AS SEATTLE EXPANDS:

Carbon Stock Changes in Soil and Biomass from House Lot Development

By Deborah Lipson

Thesis

Submitted in partial fulfillment of the requirements for the

Degree of Bachelors of Science in the Center for Environmental Studies at

Brown University

PROVIDENCE, RHODE ISLAND

MAY 2009

This thesis by Deborah Kean Lipson is accepted in its present form by the Center for Environmental Studies as satisfying the honors thesis requirements for a honors degree of Bachelor of Science

---

Stephen Porder, Advisor **Date**

Steven Hamburg, Reader **Date**

Robert Harrison

Rob Harrison, Reader **Date**

Acknowledgements

I would like to thank my advisor, Stephen Porder, for his continued willingness to both challenge and support me. This work would never have been possible without his guidance. I would also like to thank the Royce Fellowship, my readers and supporters Rob Harrison and Steven Hamburg, and Lynn Carlson and David Murray for their support in the MacMillan Labs. Finally, my parents deserve special recognition for their love and encouragement throughout my academic career.

Table of Contents

List of Equations, Figures, and Appendices

Equations

Figures

Figure 1: Puget Sound population growth model and study site location. The * indicates the location of Issaquah, Wa.

Figure 2: Percent carbon in house lot soils and forest soils. The error bars represent 1se. The significance value $p=5*10^{-5}$ refers to the significance in difference between the two black bars which represent the soil C percent from 0-25 cm in the house versus the forest. The significance value p=0.006 refers to the significance in difference between the two grey bars which represent the soil C percent from 25-75 cm.

Figure 3: Mean carbon stores on house lots versus forest lots. For the forest column "AGB-L" represents the lower bound estimate of 135 Mg C ha^{-1} and "AGB-U" represents the upper bound estimate of 289 Mg C ha^{-1} (see Sampling Methods: Carbon in Biomass). For the house lot column "AGB-L" represents the measured mean AGB of 8 Mg C ha^{-1}. The error bar for the house column refers to 1se for the soil and the biomass C measurements combined. The error bar for the forest column refers to 1se only for the soil C measurement; the biomass values are derived from the literature. A one-tailed paired t-test shows a significant difference between the amount of soil C in Mg C ha^{-1} (p=0.02), but a paired t-test for total C is impossible given no paired data for forest C values.

Figure 4: Comparison of C emissions from soil and biomass and other C emissions associated with suburban homebuilding. “Soil” represents the C lost from just soil for the average house lot over 90 years (13 Mg C/house). “Soil+AGB-L” represents the lower bound estimate C loss per house (7 Mg C/house) plus soil C loss over 90 years and “Soil+AGB-U” represents the upper bound estimate for loss (34 Mg C/house) plus soil C loss over 90 years. “Added Driving” represents the emissions from a 30% increase in driving by two drivers over 90 years and “Home Energy Use” represents emissions from a 40% increase in household energy usage over 90 years (see Discussion: Carbon Emissions in Context).

Appendices
Appendix A: Soil carbon and bulk density measurements for all sites
Appendix A II: Soil carbon in garden samples
Appendix B: Biomass measurements
Appendix C: Photograph of typical study site

Abstract

Although fossil fuel burning has been the primary driver of dramatic increases in atmospheric CO_2 since the industrial revolution, land use changes currently constitute ~20% of global anthropogenic CO_2 emissions (1.6 ±0.8 Pg C yr^{-1}), mostly from deforestation of tropical forests. In contrast, regrowing forests in the northern temperate and boreal zones have provided a carbon sink of roughly 0.6-2.3 Pg C yr^{-1}. As forests are cleared for suburban development, northern forests may begin to emit more carbon, and thus reduce the overall temperate sink. Within this context, I explored the sources of carbon emissions associated with home development in King County, WA, an area with high forest cover but rapid suburban expansion. In the 18 paired house/forest lots in this study, house lots had 83 Mg C ha^{-1} less soil C, and between 127 and 281 Mg C ha^{-1} less aboveground biomass C, than adjacent forested sites. While the fate of forest biomass once it is removed from a house lot is variable, combining soil losses with reasonable estimates of C emissions from forest products yields total emissions from housing development of 120-300 Mg C ha^{-1} over 90 years. Assuming suburban dwellers drive 30% more than their urban counterparts, it would take 54–133 years for the tailpipe CO_2 emissions of one new household to equal the C loss that results from land conversion for that household. Similarly, if all of the forestland that is projected to be converted to built environments in the greater Seattle area in the next 15 years looses similar amounts of C to the sites in this study, the CO_2 emissions from that conversion would equal ~4% of King County's annual emissions.

