MANAGEMENT INTENSITY EFFECTS ON LAWN SOIL CARBON CONTENT IN THE EUGENE–SPRINGFIELD, OREGON URBAN ECOSYSTEM

by

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THESIS ABSTRACT

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Prior research suggests lawns sequester large amounts of carbon, but the effects of different management regimes on this is poorly known. Within the Eugene–Springfield, OR urban area lawn management ranges from intensive (*high*: weekly mowing, summer irrigation, herbicide and fertilizer application) to non-intensive techniques (*low*: spring and fall mowing, clippings left on lawn). I examined if these two regimes affect soil carbon content and vertical distribution after at least 20 years of consistent management.

I sampled 17 lawns in June 2013 and four remnant prairies in midsummer. At each site, I extracted three to five soil cores to one-meter depth. Soils were separated by horizon, with horizon depth and volume measured. Measurement of soil carbon-nitrogen (CN) content revealed low-management lawns stored more CN at < 46 cm depth, but a trend of increasing CN with depth in high-management lawns.

This thesis includes unpublished co-authored material.

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This work is dedicated to soil – more than just dirt – where air, water, and earth mix in good measure, yielding the carbon flow of life.

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CHAPTER I

INTRODUCTION

The Socio-ecological Lawn System

Lawn or turfgrass systems, as managed grasslands, are a defining feature of urban ecosystems, a human-dominated environment wherein social and ecological systems are closely coupled (Cook 2012; Alberti 2008). Lawns, with a legacy of European classism (Bormann et al. 2001) now embraced by American culture (Robbins 2012), are a common socio-ecological system. Residents make lawn management decisions informed by social and cultural forces (Robbins 2001; 2003; 2012; Pickett 2008 et al.), manipulating flows of water, energy and nutrient, affecting the soil (Pouyat et al. 2006), and the urban ecosystem in which they are imbedded (Kaye et al. 2006). The biogeochemical fluxes of urban ecosystems vary along the spectrum of non-intensive to intensive lawn management practice (Kaye et al. 2004; 2006), with management intensity paralleling cascading effects in the environment (Bormann et al. 2001).

Lawn management practice, which involves some combination of mowing, irrigation, and fertilizing, is in feedback with social dynamics. In wealthy neighborhoods there tends to be greater awareness of environmental impacts associated with intensive lawn management (Pickett 2008; Osmond and Hardy 2004). In some instances, this leads to lower rates of fertilization (Law et al. 2004). In other cases, lawn chemical input (e.g. fertilizer, herbicide, pesticide, fungicide) remains common in middle to upper socioeconomic classes, as institutional forces (e.g. concern for property values, community lawn management regulations) trump environmental concerns (Robbins et al.

2001). The presence of ‘well-maintained’ lawns is shown to have a positive psychological effect (Beard and Green 1994), and may foster a sense of neighborhood cohesiveness in underserved communities (Pickett et al. 2008; Grove et al. 2006). There are socio-ecological ramifications of lawn managers’ choices, informed by an array of values (Cook 2012; Robbins 2012), which often transcends concern for soil carbon stocks.

With urban development, lawn and other managed grassland is established, and often upon the nation’s prime agricultural soils (Imhoff 1997; 2000). The land-use transition to managed grassland offers ecosystem service, i.e., ‘‘the benefits human populations derive, directly or indirectly, from ecosystem functions’’ (Costanza et al. 1997; Bolund and Hunhammer 1999). In the wake of development, perennially and densely vegetated soil helps restore and sustain ecosystem function (Alberti 2010). These functional benefits include soil protection and erosion control, water infiltration, retention, and purification, mitigation of the urban heat island effect, nutrient retention and cycling, and carbon sequestration (Beard and Green 1994; Byrne et al. 2008; Alberti 2010; Lal and Follett 2009).

Lawn management, in affecting biogeochemical flows (Pickett et al. 2008), may lead to soil enrichment and carbon sink enlargement (Pouyat et al. 2009). The carbon sequestration capacity of the lawn soil system may be greater than both agricultural and forest soils (Pouyat et al. 2009). Lawns may also cycle water and nutrient over a longer period of the year relative to other surrounding native ecosystems (Pickett et al. 2008). In comparison to agricultural soils, lawns remain relatively undisturbed belowground, providing the opportunity to sequester soil carbon, at a rate that may vary based upon management practice (Huyler et al. 2013; Gough and Fritz 2009; Singh 2007). For example, increasing soil organic matter input, such as allowing clippings to remain on the lawn, leads to increased soil carbon accumulation over time (Qian et al. 2010).

Soil carbon content tends to increase alongside enhanced soil fertility, structure, and water holding capacity (Victoria et al. 2012). Any management practice that increases productivity, while minimizing belowground soil disturbance, tends to build soil structure and improve soil quality (Bronick and Lal 2005). With further soil structuring, water infiltration rates increase (Brady and Weil 2010), enhancing storm water runoff retention, purification, and groundwater recharge (Beard and Green 1994). Grasslands develop well-aggregated carbon-rich soil (Retallack 2013) of functional value, and lawn management may accelerate this process. However, management may yield effects that diminish from the urban ecosystem services of soil carbon pool enlargement.

There are other possible effects of lawn management, which often entails high energy use and carbon emissions (Falk 1976; Jo & McPherson 1995; Townsend-Small and Czimczik 2010; Selhorst and Lal 2013), with these emissions offsetting the carbon sequestered in lawn soil over more than a century (Selhorst and Lal 2013). Compensating for management emissions, lawn soils may function as a methane sink (Kaye et al. 2004), yet also release nitrous oxide (Jiang et al. 2000; Kaye et al. 2004; Bremer 2006; Townsend-Small and Czimczik 2010), both of which have a high radiative forcing. Flux of nitrous oxide is greatest in older fertilized lawns (> 10 years since establishment), while nitrogen is better retained in young lawns (Qian and Follet 2012). Other studies note water quality issues that arise from lawn management practices. Excess lawn fertilizer, often nitrate, leaches from lawn systems, affecting human health and aquatic environments (Petrovic 1990; Schueler et al. 1995; Erickson et al. 2008). Potentially toxic herbicides and pesticides (Karr et al. 2007) also exit the lawn system, leach into ground water (Dougherty et al. 2010), or possibly are tracked into homes (Nishioka et al. 1996).

There are ecosystem and global-scale ramifications of lawn management. Lawn managers have the opportunity to contribute to urban ecosystem function in varying ways. Enhancement of urban ecosystem function, via carbon sequestration, may be one way towards resilient socio-ecological 'living systems' and improved human health (Karr 2000; Johnson and Hill 2002; Alberti 2005; Pickett et al. 2008). The question then arises: Can long-term (> 20 yrs) lawn management practice effectively enlarge the soil carbon pool, while minimizing management-related inputs, carbon emissions, and other environmental impacts? In order to begin to address this question, my research focuses on the effects of intensive (high: frequent mowing, irrigating, fertilizing, clipping removal) versus non-intensive (low: infrequent mowing, clippings remain) management practices upon the lawn system soil carbon pool.

Lawn System Carbon Dynamics

Urban ecologists view humans as participants in the energy flows of ecosystems (Cook et al. 2012). Within urban ecology, turfgrass system studies vary in their focus from residential lawns, athletic fields, and golf courses, to other urban green space (Guertal 2012). A subset of the literature in this area explores the lawn system and its carbon sequestration potential, with the majority of this research transpiring within the past decade. In this body of literature, drivers of carbon storage and distribution remain understudied (Qian and Follet 2012; Cook et al. 2012; Huyler et al. 2013).

The carbon fixing capacity of grasses is the primary mechanism by which residential lawns develop significant carbon pools (Milesi et al. 2005). In the course of the growing season, carbon is stored for varying periods of time in each part of lawn grass: (i.) the blade which is commonly clipped, (ii.) the verdure, also known as the stubble or the base of the blade, (iii.) root structures that laterally extend above-ground called stolon, and (iv.) below-ground root tissue (Guertal 2012). Following senescence, grass derived organic matter may be sequestered in the soil environment, or respired as carbon dioxide (Kirschbaum 2000).

The carbon balance of the lawn system may hinge upon the productivity of grasses in relation to management practice, all of which may influence the soil carbon sequestration capacity of lawn soils. Nitrogenous lawn fertilizer input, while increasing aboveground net primary productivity, may stimulate decomposers and result in soil carbon release (Golubiewski 2006). Similarly, lawn irrigation may enhance net primary productivity, yet also accelerates decomposition, as moisture is an important control of microbial activity in turfgrass (Wang et al. 2000; 2004).

