to increased global temperatures. *Climate Change,* Volume 22, pp. 293-303.

Townsend-Small, A. & Czimczik, C. I., 2010a. Carbon sequestration and greenhouse gas emissions in urban turf. *Geophysical Research Letters,* Volume 37.

Townsend-Small, A. & Czimczik, C. I., 2010b. Correction to "Carbon sequestration and greenhouse gas emissions in urban turf". *Geophysical Research Letters,* Volume 37.

Trumbore, S., 2000. Age of soil organic matter and soil respiration: radio carbon constraints on belowground dynamics. *Ecological Applications,* 10(2), pp. 399-411.

Trumbore, S., 2006. Carbon respired by terrestrial ecosystems - recent progress and challenges. *Global Change Biology,* Volume 12, pp. 141-153.

Tzoulas, K. et al., 2007. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landscape and Urban Planning,* Volume 81, pp. 167-178.

United Nations, Department of Economic and Social Affairs, 2011. *Urban Population, Development and the Environment 2011.* [Online]
Available at:
http://www.un.org/en/development/desa/population/publications/pdf/urbanization/urban_wallchart_2011-web-smaller.pdf
[Accessed 14 July 2013].

United Nations, 2006. *World Urbanisation Prospects: the 2005 Revision,* New York: United Nations.

Van Gestel, M., Merckx, R. & Vlassak, K., 1993. Microbial biomass responses to soil drying and wetting:The fast-and slow growing microorganisms in soils from different climates. *Soil Biology and Biochemistry,* Volume 25, pp. 109-125.

Velasco, E. et al., 2013. The role of vegetation in the CO2 flux from a tropical urban neighbourhood. *Atmospheric Chemisty and Physics Discussions,* Volume 13, pp. 7267-7310.

Velasco, E. et al., 2013. The role of vegetation in the CO2 flux from a tropical urban neighbourhood. *Atmospheric Chemistry and Physics Discussions,* 20 March, Volume 13, pp. 7267-7310.

Wang, Y., Amundson, R. & Trumbore, S., 1999. The impact of land use change on C turnover in soils. *Global Biogeochemical Cycles,* 13(1), pp. 47-57.

Wan, S. & Luo, Y., 2003. Substrate regulation of soil respiration in a tallgrass prairie: Results of a clipping and shading experiment. *Global Biogeochemical Cycles,* 17(2), pp. 1-12.

Wan, S., Luo, Y. & Wallace, L. L., 2002. Change in microclimate induced by experimental warming and clipping in tallgrass prairie. *Global Change Biology,* 8(8), pp. 754-768.

Wen, X.-F.et al., 2006. Soil moisture effect on the temperature dependence of ecosystem respiration in a subtropical Pinus plantation in southeastern China. *Agricultural and Forest Meteorology,* Volume 137, pp. 166-175.

Wu, J. & Bauer, M. E., 2012. Estimating net primary production of turfgrass in an urban-suburban landscape with QuickBird imagery. *Remote Sensing,* 4(4), pp. 849-866.

Xu, L., Baldocchi, D. D. & Tang, J., 2004. How soil moisture, rain pulses, and growth alter the response of ecosystem respiration to temperature. *Global Biogeochemical Cycles,* 18(4), pp. 1-10.

Xu, M. & Qi, Y., 2001. Spatial and seasonal variations of Q10 determined by soil respiration measurement at a Sierra Nevadan forest. *Global Biogeochemical Cycles,* 15(3), pp. 687-696.

Zak, D. R. et al., 1994. Plant production and soil microorganisms in late-successional ecosystems: A continental-scale study. *Ecological Society of America,* 75(8), pp. 2333-2347.

Zhao, Z. M. et al., 2013. Interpreting the dependence of soil respiration on soil temperature and moisture in an oasis cotton field, central Asia. *Agriculture, Ecosystems and Environment,* Volume 168, pp. 46-52.

Zha, T. et al., 2007. Total and component carbon fluxes of a scots pine ecosystem from chamber measurements and eddy covariance. *Annals of Botany,* Volume 99, pp. 345-353.

Zhou, X., Wan, S. & Luo, Y., 2007. Source components and interannual variability of soil CO2 efflux under experimental warming and clipping in a grassland ecosystem. *Global Change Biology,* Volume 13, pp. 761-775.

Zirkle, G. N., Lal, R. & Augustin, B., 2011. Modelling carbon sequestration in home lawns. *HortScience,* 46(5), pp. 808-814.