Keywords: Land use change, soil carbon, urban soils, carbon emissions, urban growth

Introduction

Anthropogenic land-use change and the burning of fossil fuels have dramatically increased atmospheric CO_2 concentrations since the industrial revolution, to a level unprecedented in the past 650 thousand years (Siegenthaler 2005). In the past decade CO_2 concentrations increased at a rate of roughly 1.9 ppm per year, and in 2005 atmospheric CO_2 levels had reached 379 ppm (IPCC 2007). While fossil fuel burning accounts for between 75-80% of global CO_2 emissions, land use change accounts for most of the rest (1.6 ±0.8 Pg C yr^{-1}), and can not be ignored as a driver of climate change (IPCC 2007, Houghton 2003). Climate models suggest that differences in land use change in the coming decades could substantially alter our climate trajectory (Feddema et al. 2005). Thus modifying patterns of land use change could be important in attempts to limit emissions of greenhouse gases (GHGs). Sixty percent of land use CO_2 emissions come from deforestation in the tropics (Houghton 2003), but forest regrowth, in the tropics and elsewhere, is an important C sink (DeFries et al. 2002). In the temperate zone, and particularly in North America, this sink (0.6-2.3 Pg C yr^{-1}) has arisen as widespread deforestation in the 1800s has been followed by substantial forest regrowth (Schimmel et al. 2001, Houghton 2003). However, some of this regrowth is now being curtailed by suburban development (Wienert 2006), which suggests that the strength of this sink may wane in the coming decades.

Urban and exurban landscapes account for 1.5 million km^2, or about 25% of the conterminous US, and have grown at an average rate of 24,600 m^2 yr^{-1} for the past half century (Brown et al. 2005). Some cities and counties are beginning to try to limit carbon emissions, but the biomass and soil C implications associated with development are rarely considered or quantified (Pataki et al. 2006). In part, this is because it is difficult to quantify C losses for both above and below ground C stores. Forest products removed from a site have a variety of fates (lumber, plywood, paper, mulch, fuel), and the C emissions from these products are hard to quantify. Nevertheless, several models have been developed to estimate these losses, and though they are subject to considerable uncertainty, they suggest that between 30 and 77% of forest carbon is lost as CO_2 emissions in the 90 years following harvest (Harmon et al.1996, Heath et al. 1996, Perez-Garcia et al. 2006).

Only recently have there been attempts to quantify below ground carbon in urban ecosystems. In two northeastern cities, Boston and Syracuse, urban soils contained ~60% less carbon than was stored belowground predevelopment, while in Chicago and Oakland soil C was slightly higher (4-6%) in urban soils (Pouyat et al. 2006). Dry systems that have inherently low soil carbon may accumulate carbon in lawns when they are watered or fertilized (Golubiewski 2006), and in general soil C losses or gains associated with development depend on site history and the fate of excavated soil (Wienert 2006, Austin 2006). Given that there is often more C stored below than aboveground, and that physical disturbances and changes in inputs by humans can greatly alter soil C (Pouyat et al. 2002), the fate of soil C during suburban and exurban development deserves more attention, particularly in high-carbon areas that may be susceptible to development-driven C losses.

In the absence of U.S. federal policy, many local governments are beginning to set targets for reducing CO_2 emissions. If the amount of CO_2 lost during development is a sizeable fraction of the other, more well constrained CO_2 emissions, then emissions from soil and biomass need to be considered for a full GHG accounting. In this context, I explored the amount of C released from both soils and biomass when forest lots are converted to house lots in the greater Seattle area, King County, WA. I was particularly interested in whether these C losses represented a substantial fraction of regional emissions. Seattle has set the aggressive C emission reduction target of bringing local annual emissions 7% below 1990 levels by 2012 (www.seattle.gov/climate /docs/Seattle%20Carbon%20Footprint%20Summary.pdf), but it will also likely experience substantial suburban and exurban growth in the coming decades (WSDOT 2003; Figure 1). The goal of this project was to begin to quantify the carbon costs of this development and thus allow a more thorough evaluation of the GHG implications for different development strategies.

STUDY AREA

Expansion in Seattle

The population of King County, where Seattle is located, grew from 1.3 million to 1.7 million between 1980 and 2000 and is expected to grow to 2.2 million by 2030 (WSDOT 2003). An estimated 18,000 ha of King County forestland were converted to urban and suburban uses between 1979 and 1989 (MacLean and Bolsinger 1997) and 36,400 ha were converted between 1988 and 2004 (Erickson and Rogers 2008). Similarly, some projections suggest that 21% of population growth in King County (an addition of 362,000 people), will occur in unincorporated areas, which translates to substantial development in forested areas (Vision 2040, 2008).

Construction Processes

While clearing forests increases exposed soil surface area which can stimulate decomposition and carbon loss (Pataki 2006), the fate of soil carbon ultimately depends on where the soil ends up post-construction. After deforestation of the house site, topsoil must be removed from at least the foundational footprint of the house because soil with a high organic content will decompose and shift the foundation. In Washington State most foundations for homes without basements must reach to 60 cm, with building code mandating that the absolute minimum foundation depth for any area under a house is 30 cm (Washington State Building Code, 2008). I interviewed 9 contractors and developers about the fate of soil during development, and all suggested 60 cm was a typical foundation depth. They also indicated that the fate of the excavated topsoil differs between development types. In a large development all of the topsoil from all of the parcels to be developed is removed at once for cost efficiency, even though much of this land will not actually need to be load bearing. It may then be shipped to a topsoil dump, shipped to a topsoil company who will amend it with compost and re-sell it, used onsite as infill for unbuilt open space such as a golf course, or utilized by another project elsewhere in the region which needs infill material. In all of these cases the builder subcontracts the excavation and disposal of the soil, making it difficult to track or measure the fate of the C in that soil. In addition to potential C losses from soil exposure after excavation, one study found that on average for every cubic meter of soil excavated 84 g C were released from excavation and transport (Lawrence 2006).