While the effect of management upon lawn soil carbon content is uncertain, former research suggests the carbon sink potential of the lawn is significant. In both temperate and arid climates, former studies have found lawns store two times more soil organic carbon than native or agricultural systems (Pouyat et al. 2009; Golubiewski 2006; Zhu et al. 2006). Pouyat et al. (2006) calculated that residential lawns of Baltimore, Chicago, and Moscow store an average of 14.4 kg C m^{-2} to 1 m depth, which is substantially greater than Baltimore forest soil (11.6 kg C m^{-2}), and Boston (6 kg C m^{-2}) and Chicago (3.2 kg C m^{-2}) agricultural soils. These results point towards the importance of lawns as a functional, carbon-rich soil system, yet the effect of management practice upon belowground carbon pools remains unclear. Studies note fertilization and irrigation likely increase soil carbon sequestration rates (Qian and Follet 2002; Selhorst and Lal 2011), although few studies directly address differences in lawn soil carbon pools that may arise from varying lawn management practice (Huyler et al. 2013).

Gough and Fritz (2009) considered the effect of management practices upon 10-year-old lawns in Virginia, finding that soil carbon content in the top 10 cm of soil negatively correlated with irrigation and fertilizing, and was significantly less than soil carbon stores of native forest soil. This result, which overlooked deeper soil carbon, was attributed to the young age of the lawns and the possibility of management stimulated microbial activity, leading to carbon losses. Huyler et al. (2013) also explored management effects upon soil carbon pools of Alabama lawns, finding soil carbon in the 0-15 cm depth increased with home age at a low accumulation rate of 0.026 kg C m^{-2} $year^{-1}$. In this study, there were no discernable effects of management practice (fertilization, irrigation, and/or clipping mulch) upon soil carbon content, which diverges from the work of others (Qian and Follet 2002; Milesi et al. 2005; Golubiewski 2006; Pouyat et al. 2009). The authors suggested this unexpected result was due to the rapid rate of decomposition in Alabama's warm, humid climate.

As turfgrass systems age, and upper soil carbon accumulation rates decline, researchers propose that the rate of soil organic carbon decomposition approaches a steady state with net primary production inputs (Byrne 2008; Shi et al. 2012). Over time, turfgrass systems remain productive, stimulating soil carbon flow, yet upper soil carbon accumulation rates tend to decrease, which may be related to microbial consumption of soil organic matter (Shi et al. 2012; Qian and Follet 2012). At first, following soil disturbance associated with land conversion to lawn, soil rapidly sequesters carbon. Tentative values for initial turfgrass sequestration rates range from 64 to 174 g C m^{-2} $year^{-1}$ (Shi et al. 2012; Qian and Follet 2002), which is significantly greater than rates associated with conversion of agricultural fields to other land uses (Post and Kwon 2000).

To observe soil carbon accumulation over time, researchers typically select a chronosequence of study sites. Shi et al. analyzed golf courses from 2 to 100 years old, and found rates slow within 25 to 40 years in the top 15 cm of North Carolina soil. Other studies establish a chronosequence of residential structures, and assume lawns were established immediately following construction. Selhorst and Lal (2012; 2013) studied residential lawns across the United States spanning 100 years of age, and found initial rates of sequestration slow after 20 years (Selhorst and Lal 2013). Qian and Follett (2002) corroborate these results to 11.4 cm depth in turfgrasses of Colorado, and determined sequestration rates approach minima after 25 to 30 years.

However, not all studies have observed a hyperbolic carbon accumulation relationship. Huh et al. (2008) found a linear soil carbon accumulation rate in the upper 25 cm of New Zealand putting green soil over 40 years. Townsend-Small and Czimczik (2010) echoed this result, finding that lawn soil carbon accumulation to 20 cm depth was linear over approximately 30 years. These results may be misleading due to a narrow chronosequence time period, small sample sizes, and ‘curve fitting’ the data (Shi et al. 2012). Conversely, carbon accumulation rates may appear increasingly linear when calculated over greater depths of turfgrass soil. Overall, turfgrass literature suggests that soil carbon most rapidly accumulates within the first 25 years following establishment (Qian et al. 2010), with the upper soil carbon pool approaching a steady state within 25 to 40 years (Shi et al. 2012; Qian and Follet 2012; Golubiewski 2006).

Given that lawn soil carbon content has an upper limit, a central question is whether lawns, with their attendant management practices, function as net carbon sinks (Selhorst and Lal 2013). Intensive management practice embodies carbon – emissions associated with the life cycle of management-related materials and activities. For example, Falk (1976) assessed the productivity of a suburban lawn in California over one year, including all management-related inputs, activities, and energy consumption. Falk calculated that annual net primary productivity was 4,467.5 kcal m^{-2}, while management (most substantially irrigation and mowing) consumed 578 kcal m^{-2} over the course of one year. Falk's research, while it did not consider soil carbon content, laid a foundation for future studies concerning the intensity of lawn management in the carbon dynamics of the lawn system.

Following Falk's study, Jo and McPherson (1995) determined turfgrass soils are a net carbon source when accounting for mowing emissions and removal of clippings in a 1-year study. Townsend-Small and Czimczik (2010), in their assessment of lawn soil carbon accumulation (140 g C m^{-2} yr^{-1} to 20 cm depth), suggested that carbon dioxide emissions related to mowing, irrigation, and fertilizer production is likely to exceed soil carbon sequestered by intensively managed turfgrass systems, although non-intensively managed lawns (no fertilizer input, less frequent mowing and irrigation) may possibly function as a net carbon sink (Townsend-Small and Czimczik 2010). Selhorst and Lal

(2013) assessed the lawn carbon sink capacity of homes across the United States, calculating that carbon equivalents associated with mowing and fertilizer use offset lawn soil carbon sequestered, on average, within 184 years. The calculation of management-related carbon emissions and energy use consists of many assumptions, yet available literature suggests that the cumulative emissions of long-term lawn management will eventually negate lawn upper soil carbon pools.

Urban ecosystem research has begun to shed light upon the carbon dynamics and carbon sequestration potential of the lawn system. There is the opportunity for contribution to this body of knowledge through study of lawns in different climates, soil types, and by assessing soil carbon content to greater depths. To the best of my knowledge, no lawn system studies as of yet address the way consistent long-term management practice (> 20 yrs.) affects the magnitude and vertical distribution of lawn soil carbon pools. The following chapter, co-authored with Scott Bridgham, is our contribution to the urban ecosystem research effort, guided by the question: What is the role of long-term lawn management, if any, in soil carbon sequestration to 1-meter depth?

CHAPTER II

LAWN MANAGEMENT AND SOIL CARBON

Chapter II has been extensively edited by Scott Bridgham and reviewed by Bart Johnson. Scott Bridgham, Bart Johnson and other members of the Bridgham Laboratory Group provided guidance in experimental design and interpretation of results, which is reflected in the pages to follow.

Introduction

Urban areas are expanding worldwide to accommodate human population growth, with 4.9 billion people, 60% of the world population, expected to live in cities by 2030 (Alberti 2005). With the development that accompanies urban expansion, lawn grasses take root in residential lots, parks, roadsides, and recreational fields. Lawns occupy 10-16 million hectares in the continental United States (Zhou et al. 2008; Robbins and Birkenholtz 2003), three times more area than any irrigated crop in the country (Milesi et al. 2005). The lawn, with an established place in American culture and urban ecosystems (Robbins 2012), offers the opportunity to enlarge soil carbon pools, build soil, and buffer global change (Pouyat 2006; 2009; Golubiewski 2006; Qian et al. 2010; Lal and Follet 2009; Victoria et al. 2012). Expansion of soil carbon pools, and the associated soil structuring, provides nutrient retention, biomass production, and improvement of water quality (Bronick and Lal 2005; Lal and Follett 2009).

Residential lawns have the largest soil carbon pool among land uses in urban ecosystems (Pouyat 2006). Upon establishment, turfgrass rapidly accumulates carbon in the upper soil at a rate of 64 to 174 g C m^{-2} $year^{-1}$ (Shi et al. 2012; Qian and Follet 2002). Soil carbon sequestration stabilizes over time in turfgrass upper soil, approaching a steady state within 25 to 40 years (Shi et al. 2012; Qian and Follet 2012; Golubiewski 2006), at which point net primary production is increasingly offset by decomposition in the upper soil (Shi et al. 2012). In the deep soil, soil carbon may continue to accumulate after this 25-40 year time period (Huh et al. 2008; Carley et al. 2011; Qian and Follet 2012).

Climate acts as one control of the carbon sequestration capacity of lawns (Selhorst 2011; Selhorst and Lal 2012), and in part, determines the duration and frequency of mowing and irrigation in lawn systems. Fertilizer and herbicide application, while commonplace across the United States (Robbins 2012), is not required to sustain the lawn plant community, while mowing and irrigation is more essential. The Mediterranean climate of the Pacific Northwest features moist, relatively warm conditions from October through May, which allows lawn grasses and forbs to be sustained with minimal management. In cool temperate regions, summer precipitation leads to lawn growth and regular mowing, while occasional summer irrigation is common in warm temperate zones. In arid climates, lawns are sustained by heavy irrigation, and mown throughout the course of the year. In contrast, Mediterranean climates are well suited to adoption of non-intensive lawn management practices, in which un-irrigated lawns are viable, and only require mowing during the productive growth periods of spring and fall.

Lawn management may affect soil carbon pools (Golubiewski 2006; Pouyat et al. 2009). Golubiewski (2006), evaluated above- and belowground carbon stores in residential landscapes of the greater Denver, CO area, and found that following development, lawn soil carbon pools recover and eventually surpass native soil carbon stocks. She concluded that lawn soil carbon pools are primarily affected by anthropogenic factors, such as the age of the lawn and management activities, as opposed to climate or soil texture. Pouyat et al. (2009) echoed this result in their assessment of Denver, CO and Baltimore, MD lawn soil carbon, finding that lawn soils store two times more carbon than surrounding native soils.

Intensive lawn management practices, however, have carbon costs that diminish the benefits of soil carbon sequestration (Selhorst and Lal 2013). Mowers emit greenhouse gases (CO_2, N_2O), as does the manufacture, shipment, and use of fertilizer, herbicide, pesticide, and irrigation components (Bormann et al. 2001). The varying intensity of lawn management, with associated carbon emissions and energy use, may over time negate the carbon sequestered in soil (Jo and McPherson 1995; Townsend-Small and Czimczik 2010; Selhorst and Lal 2013), although on average this takes 184 years (Selhorst and Lal 2013). With cognizance of the carbon costs of lawn management, we asked, do intensive versus non-intensive long-term lawn management practices affect the extent and vertical distribution of soil carbon pools? We hypothesized that long-term lawn management (> 20 yrs.) has a discernable effect upon soil carbon pools, with intensive management practice storing more soil carbon. Additionally, we compared soil carbon pools in lawns to remnant prairie sites that were thought to reflect the antecedent condition of the lawns.

Materials & Methods

Study Area

The Eugene–Springfield urban area, with approximately 1,400 people per square kilometer (US Census Bureau 2010), is largely medium density single-family residential development. There are 157,986 residents of the city of Eugene accompanied by 59,869 residents in Springfield (US Census Bureau 2010). The urban area rests in a basin defined by the Coast Range to the west, and the Cascade foothills to the south and east. Oregon's South Willamette Valley (SWV) has a Mediterranean climate (Kottek et. al 2006) with a mean annual temperature of 11.6 °C, a mean July high of 28.6 °C, and a January low of 1.7 °C. Over the past twenty years, the SWV has averaged 103.3 cm of rainfall annually, with 8.4 cm during the dry season of June through September (NOAA *Annual Climatological Summary 1993-2013*).

The seasonal cycle of the SWV Mediterranean climate is an important driver of lawn productivity. By July, un-irrigated SWV lawns senesce and remain dormant until fall season wet up. Lawn productivity increases as soils hydrate in October, until growth slows due to temperature limitation through the winter season (December-February). By March, with increasing temperature and available moisture, lawn growth accelerates.

Lawn Site Selection

All lawns studied in the Eugene–Springfield urban area fell into two management groups defined frequency of mowing and inputs – intensively managed (High; H) and non-intensively managed (Low; L) (Table 1). Homeowners tended to fall into one of the categories, which made evaluation of individual management practices impractical.

Table 1. Lawn Management Regimes

	Mow	**Irrigation**	**Chemical Input^**	**Clipping Input**
High (H)	weekly	2-3 times per week*	yes	no
Low (L)	monthly to bimonthly**	no	no	yes

^annual fertilizer and herbicide application
**summer*
***spring and fall*

Historic neighborhoods, with suspected long-time residents and mature lawns, were targeted as study site areas. Homeowner interviews documented all inputs and disturbances to their lawns over time. Selected lawns had been established and managed consistently for at least 20 years (Table 2). By this lawn age, we assume upper soil carbon stocks had reached approximate steady state (Golubiewski 2006; Shi et al. 2012; Qian and Follet 2012). This allowed us to examine the effect of consistent management upon the extent of a relatively stable upper soil carbon pool. We also assessed deep soil carbon pools, as prior research often focused on lawn management effects in only the upper A horizon (e.g., Huyler et al. 2013; Gough and Fritz 2009; Singh 2007).

Table 2. Lawn Age and Management Duration

Management Group	**Years Since Establishment* (*Range*)**	**Years of Management* (*Range*)**
High (H)	32.2 +/- 2.0 (*20-40*)	31.8 +/- 2.1 (*20-40*)
Low (L)	42.4 +/- 7.5 (*24-70*)	28.1 +/- 3.7 (*20-48)*
All Lawns	36.4 +/- 3.4	30.3 +/- 1.9

* +/- 1 SE

Seventeen lawns met our selection criteria, distributed among three neighborhoods of the Eugene–Springfield urban area, Springfield (SP), South Eugene (SE), and West Eugene (WE). All are designated as historic upland prairie in the 1851 Government Land Office Survey (U.S. Department of the Interior Bureau of Land

Management 2014). We sought an even number of lawns within each management group overall and within neighborhoods. However, mature L lawns were rare in SP relative to SE, giving rise to an uneven distribution of management types among neighborhoods (Table 3). All lawn soils were in the series Hazelair, Dixonville, Malabon, Awbrig, Coburg, and Panther with clay-rich mollic epipedons (Appendix A: Texture). The possibility of cut-and-fill excavation methods in lawn establishment, which could affect total soil carbon pools, was accounted for in homeowner interviews, site selection parameters, or in analyses to follow.

Table 3. Management Group by Neighborhood

	High	**Low**
Springfield (SP)	5	2
South Eugene (SE)	3	5
West Eugene (WE)	2	--
Total	10	7

Lawn Sites by Neighborhood

All neighborhoods (Figure 1), as historic upland prairie, may have been maintained via indigenous fire management prior to Euro-American settlement (Boyd 1986), grazed as prairie in the mid 19th century, followed by residential development in the early to mid 20th century. We assume lawn topsoil carbon pools, which may have been cultivated pre-20th century, have since recovered (Golubiewski 2006).

The South Eugene neighborhood (8 Sites; 3 H, 5 L), rising into the foothills (elevation: ~140 m), consists of shallow clay loam soil. Springfield's Washburne Historic District (7 sites; 5 H, 2 L; elevation: ~140 m), to the east of Eugene, rests between the Willamette and McKenzie Rivers on a plain of deep silty clay loam soils. West Eugene (2 sites; 2 H), also consists of deep silty clay loam soils, to the northwest of the Eugene-Springfield urban center (elevation: ~120 m).

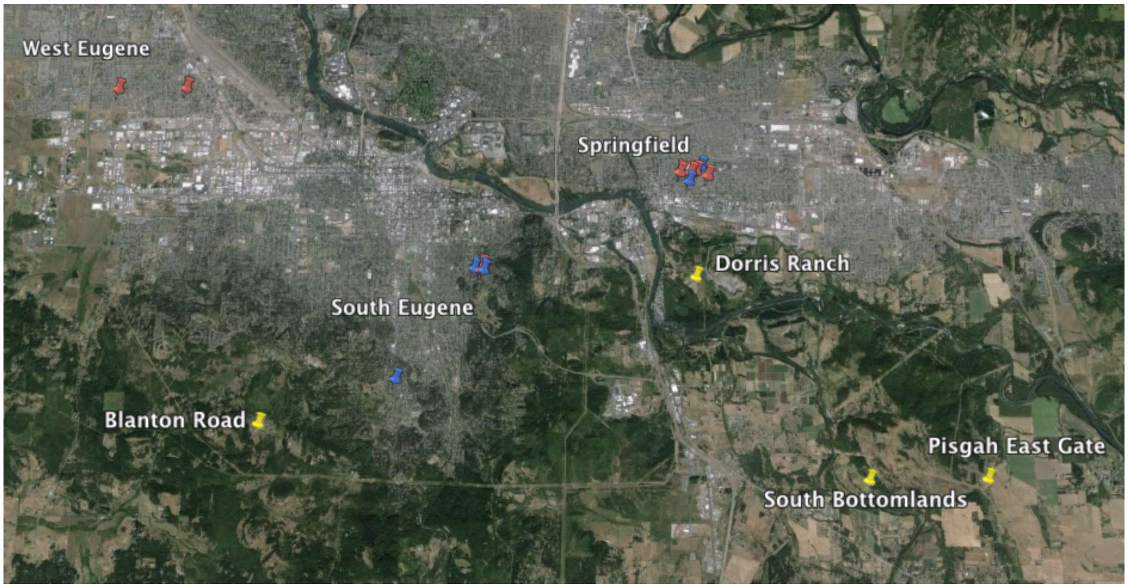

Figure 1. Eugene–Springfield Urban Area [Red (H); Blue (L); Yellow (RP)] (Google Earth Image)

Remnant Prairie Sites

Four remnant prairie sites (RP) were sampled in the Eugene–Springfield region to compare the soil carbon pools of lawns to the best available approximation of their reference state. Over at least the past twenty years, each RP site has been managed as prairie with annual to biennial mowing. In the era of Euro-American settlement, RP sites were never tilled nor subjected to other soil disturbance aside from light livestock grazing (Eugene City Parks *personal communication*; Buford Park Mt. Pisgah *personal communication*). Prior to the 19th century, RP sites were likely maintained via Native American burning, although areas of the South Bottomlands site may have been riparian forest according to the 1851 Government Land Office Survey (U.S. Department of the Interior Bureau of Land Management 2014).