Soil management in the development of single homes (the focus of this study) is quite different. When a single house lot is developed topsoil only needs to be removed from the foundation footprint and it is cheaper to keep this relatively small amount of soil onsite than to ship it off. Most commonly the excavated soil from such sites is spread around the rest of the site and/or used to landscape; rarely it is taken off site.

On a forest site being cleared for development, there are also several fates for aboveground biomass. If any of the trees are of high enough quality they are usually sold as lumber. What cannot be turned into lumber or plywood will likely end up as pulp for paper, fuel, or mulch, which all have faster rates of decomposition and C release than lumber (Harmon et al. 1996, Perez-Garcia et al. 2006). Given limited information about the fate of wood products from the specific house lots I sampled, I explore different scenarios for carbon loss from above ground biomass to constrain the range of potential losses associated with home development.

SAMPLING METHODS

Site Description

I selected 18 paired forest/house sites in the City of Issaquah, Washington, for which site surveillance and home owner interviews confirmed that the house lot had been cleared from the adjacent forest and was not previously farmland. I selected only sites whose lots had been cleared for the development of <5 homes, which makes it probable that soil was not removed from the property during construction. The majority of sites were cleared for only one house lot, and none were part of large scale developments. Sites were also selected to be evenly distributed throughout the Issaquah area. Although they were not selected for elevation or slope, because of the requirement that sites were previously forested, they were primarily located in the hills rather than in flat lowland areas where farming was historically practiced.

Issaquah (22 km^2) is located in east-central King County to the east of Seattle and Lake Washington, in the foothills of the Northern Cascades (Figure 1) . The climate is temperate, with an annual precipitation of 150 cm (Brown 2008). The region is home to a wet conifer forest. Significant swaths of forestland are still present in the area, although all of the forest within several miles of Issaquah was logged in the late 1800s and early 1900s, and the current forests are thus ~100 year old secondary growth (Robbins 1985).

The 18 house sites in this study ranged in elevation from 23 m to 334 m above sea level. The houses were all built on Inceptisols and Entisols (soil series Alderwood, Everett, Beausite and Neilton (Soil Survey Staff 2008)), which are typical of the glacial till-rich soils of the region. Some of the soils in this group have a very shallow O horizon of a few centimeters in depth while others have no O horizon. The A horizons extend between 5 and 15 cm and B horizons grade into parent material between 50 and 60 cm. The depth of the C horizons varies among the soils, sometimes reaching as deep as 1.5 m.

All these soils are sandy-gravelly loam derived from glacial till and are well-drained (Soil Survey Staff 2008).

I originally planned to study changes in soil C with time since development, and selected house lots that ranged from 1 to 88 years since development (mean 28 years). Lot size, landscaping and house size varied among sites, with the lot size (including uncleared forest areas) ranging from 590 m^2 to 27,780 m^2 (mean=7,610 m^2), total area cleared on each parcel ranging from 400 m^2 to 5,300 m^2 (mean=1,600 m^2), and house footprint ranging from 130 m^2 to 340 m^2 (mean=300 m^2). For most house lots landscaping was dominated by lawn, from which soil samples were collected. If there was intact forest left in place on the property, I assumed this intact area did not lose any carbon during development.

Soil Carbon

At each house lot I took three samples from the house lot and one sample from an adjacent forest site; the forest sample was taken from within 200 m of the lawn sample location in order to minimize variation in soil type. I took soil samples from the lawn at 1 m, 5 m and 10 m away from the house in order to test for variation in soil carbon with distance from house, but since there was none, the data from the three lawn locations were pooled to yield one house and one forest soil C measurement per depth per site. For each sampling location I used a hammer core to collect a single sample of known volume to a depth of 25 cm. Below 25 cm I used a twist auger to collect three samples to a total depth of 75 cm (25-42, 42-59, and 59-75), but again there was no variation in percent carbon among these samples with depth, so these samples values were pooled to yield a mean value for each 25-75 cm core. Because of the high rock and gravel content of the soils I was not able to sample to 75 cm at every distance from the house, but I was able to collect at least one core per house, and one per forest, to a depth of 42 cm for every house and to a depth of 59 cm for all but four houses and four forests.

All samples were air-dried at room temperature for a minimum of 48 hours and sieved through a 2 mm screen. Bulk density of the <2 mm fraction was determined for the 0-25 cm cores, and assumed to be the same below 25 cm. This likely causes me to underestimate soil losses from house lots, since surface soils were significantly less dense in forests than in house lots (0.8 vs. 1.0 g cm^{-3}, respectively, $p = 0.003$), and this difference is likely less pronounced at depth. For <5% of the 0-25 cm samples I was unable to obtain a bulk density measurement; in this case I assumed the bulk density to be the same as the measured mean bulk density from lawns or house lots respectively.

I ground soil subsamples, dried them at 65°C for at least 48 hours, and analyzed them for C concentration on a Carlo Erba NC2100 model C/N analyzer. I ran samples in duplicate, and a randomly chosen 10% of samples in triplicate. Greater than 95% of the standards run as unknowns (Acetanilide, Cyclohexane, Pine and Montana Soil) were within 5% of their accepted value. All reported values are means ± 1se unless otherwise noted.