Samples were taken from the Mt. Pisgah East Gate and South Bottomlands, respectively. The Pisgah East Gate is a prairie expanse, of little to no slope, at the toeslope of Mt. Pisgah. In the South Bottomlands, adjacent to the Coast Fork Willamette River, we sampled on a toeslope (< 5°), on the east side of a historic fence line, where only light grazing occurred in the past. At Dorris Ranch, which abuts the Middle Fork and Coast Fork Willamette River confluence, we sampled on a midslope terrace. At Blanton Road, in the South Hills of Eugene (elevation: ~315 m), sampling occurred in an upland prairie saddle between two buttes, consisting of shallow clay loam soils relative to the valley.

Field Sampling

All lawn sampling was completed in June 2014, prior to the drying of soils in summer. Three soil cores per lawn were selected randomly within the parameters of avoiding belowground infrastructure, areas of recent soil disturbance, 3 m from the base of any tree or structure, and on level ground to gentle slopes (< 5° at two sites in South Eugene). Cores were extracted from the upper 20 cm using a driven metal cylinder (dia. = 7.3 cm), followed by auguring (dia. = 5 cm) to 1 m or an impenetrable horizon, often indicated by paralithic fragments, whichever was less. Four to five cores were often necessary to confirm the depth to obstruction. Features of the soil (structure, texture, color, moisture content, presence of redox features, root characteristics) were examined visually and via the texture-by-feel method (Brady and Weil 2010), separated into horizons, with horizon depths recorded. The core hole was volumetrically backfilled with sand until reaching the depth at which auguring began.

In addition to coring, three random counts of grass and forb species richness were performed, over the area of a 1 m^2 quadrat. Grasses, in a mown state, were distinguished from each other based upon root structure and leaf morphology, while forb species were readily identifiable (Appendix C: Species Richness & Root Mass).

Laboratory Analyses

The pH of soil was measured immediately following sampling in a 1:1 slurry of soil to deionized water, which was acidic in all cases (mean: 5.9; range: 4.9 - 6.7). This allows for the assumption that total soil carbon (TSC) is equivalent to soil organic carbon (SOC) content (Bohn et al 2002; Selhorst and Lal 2012).

Soils, separated by horizon within each study site, were composited and homogenized prior to passing through a 2 mm sieve, isolating the fine-earth fraction. Soil was air dried to constant mass and a subsample was then oven dried at 60 °C for 48 hours to convert all values to oven-dry mass equivalence. A subsample of the A horizon soil was root washed (Gillison’s Variety Fabrication, Inc, Benzonia MI), followed by two additional one minute washings over a 425 μm sieve to remove all remaining soil particulates. Clay content was determined by the hydrometer method (Day 1965), sand by collection on a 53 μm sieve, and silt by difference. Root-free samples were used to determine total soil carbon and nitrogen content with an ECS 4010 Costech Elemental Combustion System (Valencia, CA). Total soil carbon to one meter was calculated using %C data in conjunction with average horizon depth, volume, and oven dry soil mass.

Statistical Techniques

Depth of horizons, percent soil carbon (%C), percent soil nitrogen (%N), textural content (sand, silt, clay), species richness, A-horizon root mass, neighborhood location, management duration, and total soil carbon (TSC) by horizon were analyzed via one-way ANOVAs, with management group (H, L, NLU) applied as a fixed factor treatment effect across sites, and in each horizon within a site. We further compared management groups with LSD post-hoc pairwise comparison.

To better disentangle possible drivers of soil carbon accumulation and distribution, a forward stepwise regression technique was employed with dummy variables for categorical data, with a p-value threshold of 0.05 (Appendix B: Regression). Percentage soil carbon and depth of horizons were not included in regressions of total soil carbon content because they were part of the calculations. 'Mature tree present' describes whether a tree is within the lawn sampled, a variable ranked from zero to two, corresponding to absent(0), light to moderate(1), and heavy(2) tree overstory. This variable was further specified via assessment of *Google Earth* satellite images of lawns ('canopy cover by satellite'), with tree canopy cover ranked from 0 to 4 (0-25%, 25-50%, 50-75%, 75%-100%).'Redox features present' describes the extent of iron and manganese mottling observed in lawn soils, ranked none(0)-few(1)-prominent(2). 'Possible cut and fill' is a yes-no dummy variable, with yes, in the case of four lawns, indicated by a berm about the foundation of the residential structure. 'Reached B horizon' denotes whether or not the B horizon was reached within 1 meter depth. 'Reached one meter' describes instances in which an impenetrable layer was encountered at < 1 m depth (four lawns; 2H & 2L).

Results

Horizonation & Location

The South Willamette Valley (SWV) lawn soils sampled, regardless of profile depth, are predominately clay loams (Appendix A: Texture), while remnant prairie (RP) sites are more clay rich. In lawns, there is a general pattern of loamy upper soil becoming increasingly clay rich with depth (A-AB-BA-B), with variability in the presence or absence of deeper horizons (AB, BA, & B) among RP sites and lawns (Table 4). Notably, B horizons occurred in only two H lawns. Additionally, deep soil horizons are poorly represented at the four RP sites. One meter was reached at the South Bottomlands, while other RP soils were shallow (< 50 cm). Therefore, RP's are not considered in analyses of these deeper horizons.

Table 4. Horizonation by Management and Location

		Horizons Present			
		A	**AB**	**BA**	**B**
Management	**High (H)**	10	6	6	2
	Low (L)	7	4	4	4
Location	**South Eugene (SE)**	8	6	4	3
	Springfield (SP)	7	3	4	3
	West Eugene (WE)	2	1	2	--
	Remnant Prairie (RP)	4	2	--	2

Four lawns (2L, 2H) in SE had average depth-to-obstruction from 46 to 77 cm. As a result, total soil carbon to 1 m depth tends to be lower in SE, regardless of management regime (Table 5) (LSD; SE v. SP, P = 0.43; SE v. WE, P = 0.067). In these four SE lawns, sandy transitional horizons (BC) were omitted from analyses. There is also soil carbon not accounted for beyond one meter in the nine valley bottom lawns of Springfield and West Eugene.

Table 5. Total Soil Carbon Pool by Neighborhood to 1 m depth

	Total Soil Carbon (kg C m^{-2} +/- 1 SE) (*Range*)
Springfield (SP)	17.09 +/- 0.62 (*14.91 - 19.53*)
South Eugene (SE)	14.06 +/- 0.93 (*10.88 - 18.18*)
West Eugene (WE)	18.20 +/- 4.03 (*14.2 - 22.23*)

Carbon, Nitrogen, and Clay Distribution

The largest management effect was evident in % carbon in the A horizon (P = 0.010), with higher % carbon in L lawns compared to H lawns (LSD; P = 0.003) (Figure 2). The % carbon in the A horizon of RP sites was not different than either lawn management regime (P = 0.18). There is a statistically non-significant trend of H lawns having higher % carbon than L lawns in the BA and B horizons (BA; P = 0.209 & B; P = 0.302). Soil % nitrogen distribution paralleled the soil carbon trend, with L lawns having greater % nitrogen in the A horizon than H lawns (P = 0.011) (Figure 3). There was also a statistically non-significant trend of greater % nitrogen in the BA horizon of H versus L lawns (P = 0.241). Mirroring % carbon and nitrogen depth trends, BA horizon clay content was marginally greater in H lawns than in L lawns (P = 0.065) (Figure 4). Percent clay of RP A horizons were significantly greater than H (P = 0.004) and L (P = 0.010) lawns.

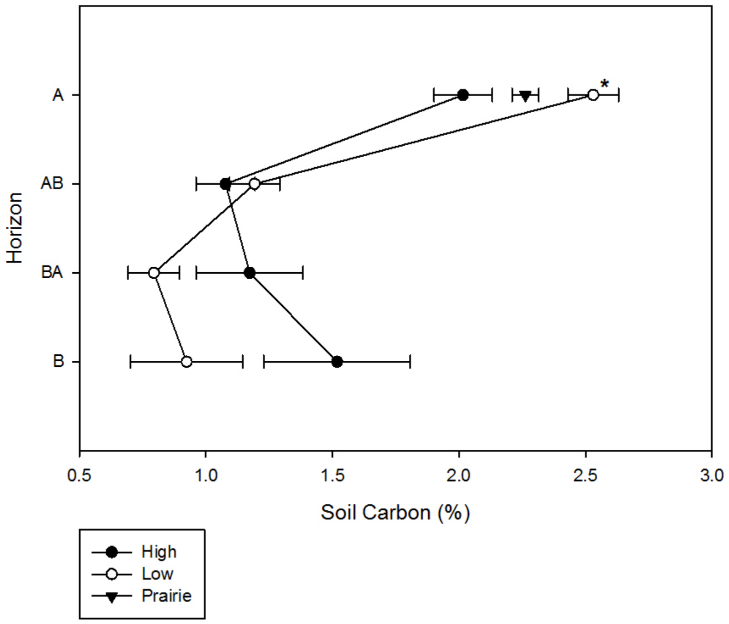

*Figure 2. Percentage soil carbon in high management and low management lawns and prairie remnants. * L v. H, P = 0.003*

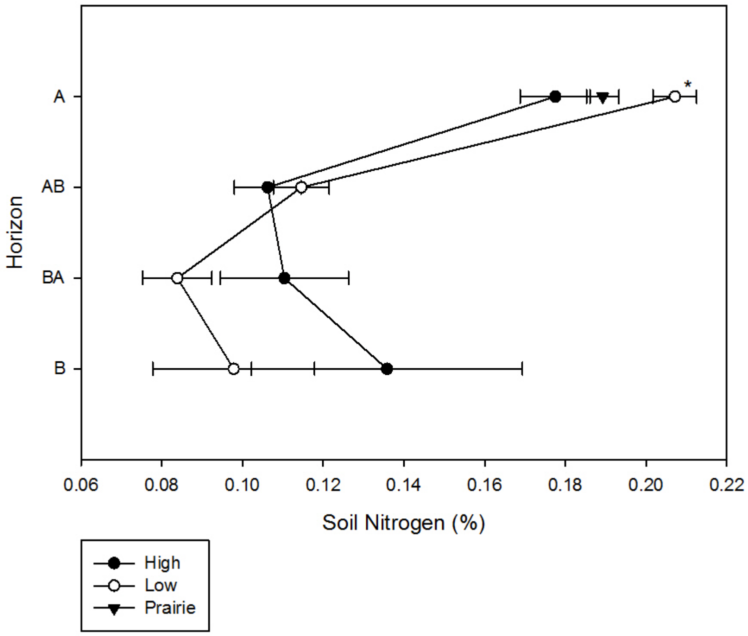

*Figure 3. Percentage soil nitrogen in high management and low management lawns and prairie remnants. *L v. H, P = 0.011*

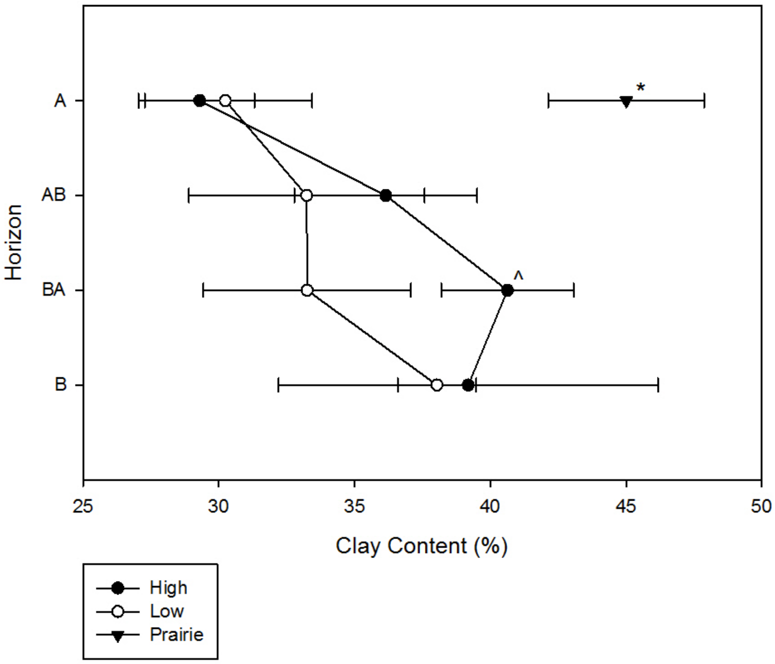

*Figure 4. Percentage clay in high management and low management lawns and prairie remnants. ^H v. L, P = 0.065; *RP vs. H, P = 0.004; RP v. L, P = 0.010*

Total Soil Carbon Pools

There were no differences in total soil carbon content either among horizons or integrated to 1 m depth between H and L lawns (Table 6)**.** We also examined total soil carbon to the depth of the shallowest lawn soil (46 cm) to control for differences due to shallow soil depths in SE (Figure 5). In this case, L lawns store more soil carbon than H lawns (LSD; P = 0.075) and RP sites (LSD; P = 0.031), while total soil carbon content was similar in H lawns and RP A horizons (LSD; P = 0.377)

*Table 6. Soil Carbon Pools by Horizon (kg C m^{-2})**

Management	A		AB		BA		B	
H	10.33	*1.04*	2.26	*0.33*	4.50	*1.29*	8.12	*3.67*
L	10.16	*1.08*	2.52	*0.33*	2.44	*0.78*	4.38	*2.03*
RP	7.75	*1.49*						

** +/- 1 SE in italics*

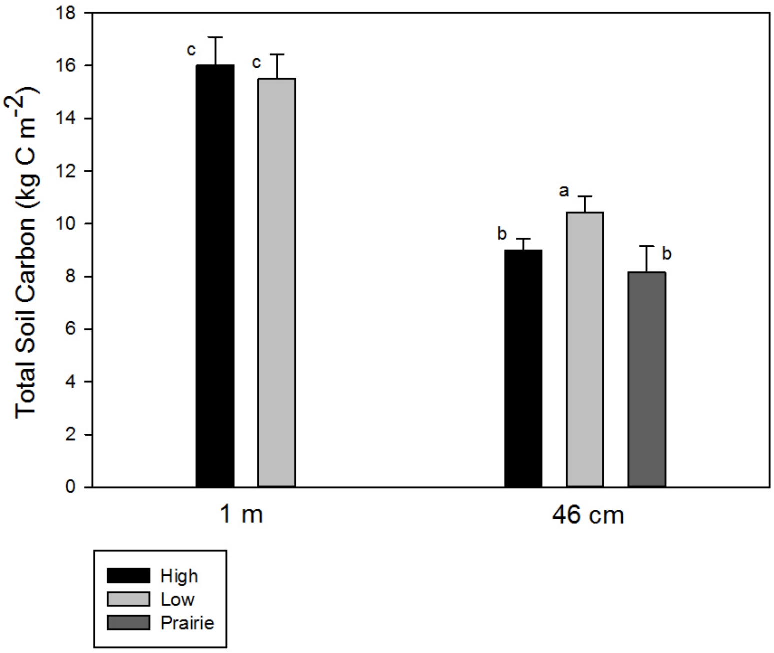

Figure 5. Total soil carbon to one meter and 46 cm depth, among lawn management groups and remnant prairie. L (a) v. H (b), P = 0.075; L (a) v. RP (b), P = 0.031

Regressions

Percentage carbon in the A-horizon was correlated reasonably well with clay content when samples from all management regimes were considered together (Adj. $R^2 = 0.43$; $P = 0.002$). However, when broken down by management regime, % carbon was well predicted in RP and H lawns but not L lawns (Figure 6). The strong correlation in the RP sites occurred despite a narrow range of high clay contents (38-52%).

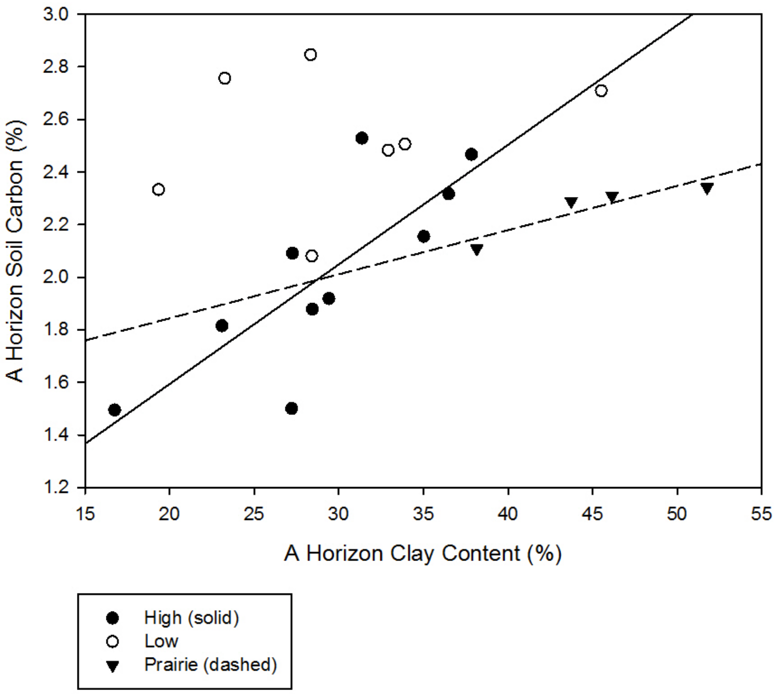

Figure 6. A horizon % carbon of high management lawns and remnant prairie correlated with clay content.