Carbon in Biomass

I calculated changes in above ground biomass (AGB) by comparing AGB on each house site with estimates of regional forest AGB in the Pacific Northwest (135 - 289 Mg C ha^{-1}; Adams et al. 2005, Binkley et al. 1992). Because of the complexity of following

C in biomass from the forest to its many fates there are a range of estimates in the literature about how much C in biomass from a cleared site ends up as atmospheric C and over what timescale. Heath et. al. (1996) estimated that 30% of biomass C from cleared forests in the United States is emitted as CO_2 over 90 years, and another 35% is emitted from biomass burning for energy. Because the latter likely replaces fossil fuels, and thus is not necessarily a net carbon loss to the atmosphere, I chose 30% over 90 years as a lower bound of loss for this study. Harmon et al. (1996) suggest that 77% C loss occurs specifically from Pacific Northwest forests over the same time period, and I used this as an upper bound estimate.

Biomass on each house lot was calculated by measuring DBH for all trees on the site and using a generic allometric equation to determine biomass (Jenkins et al. 2004):

$$\text{Above Ground Biomass}=\text{Exp}(B_0+B_1 \ln \mathit{dbh}) \qquad \text{(Eq. 1)}$$

where B_0=-2.48 and B_1=2.48, mean values for mixed hardwoods (most house lots contained a broad mix of native softwoods and non-native planted hardwoods). Although these parameters are meant specifically for trees growing in canopied forests, the sensitivity of overall AGB loss to this inconsistency is small. Sensitivity of overall AGB loss from the site to the range of possible values for these parameters was also small: loss varied by <5 Mg C ha^{-1} among the range of values, or by <5% of loss. Biomass loss was only measured on the cleared portions of the house lot; uncleared portions of the lot were considered undisturbed for the purposes of this study and not included in the C loss calculation. Carbon was assumed to be 50% of all biomass (Schlesinger 1997). In calculating biomass for the site, I omitted both grass and shrubs under 1 m tall. Other studies have indicated that biomass in grass and shrubs account for <2% of total biomass in urban and suburban settings (Golubiewski 2006, Jo and McPherson 1995).

House Lot Characteristics and Loss Assumptions

In addition to determining soil C in the lawn, I made several assumptions as to carbon loss under the house footprint, the driveway, and the garden. I assumed that carbon below 75 cm was unaffected by development and that the majority of carbon was stored at 0-75 cm (Jobbagy and Jackson 2000). I also assumed that the average house foundation was 60 cm deep, and therefore that 80% of the soil C under the house footprint was removed during construction (Washington State Building Code 2008). Since the excavated soil C removed from the foundation is most often spread around the site, I assumed that this C contributed to the soil C values for the lawn. I conservatively assumed that no soil C was lost from beneath the driveway. Finally, there was no difference in soil C between lawns and gardens, so these were lumped in the analyses (Appendix A II).

Results

Soil Carbon

The mean surface (0-25 cm) soil C concentration was significantly higher in forests (6.4±0.8%) than on house lots (3.8 ±0.3%; one-tailed paired t-test p =.00005, n=18; Figure 2). Similarly, the 25-75 cm soils were significantly more C rich in forests than lawns (3.6 ±0.6% versus 1.9 ± 0.2%; one-tailed paired t-test p=0.006, n=18). The mean bulk densities for the forest and house lots were 0.8±0.2 and 1.0± 0.1 g cm^{-3}, respectively (one-tailed paired t-test, p=0.003, n=18). There was no significant difference between the three depths for the 25-75 cm samples (one way ANOVA, p = 0.71). There was also no significant difference in either the bulk density or the means of the C concentration among the three distances to the house (one way ANOVA, p = 0.55 and 0.18 respectively), so all further discussion will focus on house lot and forest lot means. Finally, there was no significant relationship between house age and soil C concentration on the house lot soils (r^2=0.04, p = 0.4).

House soils stored 155±11 Mg C ha^{-1} to a depth of 75 cm (accounting for no loss from the driveway and including the assumption of 80% removal from house footprint). In contrast, forest soils store 238±25 Mg C ha^{-1} to the same depth, which is significantly more (one-tailed paired t-test, p = 0.002). Thus the mean loss of soil C associated with house construction and landscaping is 83±28 Mg C ha^{-1}. Given that there was no trend in soil C with house age, and the youngest house in the study was only one year old, I assume that this carbon is lost in the first year of construction.

Carbon in Biomass

The aboveground C in biomass on the house lots ranged from 0-44 Mg, averaging 8±3 Mg C ha^{-1} (figure 3). There was no correlation between age and biomass on house sites (r^2=0.05, p=0.38). In contrast, forest biomass C estimates drawn from the literature suggest that there is 135 - 289 Mg C ha^{-1} in AGB (Adams et al. 2005, Binkley et al. 1992). Assuming between 30 and 77% C emitted from this biomass over 90 years, this suggests that between 38-217±3 Mg C ha^{-1} are lost as CO_2 in this time. If loss rates are invariant over 90 years, this suggests emissions of 0.40 - 2.4 Mg C ha^{-1} yr^{-1}. There was no correlation between age and biomass on site (r^2=0.05, p=0.38).

Discussion

Soil Carbon and Biomass Loss

These data suggest that a pulse of C is released from a house lot during development and that it does not substantially re-accumulate in either soils or biomass after development. The assertion that substantial soil C is lost is robust: even assuming all soil C originally under the house footprint remains sequestered there, total soil C loss for the average house lot decreases by only 9% because the total cleared area of the house lots are so large compared to the house footprints. This finding of lower levels of soil C on developed soils compared to native forest soil agrees with similar sites in Pouyat's study (2006) across five US cities but contrasts with those of Golubiewski (2006), who found that lawns built on previous grasslands in Colorado returned to or exceeded assumed predevelopment levels after two decades. Part of this deviation from Golubiewski and other studies which have found elevated soil C levels in urban soils (Qian and Follett 2002) may be explained by a high C level in native soils and a relatively low level of inputs to house lot soils in the region of this study. Pouyat et al. (2009) suggest that similar lawn care practices across regions lead to a convergence of urban soil C values which may often be higher than the native soils, but that in wet, temperate forested regions, such as Western Washington, where lawns do not require many inputs, soil C values may be lower than native soils.

Not surprisingly, the conversion of forest to house lots led to a decrease in aboveground biomass, since house lots contained only 8±3 Mg C ha^{-1} on average. This means that the vast majority (>90%) of C on house lots comes from soils (figure 3). Similar C distributions have been observed in other urban areas, such as Jo and McPherson's (1995) study of Chicago which found that as much as 88% of C in urban areas was stored in soil. However, while there is a large difference in the amount of AGB between forest and house lots, because there is uncertainty as to the ultimate fate of AGB C, and the rate at which it is lost to the atmosphere, AGB C loss is poorly constrained (30-77%).

Assumptions and Error

By sampling using vertical soil cores to a fixed depth, I implicitly assume that I am sampling to a depth below which no significant C is lost. If a significant amount of C was lost below 75 cm or if C-rich soil was somehow buried below 75 cm then I could be either under or overestimating soil C loss. By sampling to a fixed depth I also assume samples were taken from the same horizons in the soil on both forest and house sites. Yet the increased bulk density of house lot soils suggests that soil compaction accompanies development, and thus a 75 cm core from house sites will reach lower horizon than an identical depth core in the forest. However, this would cause an underestimate of C loss from development, and thus the results presented above are conservative.

Assuming that bulk density was invariant from 0-25 and from 25-75 cm is also likely an oversimplification, since bulk density usually increases with depth (USDA-NRCS 2008). If compaction did not affect the lower horizons, this estimate may lead me to underestimate soil C losses from house lots. To test the size of this potential error, I computed soil C losses assuming forest soil bulk density, instead of the house lot bulk density, below 25 cm on the house lots. Changing this assumption decreased average soil C for the house lot by ~10% (from 155 to 139 Mg C ha^{-1}).

Finally, I assume that soil C losses from the site result in CO_2 emissions – that is that C that originally was in forest soils was decomposed and respired upon conversion to house lots. However, it is possible that some portion of the "lost" soil C is transported off of the site via erosion, where its fate is unclear. While in transport to a large body of water, such as Puget Sound, the soil C may experience an increased rate of decomposition, but when the soil particles are eventually deposited, their decomposition rates may drop (Behre et al. 2007). Although there is some indication that erosion from agricultural fields is a net C sink (van Oost et al. 2007), there is no data of which I am aware that speaks to this issue in the context of housing development.

Lost Carbon Sequestration Potential

In considering the C impact of converting a forest lot to a house lot, lost C sequestration potential at that site is an additional factor to consider. Many of the forestlands into which Seattle is expanding were last logged in the late 1800s and early 1900s, meaning that most of these stands are currently around 100 years old (Robbins 1985). Stands of northwest evergreens, such as Douglas Fir and Western Hemlock, take up to 250 years to mature after being logged, and some Firs can live up to 700 years (Spies and Franklin 1996). Smithwick et al (2002) found that on average an additional 338 Mg C ha^{-1} could be stored in the biomass and soils of coastal Washington and Oregon forests if second growth stands were allowed to return to their maximum C holding capacity, and that the upper bound C potential for just the biomass of these old growth forest is 380 Mg C ha^{-1}.

For carbon losses, and loss rates, I have used a range of between 135 Mg C ha^{-1} and 289 Mg C ha^{-1} to estimate background biomass (Adams et al. 2005; Binkley et al.1992). But the development of housing on regrowing forest land represents a lost carbon uptake in the future. Assuming that the forests reach their full C holding potential after an additional 150 years (given an average stand age of ~100 years) (Smithwick et al. 2002, Franklin et al. 1986), the lost sequestration potential (LSP) is the difference between the biomass at the time of removal and the assumed biomass of a fully grown forest. LSP ranges from 92-245 Mg C ha^{-1} developed, or 0.6 - 1.6 Mg C ha^{-1} yr^{-1} for the next 150 years.

Carbon Emissions in Context

Although there are considerable uncertainties in the estimate, the C loss due to development is substantial. Assuming lower bound forest carbon and loss rates, 120±31 Mg C ha^{-1} is liberated from soils and AGB within 90 years of conversion, while upper bound estimates suggest a 300±31 Mg C ha^{-1} loss (Figure 3). This loss is comparable to other major carbon costs of suburban development (Figure 4). For every house that is built on forest lot rather than dense urban infill, there is a 31% increase in the amount that that household drives (Kahn 2000). If the average person in the Puget Sound region drives around 13,500 km yr^{-1}(Overby 2008), a household with two drivers travels an additional 8,000 km yr^{-1} by building in suburbia rather than living in urban areas. Assuming an average car gets the 2004 CAFÉ standard of 11.7 km l^{-1} (27.5 miles per gallon) (EPA 2003) and that emission are 1 kg C l^{-1} (Glaeser and Kahn 2008), then the transportation-based carbon impact of building a single family home in the forest instead of as urban infill is 0.35 Mg C yr^{-1}(figure 4). It would take 37 years for the emissions from increased driving to be equal to just the soil carbon emissions from building, 54-134 years for tailpipe emissions to equal emission from soil and biomass combined, and even longer for driving emissions to equal soil and biomass emissions if LSP was included.