High Management: R^2 = 0.64 (Adj. R^2 = 0.59) P = 0.006

Remnant Prairie: R^2 = 0.83 (Adj. R^2 = 0.74) P = 0.092

Low Management: R^2 = 0.06 (Adj. R^2 = -0.13) P = 0.597

In step-wise regression, management best explained A-horizon % carbon (Table 7). Redoximorphic features, when prominent in the A-horizon, correlated with low % carbon in this same horizon. A-horizon total soil carbon correlated with increasing clay content and lawn canopy cover. Depth of the A-horizon was predicted only by the presence of a mature tree in a lawn. The location of lawns did not explain A-horizon depth, which was similar among neighborhoods (P = 0.431). The deep soil carbon pool correlated with years of management and the possibility of cut-and-fill excavation techniques. Whether or not 1 meter was reached in coring, and years of management were predictors of total soil carbon pools to 1-meter depth. When the four lawns in which 1 meter was not reached were removed from the regression, no variable adequately predicted total soil carbon to 1 meter.

Table 7. Step-wise Regression Results

Dependent Variable *Predictors*	***Cumulative R^2***	***P value***
A Horizon % Carbon		
Management	0.40	0.006
(1) Management (2) Redox Features Present ↓	0.67	<0.001
A Horizon Total Soil Carbon		
A Horizon % Clay ↑	0.47	0.002
(1) A Horizon % Clay ↑ (2) Canopy Cover ↑	0.67	<0.001
A Horizon Depth		
Mature Tree Present ↑	0.38	0.009
Total Soil Carbon to 1 m*		
Reached One Meter	0.33	0.016
(1) Reached One Meter (2) Years of Management ↑	0.52	0.006
Deep Soil Carbon (46 cm to 100 cm)**		
Years of Management ↑	0.39	0.023
(1)Years of Management ↑ (2) Possible Cut and Fill ↑	0.62	0.008

**No variable predicts total soil carbon to 1m when four lawns of <1m depth are excluded*
***Excludes four lawns (2H & 2L) of <1m depth*
↑ *indicates positive correlation;* ↓ *indicates negative correlation*

Discussion

The total soil carbon pool in the A-horizon and to 1 meter depth did not differ between management regimes, but it was higher in L than in H lawns in the upper 46 cm (Figure 4). Additionally, % soil carbon was higher in the A-horizon in L lawns (Figure 1). These results can be explained by the interaction of soil horizon depths, horizon development, and management (high vs. low, years of management regime, and presence of mature trees).

The regression results also indicated that management regime was the primary control over % soil carbon in the A-horizon (Table 7), but variation in A-horizon depth among lawns and remnant prairies overwhelmed the management effect in determination of total soil carbon pool in that horizon. In turn, increased A-horizon depth was best explained by the presence of mature trees, which apparently was not related to high versus low management lawn care in our study. Since % soil carbon content and horizon depth were not entered into the regression on total soil carbon content of the A-horizon (being part of that calculation), clay content was the best predictor of that variable, in agreement with other studies of grasslands (Burke et al. 1989; Tate and Ross 1997), which find clay content, temperature, and precipitation control soil organic carbon content. Jobbagy and Jackson (2000) echo this result in their global analysis of soil carbon stocks, finding soil organic carbon tends to increase with clay content and precipitation, and decrease with temperature.

Our results suggest that lawn management may have had a gradual, cumulative effect upon the vertical distribution of the soil carbon pool in the Mediterranean climate of the South Willamette Valley (SWV). In the deeper soil horizons, where management effects are difficult to discern due to small sample sizes, H lawn carbon pools tend to increase relative to L lawns (Figure 1). The distribution of clay conforms to this trend (Figure 3), suggesting a translocation of clay and soil carbon into deeper soil with heavier irrigation of the H lawns. The regressions supported this interpretation with deep soil carbon pool content best explained by years of management, with the possibility of cut-and-fill excavation also important, in which soil extracted constructing residential foundations may have been deposited on A horizon soil of the site.

Potential Mechanisms of SWV Lawn Soil Carbon Flux & Storage

In the low-management (L) lawn system, mowing was at most monthly, soils were un-irrigated, there were no synthetic chemical inputs, and clippings remained on the lawn. In high-management (H) practice, mowing was frequent (once weekly), clippings were always removed, fertilizer and herbicide application was annual, and soils were irrigated throughout the summer months. Our study suggests at least 20 years of consistent H or L lawn care has affected the distribution of carbon and nitrogen throughout the soil profile. In the upper soil, where the effect of management is most apparent, low-management activities develop carbon-rich soil relative to H lawns and prairie. This result points toward two, potentially interacting scenarios: (1) L lawns allocate more carbon to the upper soil than H lawns and prairie; (2) L lawns retain more carbon in the upper soil than H lawns and prairie.

Management stimulates lawn grass root and shoot growth (Falk 1976; 1980), which increases inputs of soil carbon via roots, exudates, and clippings (Qian and Follet 2012). Clippings, which remain on L lawns in the growing season, are likely a significant contribution to the upper soil carbon pool. Clipping input increases lawn biomass production, soil carbon sequestration, and nitrogen retention (Kopp and Guillard 2002; Qian et al. 2003; Qian et al. 2010). Increasing soil nitrogen content parallels soil carbon pool enlargement, as carbon and nitrogen stores appear to be coupled in lawn systems (Kaye et al. 2005; Raciti 2008; Qian and Follet 2012), which our study corroborates.

In grasslands, greater belowground carbon allocation tends to enlarge soil carbon pools relative to other terrestrial ecosystems (Sims and Coupland 1979; Jobaggy and Jackson 2000). The extent and depth of roots, in grasslands and forests, is correlated with increasing belowground carbon allocation (Jackson et al. 1996). Droughty conditions may stimulate more extensive rooting in grasslands (Marcum et al. 1995, Huang and Fry 1998; Bonos 1998), which may be comparable to the response of lawn grasses to summer drought (Qian et al. 1997), although there may be turfgrass species-specific rooting responses to soil moisture content (Qian et al. 2010). If deep rooting occurs in drought-stressed L lawns in the SWV summer, or extensive shallow rooting in productive irrigated H lawns, this is accompanied by increased allocation of carbon and nitrogen to roots, and eventually soil (Qian et al. 2010; Qian and Follet 2012). In this study, we observed no difference in A-horizon root mass between management regimes, and no significant correlation between root mass and % soil carbon in the A horizon, suggesting that belowground allocation via roots is not an important control of soil carbon accumulation among SWV lawns and RP. Alternatively, differences in root mass among management groups may have been obscured by inadequate replication, a one-time sampling, or rapid rates of root growth and turnover.

Mowing of grasses encourages lawn grass production (Falk 1976; Golubiewski 2006) and may affect soil carbon accumulation. In L lawn systems, allowing grasses to grow taller may allocate more carbon belowground than aboveground relative to H lawn grasses (Madison 1962; Qian et al. 1997; Shahba 2010). Frequent clipping of the H lawn reduces photosynthetic leaf area, may lead to greater soil nitrogen uptake by roots (Kammann et al. 1998), and remaining grass stubble may allocate a greater proportion of carbon aboveground to tissue re-growth (Beard et al. 1994), all of which eventually exits the lawn system as clippings. Further, Allaire et al. (2008) found carbon flux from Quebec city, Canada turfgrass soils increased with mowing frequency. Weekly mowing resulted in four times higher carbon release from soil relative to turfgrass mown one to three times a growing season (Allaire et al. 2008).

Nitrogen fertilizer input enhances lawn productivity (Heckman et al. 2000; Kopp and Guillard 2002; Golubiewski 2006), and may encourage grass shoot growth at the expense of root growth (Oswalt et al. 1959; Madison 1962; Markland et al. 1969; Christians et al. 1979; Schlossberg and Karnok 2001). Aboveground biomass production in H lawns eventually leads to carbon losses following clipping removal. Although, the annual net primary productivity of L lawns, regardless of the proportion of carbon allocated to roots or shoots, is likely less than H lawns (Gough and Fritz 2009).

High-management lawns, due to irrigation, remain productive throughout the arid summer months of the SWV Mediterranean climate, as opposed to L lawns, which go largely dormant. Soil respiration, while not directly measured in this study, offers one explanation for the smaller upper soil carbon pools of productive H lawns. Low soil moisture content may limit microbial respiration in turfgrasses (Bandaranayake et al.

2003; Wang et al. 2000). During the hot and dry SWV summer, moisture, as opposed to temperature, functions as the primary control of soil respiration in prairies (L. Reynolds *submitted manuscript*; Pfeifer-Meister and Bridgham 2007). Thus, it is likely that summer drought suppresses soil respiration in un-irrigated L lawn soils, conserving carbon in the soil environment. The negative correlation of the presence of redox features with decreasing A horizon % carbon (Table 7) further suggests lawn soil moisture content may be an important control of soil carbon dynamics, as revealed by iron and manganese redox concentrations that grow in prominence with reoccurring wet up-dry down, shrink-swell dynamics in soils (Brady and Weil 2010).