Suburban houses also tend to be larger (~40%) than their urban counterparts, and thus consume 40% more energy than their smaller urban counterparts (Kahn 2000). If the average house in Seattle is responsible for the emission of 3.7 Mg C yr^{-1} (Glaeser and Kahn 2008), a 40% larger suburban home emits an additional 1.5 Mg C yr^{-1} . It would take nine years for these emissions to equal soil C emissions, and 13-32 years to equal soil and biomass C emissions.

Scaling up

Although the recent economic downturn and a new national awareness of environmental issues could slow Seattle's growth into forestland, it is likely that substantial suburban encroachment into forest will occur in the coming decades. Assuming that ~36,000 ha will be converted from forestland to suburbs in the next 15 years in King County, similar to the conversion between 1988 and 2004 (Erickson and Rogers 2008), ~ 2,400 ha yr^{-1} will be converted between now and 2024 given a constant conversion rate. This means that emissions from soil and biomass C will be between ~210,000 and 240,000 Mg C yr^{-1}. Washington State estimates that the state now emits 21.8 million Mg C annually, that King County emits 5.7 million Mg C annually, and that

Seattle emits 1.6 million Mg C annually (www.seattle.gov/climate /docs/Seattle%20Carbon%20Footprint%20Summary.pdf). Given this, emissions from soil and biomass could represent between 3.7% and 4.3% of King County's annual emissions over the next 15 years.

Such extrapolation is subject to uncertainty. Not all of the land which is converted from forest to suburbs will be deforested and built as single house lots; according to estimates from the King County Department of Development and Environmental Services, single house lots likely represent just over half of total homes developed in the past decade around Issaquah and similar suburbs. In large subdivisions or shopping centers the treatment of biomass and especially of soils is different and therefore the CO_2 emissions may be different. Different soil types may respond to development differently, and because the sites in this study were located primarily in highland areas, riparian and other particularly soil C-rich areas were excluded. Furthermore, certain soil types may be systematically excluded from development because of environmental regulation, which could affect overall C emissions from soil and biomass in King County. Given the substantial emissions that this study shows forest to house lot conversion to be potentially responsible for, additional study of the fate of biomass and soil C from both larger housing developments and across more soil types may be valuable.

Conclusion and Policy Implications

Even the most conservative estimates of soil and biomass emissions from development suggest that they could account for 3.7% of annual King County emissions over the next 15 years. Thus policy makers, to the extent that they are concerned with both emissions and land use planning, may want to take these emissions into account. To the extent that urban infill is being encouraged by laws already in place in King County, such policies could have the added benefit of avoiding this previously undocumented source of C emissions, as well as more commonly cited sources such as vehicle miles traveled and household energy usage. As of 2007 King County requires developers to estimate GHG emissions for every project in a GHG worksheet, and while there is currently no tax or mandatory emissions reduction, such policies may not be far off (KCDDES 2009). This study suggests that when construction occurs in a greenfield, a full accounting of C emissions needs to include soil and biomass C changes.

References

Adams A, Harrison R, Sletten R, Strahm B, Tumblom E, Jensen C (2005) Nitrogen-fertilization impacts on carbon sequestration and flux in managed coastal Douglas-fir stands of the Pacific Northwest. Forest Ecol Manag 220: 313–325

Berhe A, Harte J, Harden J, Torn M (2007) The Significance of the Erosion-induced Terrestrial Carbon Sink. Bioscience 57(4): 337-346

Binkley D, Sollins P, Bell R, Sachs D, Myrold D (1992) Biogeochemistry of Adjacent Conifer and Alder-Conifer Stands. Ecology 73 (6): 2022-2033

Brown DG, Johnson KM, Loveland TR, Theobald DM (2005) Rural land-use trends in the conterminous United States, 1950– 2000. Ecol Appl 15:1851–63

Brown T [dir.] (2008) Period of Record Monthly Climate Summary. In: NOAA Washington Climate Summar. Available via http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa7468. Accessed 2008 December 20.

Defries R, Houghton R, Hansen M, Field C, Skole D, Townshend J (2002) Carbon Emissions from tropical deforestation and regrowth based on satellite observation for the 1980s and 1990s. Proceedings of the Natl Acad Sci. 99(22), 14256-14261

Erickson A, Rogers L (2008) Western Washington Land Use Change. Rural Technology Initiative.

Feddema J, Oleson K, Bonan G, Mearns L, Buja L, Meehl G, Washington W (2005) The Importance of Land-Cover Change in Simulating Future Climates. Science 310:1674 – 1678

Franklin J E, Hall F, Laudenslayer W, Maser C, Nunan J, Poppino J, Ralph C J, Spies T (1986) Old growth Definition task group report: Interim definitions for old-growth Douglas-Fir and Mixed-Conifer forests in the Pacific Northwest and California. USDA Forest Service, Pacific Northwest Research Station Research Note PNW-447

Golubiewski N (2006) Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's Front Range. Ecol Appl 16:555-571

Glaeser E, Kahn M (2008) The Greenness of Cities: Carbon Dioxide Emissions and Urban Development. National Bureau of Economic Research. Working Paper 14238

Harmon M, Harmon J, Ferrell W, Brooks D (1996) Modeling carbon stores in Oregon and Washington forest products: 1900–1992. Climatic Change 33(4).

Heath L, Birdsey R, Clark R, Plantinga J (1996) Carbon pools and flux in US forest products. Forest Ecosystems, Forest Management and Global Carbon Cycle. NATO ASI Series I: Global Environmental Changes, Volume 40, Springer-Verlag, p.271-278

Houghton R (2003) Revised Estimates of the Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use and Land Management 1850–2000. Tellus 55B: 378–390

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jenkins J, Chojnacky D, Heath L, Birdsey R (2004) Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species. Gen. Tech. Rep. NE-319. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 45 p

Jo H, McPherson E (1995) Carbon storage and flux in urban residential green space. J Environ Manag 45: 109–133

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10: 423–436

Kahn M (2002) The Environmental Impact of Suburbanization. J Policy Anal and Manag

17(4): 569-586

KCDDES (2009) SEPA GHG Emissions Worksheet Version 7.1 In: King County Department of Development and Environmental Services Publications. Available via www.metrokc.gov/ddes/forms/SEPA-GHG-EmissionsWorksheet-Bulletin26.pdf. Accessed 12 February 2009

Lawrence L, Green J, Lee S (2006*)* Carbon Footprint of Construction Capstone Project. University of Washington Program on the Environment.

MacLean C, Bolsinger (1997) Urban Expansion in the Forests of the Puget Sound Region. Resource Bulletin PNW-RB-225. Portland: USDA Forest Service. 19 pgs.

Oost K, et al. (2007) The Impact of Agricultural Soil Erosion on the Global Carbon Cycle. Science 318: 626-629

Overby, K (2009) Puget Sound Trends: Trends in Vehicle Miles Traveled. In: Puget Sound Regional Council Publications. Avaliable via psrc.org/publications/pubs/trends/t2sep08.pdf. Accessed 31 January 2009

Perez-Garcia J, Lippke B, Comnick J, Manriquez C (2006) An Assesment of Carbon Pools, storage and Wood Products Market Substitution using life-cycle analysis results. Wood Fiber Sci, 37 Corrim Special Issue: 140-148

Pataki D, Alig R, Fung A, Goliubski E, Kennedy C, McPherson E, Nowak K, Pouyat R, Pomero Lankao P (2006) Urban ecosystems and the North American carbon cycle. Glob Change Biol 12 (11): 2092–2102

Pouyat R, Groffman P, Yesilonis I, Hernandez L (2002) Soil carbon pools and fluxes in urban ecosystems. Environ Pollut 116:107-118

Pouyat R, Yesilonis I, Nowak D (2006) Carbon Storage by Urban Soils in the United States. Journal of Environmental Quality 35:1566-1575

Pouyat R, Yesilonis I, Golubiewski N (2009) A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosyst 12: 45-62

Qian Y, Follet RF (2002) Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agron 94: 930–935.

Robbins W (1985) The social context of forestry: the Pacific Northwest in the twentieth century. The Western Hist Quart 16(4): 413-427

Schlesinger W (1997) Biogeochemistry: An Analysis of Global Change. London: Elsevier. 588 p.

Siegenthaler U (2005) Stable Carbon Cycle-Climate Relationship During the Late Pleistocene. Science 310: 1313-1317

Smithwick E, Harmon M, Remillard S, Acker S, Franklin J (2002) Potential Upper Bounds of Carbon Stores in Forests of the Pacific Northwest. Ecol Appl 12 (5): 1303-1317.

Soil Survey Staff (2008). Soil survey of King County, Washington. In: Natural Resources Conservation Service, United States Department of Agriculture Soil Survey. Available via http://soildatamart.nrcs.usda.gov/Survey.aspx?State=WA. Accessed 10 December 2008

USDA: NRCS (2008) Bulk Density In: US Department of Agriculture, Natural Resources Conservation Service. Available via: soils.usda.gov/sqi/assessment/files/bulk_density_sq _physical_indicator_sheet.pdf Accessed 10 December 2008

EPA (2003). U.S. Inventory of Greenhouse Gas Emissions and Sinks 1990-2001. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC. EPA 430-R-03-004.