The positive correlation between carbon and clay in H lawns, and the lack of this correlation in L lawns, further supports the possibility of irrigation-controlled soil respiration. Carbon complexed with clay may be occluded in soil structure or adsorbed to charge sites, providing physical and chemical protection from microbial breakdown (Six et al. 2002, 2006; Jastrow et al. 2007; Shi et al. 2012). Eugene–Springfield lawns contain high concentrations of reactive smectitic clays (Natural Resources Conservation Service 2013) with considerable interstitial space (Brady and Weil 2010), that may offer physico-chemical protection to soil carbon. Thus, we have circumstantial evidence that this physico-chemical protection of clays is more important in retaining soil carbon in well-watered H lawns than in droughty L lawns.

Carbon translocation to the deep soil is another possible mechanism to explain the low carbon content of H lawn upper soil. Both dissolved organic matter (DOM) and clay are known to solubilize and leach downward through the soil profile (Wright 2005; Warrington 1997). The BA and B horizons of H lawns, showed a trend toward greater carbon, nitrogen and clay content relative to L lawns (Figures 1-3). Over the course of many years, H lawn irrigation may leach a discernible quantity of DOM and clay to the deep soil.

Years of management best explained deep soil carbon pools (R^2: 0.39), suggesting lawn soils to 1 m depth may continue to accumulate carbon. Other studies corroborate this result, finding carbon and nitrogen pools of residential yards tend to increase over time (Law et al. 2004; Scharenbroch et al. 2005; Golubiewski 2006; Smetak et al. 2007; Pouyat et al. 2009), although as previously discussed, upper soil carbon pools likely reach a steady state within 25 to 40 years. The possibility of cut-and-fill excavation explains an additional 23% of the variance in deep soil carbon pools. Original A horizon soil may have been buried in four H lawns and one L lawn, possibly enlarging the deep soil carbon and nitrogen pool and confounding the effect of management.

While this study focuses upon lawn management, other factors influence carbon dynamics in lawns. We found that trees appear to be a control of the magnitude of upper soil carbon pools (Table 7). Trees may enhance belowground soil carbon allocation via fine root hair turnover and woody root decay (Jo and McPherson 1995; Rasse et al. 2005; Trumbore et al. 2006; Persson 2012; Huyler 2013), which over time may enlarge A-horizon carbon pools. Jobbagy and Jackson (2000) support this result, finding forests store a greater proportion of soil organic carbon in the 0-20 cm depth relative to grasslands. The presence of a mature tree in a lawn system also correlates with A-horizon depth, suggesting that trees, coupled with understory lawn, may deepen the A horizon over time. Trees may also influence the extent of soil carbon pools through understory shading, retaining moisture in the lawn (Simpson and McPherson 1998).

The remnant prairie soils had lower soil carbon content to 46 cm depth than L lawns, and were similar to H lawns (Figure 4). This unexpected result may reflect that these areas were never cultivated or converted into housing because they represent poorer sites in terms of soil carbon, nitrogen and workability of the soil, as shown by their much higher clay content in the A horizon (Figure 3). Alternatively, this result may reveal the cumulative effect of low-management practices over time, enhancing productivity and soil carbon input relative to prairie conditions, while minimizing carbon losses from upper soil.

Summary

In the Eugene–Springfield lawn system, seasonal climatic and long-term management patterns influence soil carbon dynamics and distribution. L lawns stored more carbon in the upper soil relative to H lawns and RP, while H lawns trended toward larger deep soil carbon pools. Clay content also increased with depth in H lawns, and correlated with A horizon % carbon in H lawns and RP. Trees in the lawn system helped explain the extent of upper soil carbon pools while years of management correlated with the extent of total soil carbon pools to 1 meter depth and in the deep soil (46 cm to 100 cm).

It is likely that H lawns have higher net primary productivity than L lawns because of fertilization, regular mowing, and frequent irrigation during the summer, but much of that carbon is removed as clippings and, furthermore, may be decomposed with favorable summer-time conditions or leached downward into the soil profile. Conversely, L lawn upper soil carbon pools may be enlarged by mulching of clippings, a number of potential mechanisms that may increase belowground carbon allocation, and dry summer conditions that inhibit decomposition. Overall, our results show that a low management regime enhances surface soil carbon storage in the Mediterranean climate of the SWV. However, a convergence of evidence suggests that a high-management regime increases deeper soil carbon storage, possibly through enhanced vertical translocation of carbon with regular irrigation, which apparently offsets the lower surface soil carbon accumulation. While not the focus of our study, we found evidence that trees increase soil carbon storage and depth of the A horizon, which deserves further study.

On the long-term, South Willamette Valley lawn management affects soil carbon storage and distribution, yet to 1 m depth there is no difference in the soil carbon pool between management groups. Therefore, management-related emissions are a critical factor determining whether SWV lawn soils are a net carbon sink. The benefits of enlarging soil carbon pools must be considered in light of the carbon costs and environmental ramifications of management practice.

CHAPTER III

CONCLUSION

Findings & Uncertainties

The cumulative effect of long-term (> 20 yrs) lawn management, through manipulation of environmental controls and disturbance of lawn plants, influences the extent and vertical distribution of carbon in lawn soils. Low-management practices stored more carbon in the upper soil relative to high-management lawns and remnant prairies, while high-management lawns trended towards greater carbon, nitrogen, and clay content in the deep soil. There is correlation evidence that the deep soil carbon pool enlarges with additional years of management, while the upper soil carbon pool enlarges with tree growth in the lawn system. In the A-horizon of high-management lawns and remnant prairie soils, clay content best explained carbon content.

While we did not measure net primary productivity or aboveground-belowground plant carbon allocation because of logistical constraints, we use our findings in concert with published literature to surmise likely factors that explain our results. Low-management lawns may either allocate more carbon belowground relative to high-management lawns, or retain a greater proportion of the carbon in the upper soil. We suspect the annual net primary productivity of high-management lawns is greater due to irrigation and fertilizing, while soil carbon accumulation in the upper horizons may be less than in L lawns due to irrigation driven soil respiration, the removal of clippings, and leaching. More frequent mowing may yield greater aboveground carbon and nitrogen allocation and soil carbon flux in H lawns, while tall L lawn grasses may translocate carbon and nitrogen to root systems with the onset of summer drought. Fertilization likely spurs high-management lawn productivity, although the balance between above- versus belowground carbon allocation in lawns remains uncertain, as does the extent of carbon losses due to soil respiration or leaching. We found a number of lines of evidence that suggest H lawns have translocated soil carbon downwards, likely through frequent irrigation, and thus there may be a trade-off between surface soil carbon accumulation and deep soil carbon accumulation with this management regime.

Implications

We live in an era of widespread and rapid urban development, with managed grasslands covering 39% to 54% of urban land area in the United States (Milesi et al. 2005). The management of grassland in urban environments, its associated energy use and socio-ecological ramifications are important considerations when weighing the relative benefits of soil carbon sequestration. Lawns offer a number of urban ecosystem services, as increasing soil carbon content correlates with improving soil structure, fertility, and water quality, yet management practice carries a carbon cost.

Our work demonstrates that long-term management practices in the Eugene-Springfield urban ecosystem had a discernable effect upon the vertical distribution and extent of soil carbon pools. However, overall we found no difference in soil carbon pools to 1 m depth among SWV lawns, suggesting a trade-off between shallow and deep soil carbon storage between management regimes, while highlighting management-related emissions as a determining factor of the net carbon sequestration capacity of SWV lawn soils. With this result in mind, from the standpoint of urban ecosystem functionality, low-management lawn practice may offer greater ecosystem service relative to high-management practice. Low-management practices minimize energy use, emissions, and chemical inputs, while maintaining a larger upper soil carbon pool. As there is no difference in the extent of soil carbon pools to 1 m depth between high and low long-term SWV lawn management, minimizing management-related carbon emissions provides the greatest net carbon sequestration potential.

We also found evidence that the deep broad root system and canopy of mature trees are important in storing soil carbon. Introduction of perennial woody vegetation into the residential landscape, and urban environment in general, may provide the potential for enlargement of soil carbon pools and improvement of soil quality, in addition to providing shade and aesthetic appeal. Residents of urban ecosystems along the Pacific West Coast of the United States should consider planting trees and maintaining grassland non-intensively, as a means to soil carbon sequestration over their lifetime, and as a form of contribution to their urban ecosystem community.

Opportunities for Future Research

Future studies should consider the effect of specific management practices upon soil carbon pools over longer time periods and in other climatic contexts. Measurement of net primary productivity, above- and belowground plant carbon allocation, and rates of DOC leaching would help to shed light upon the mechanistic underpinnings of this study. Assessing soil carbon pools and horizonation patterns to a greater depth, as well as isolating additional deep soil horizons, would be of great value in future research concerning management-accelerated pedogenesis. This research provides a foundation for future studies in exploration of culturally embraced soil building practices and the functional contributions of the soil system in the built environment. In time, urban ecological research may lead to a notion of urban ecosystem community, in which residents, through management practice, foster human and ecological health.

APPENDIX A

TEXTURE

Table A.1 Soil Texture by Location

	NRCS Soil Series	Empirical A Horizon Texture	NRCS Taxonomic Class
Springfield (SP)	Malabon	silty clay loam/clay loam	Fine, mixed, superactive, mesic Pachic Ultic Argixerolls
South Eugene (SE)	Hazelair	clay loam/sandy clay loam/loam	Very-fine, smectitic, mesic Vertic Haploxerolls
	Dixonville	clay loam/sandy clay loam/loam	Fine, mixed, superactive, mesic Pachic Ultic Argixerolls
	Panther*	clay	Very-fine, smectitic, mesic Vertic Epiaquolls
West Eugene (WE)	Coburg	clay loam/silty clay loam/loam	Fine, mixed, superactive, mesic Oxyaquic Argixerolls
outh Bottomlands (R	Panther	clay	Very-fine, smectitic, mesic Vertic Epiaquolls
Pisgah East Gate (RP)	Panther	clay loam	Very-fine, smectitic, mesic Vertic Epiaquolls
	Courtney	clay loam	Fine, smectitic, mesic Abruptic Argiaquolls
Dorris Ranch (RP)	Dixonville	clay	Fine, mixed, superactive, mesic Pachic Ultic Argixerolls
	Philomath	clay	Clayey, smectitic, mesic shallow Vertic Haploxerolls
	Hazelair	clay	Very-fine, smectitic, mesic Vertic Haploxerolls
Blanton Road (RP)	Dixonville	clay/silty clay	Fine, mixed, superactive, mesic Pachic Ultic Argixerolls
	Philomath	clay/silty clay	Clayey, smectitic, mesic shallow Vertic Haploxerolls
	Hazelair	clay/silty clay	Very-fine, smectitic, mesic Vertic Haploxerolls

**Only one lawn in South Eugene represents this soil series*
**Soil series listed in order of prevalance within neighborhoods*

Table A.2 Empirical Soil Texture by Horizon

Horizon	Management Group	% Clay	USDA Texture
A	H	36	silty clay loam
A	H	35	clay loam
A	H	17	sandy loam
A	H	23	loam
A	H	31	silty clay loam
A	H	27	clay loam/loam
A	H	38	silty clay loam
A	H	29	silty clay loam/clay loam
A	H	27	clay loam/loam/sandy clay loam
A	H	28	clay loam/loam
A	L	28	sandy clay loam/clay loam/loam
A	L	23	loam
A	L	28	sandy clay loam
A	L	46	clay
A	L	33	silty clay loam
A	L	19	sandy clay loam/sandy loam
A	L	34	silty clay loam
A	RP	44	clay
A	RP	38	clay loam
A	RP	46	clay
A	RP	52	clay/silty clay
AB	H	43	silty clay
AB	H	26	sandy clay loam
AB	H	28	clay loam/loam
AB	H	47	silty clay
AB	H	34	clay loam
AB	H	39	silty clay loam/silty clay
AB	L	27	sandy clay loam
AB	L	43	silty clay
AB	L	25	sandy clay loam
AB	L	38	silty clay loam/silty clay
BA	H	46	silty clay
BA	H	34	clay loam
BA	H	39	silty clay loam/silty clay
BA	H	50	silty clay/clay
BA	H	37	clay loam
BA	H	38	clay loam
BA	L	38	clay loam
BA	L	26	sandy clay loam
BA	L	42	silty clay
BA	L	28	silty clay loam/silty loam
B	H	32	clay loam/sandy clay loam
B	H	46	silty clay
B	L	40	clay loam/clay
B	L	39	clay loam/clay
B	L	39	clay loam/clay
B	L	34	clay loam

**Table features all horizons included in the total soil carbon calculation*
**All lawn soils are considered part of a urban land complex in the NRCS soils database*

APPENDIX B

REGRESSION

Table B.1 Regression Dummy Variables

Management Group	Reached B Horizon	Reached One Meter	Mature Tree Present	Redox Features Present	Possible Cut and Fill	Canopy Cover by Satellite
H	-	*	**	-	*	****
H	-	*	-	*	-	*
H	*	*	-	**	-	**
H	*	-	*	*	*	****
H	-	*	-	-	*	**
H	*	*	-	*	-	-
H	-	*	*	*	*	****
H	*	*	**	**	-	****
H	*	-	*	*	-	***
H	-	*	*	*	-	***
L	*	*	-	*	*	****
L	*	*	*	*	-	**
L	*	-	*	**	-	**
L	*	-	**	*	-	***
L	-	*	-	*	-	*
L	*	*	-	*	-	**
L	-	*	**	*	-	****

Step-Wise Regression – Model Independent Variables

- Years of Management
- Management
- Neighborhood Location (SE, SP, WE)
- Presence of Blue Clay – insignificant, not included in table above
- Reached B Horizon (Y/N)
- Reached One Meter (Y/N)
- Canopy Cover by Satellite – ranked 1 (0-25%) to 4 (75-100%)
- Brown by Satellite – insignificant, not included in table above
- Mature Tree Present – ranked absent - light to moderate - heavy
- Redox Features Present – ranked none - few - prominent
- Possible Cut and Fill (Y/N)
- A Horizon % Clay

APPENDIX C

SPECIES RICHNESS & ROOT MASS

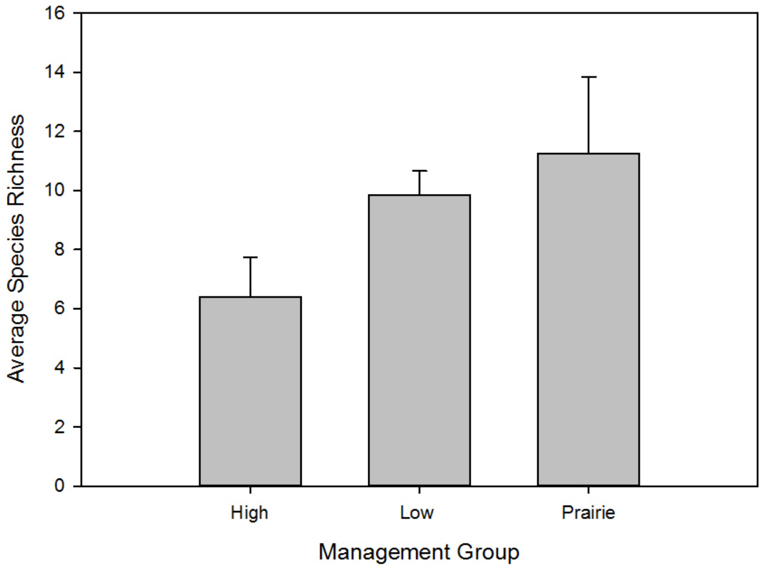

Figure C.1. Average species richness (forbs and grasses) in lawns and remnant prairie.

H v. L, P = 0.19; RP v. H, P = 0.114; RP v. L, P = 0.836

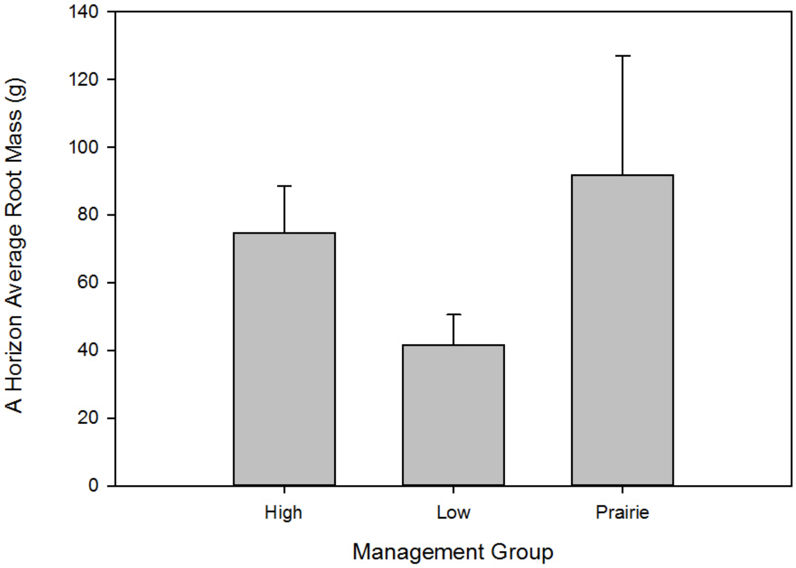

Figure C.2. Average root mass of A horizon bulk soil of lawns and remnant prairie.

H v. L, P = 0.308; H v. RP, P = 0.796; L v. RP, P = 0.197

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