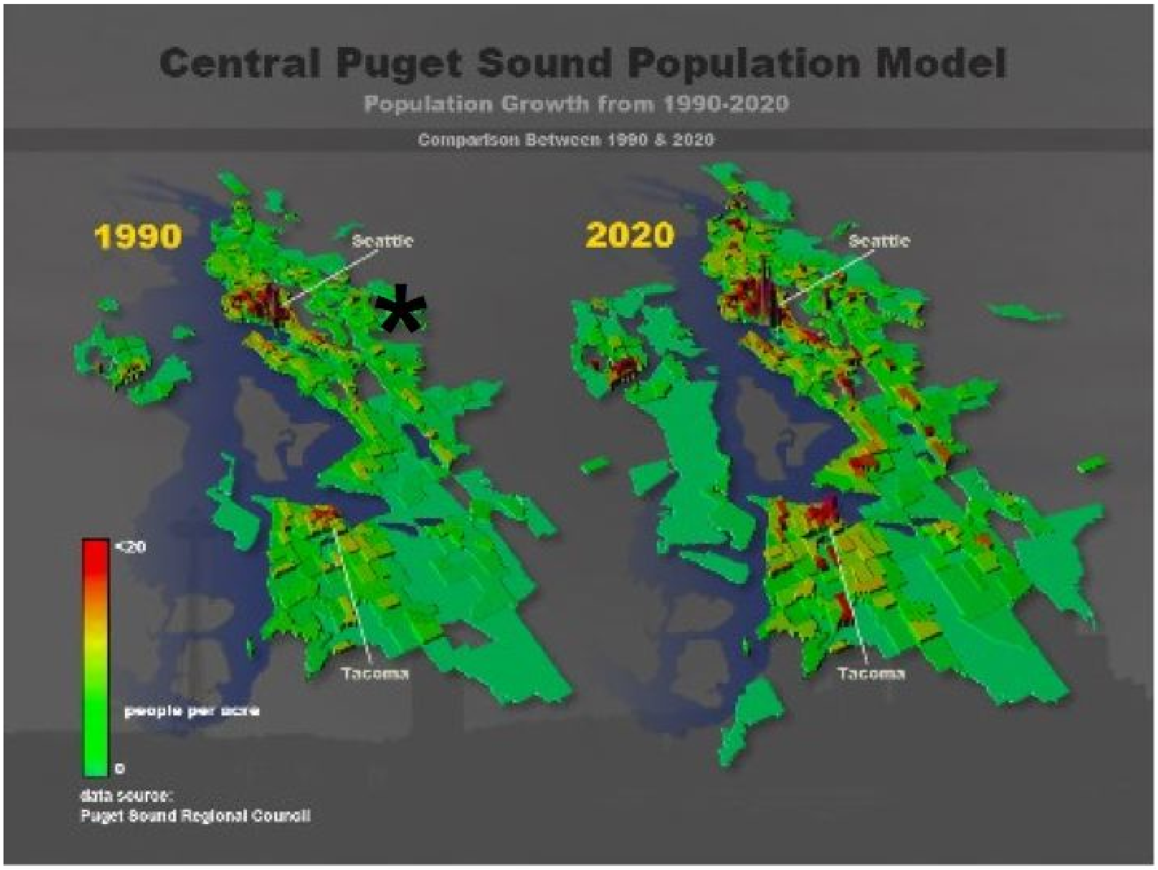
Vision 2040. February 2008. Puget Sound Regional Council. http://psrc.org/projects/vision/pubs/vision2040/index.htm

Washington State Building Code Chapter 51-51 WAC. 2008. Washington State Building Code Council. Fourth Edition: International residential code.

Wienert A (2006) From Forestland of House Lot: Carbon Stock Changes and Greenhouse Gas Emissions from Exurban Land Development in Central New Hampshire. Masters Thesis. Brown University, Providence, Rhode Island, USA.

WSDOT (2008) Population Growth in Relation to State’s Counties. In: Washington State Department of Transportation publications. Available via http://www.wsdot.wa.gov/planning/wtp/datalibrary/population/PopGrowthCounty.htm Accessed 20 December 2008.

Figure 1



Source: http://www.prism.washington.edu/lc/REGNLS/urbangrowth.jpg

Figure 2

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 3

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Appendix A: Soil carbon and bulk density measurements for all sites

HOUSE								
Site	Distance from house	Bulk Density (g cm^{-3})	C content 0-25 cm depth(%)	C content 25-75 cm depth(%)	Lawn soil C 0-75cm (Mg C ha^{-1})	Cleared Area (ha)*	House Footprint (ha)	Average Soil C for House Lot (Mg C ha^{-1})
1	1	1.0	1.4	1.2	102			
1	5	0.9	3.3	1.7	147			
1	10	0.7	2.7	1.0	83			
avg 1		0.9	2.5	1.3	112	0.1	0.0	83
2	1	1.4	1.9	0.8	117			
2	5	1.1	0.9	0.7	63			
2	10	1.1	4.2	1.4	184			
avg 2		1.7	2.3	1.0	185	0.1	0.0	165
3	1	1.0	2.1	2.6	186			
3	5	1.2	2.9					
3	10	0.7	1.7	1.4	78			
avg 3		1.5	2.2	2.0	227	0.0	0.0	150
5	1	0.9	3.0	2.8	193			
5	5	0.9	3.3					
5	10	1.0	3.0	2.6	214			
avg 5		1.0	3.1	2.7	203	0.2	0.1	158
7	1	1.0	2.7	0.8	109			
7	5	1.0	2.9	1.0	117			
avg 7		1.0	2.8	1.5	143	0.1	0.0	120
8	1	1.3	2.9					
8	5	1.0	2.8	0.3	86			
8	10	0.8	2.8	0.4	73			
avg8		1.0	2.8	0.4	91	0.0	0.0	59
9	1	1.0	6.1	1.4	234			

9	5	1.0	5.6	1.3	215			
9	10	1.0	7.2	2.2	302			
avg 9		1.0	6.3	1.7	250	0.0	0.0	165
10	1	0.8	3.5	0.6	92			
10	5	1.4	4.6					
10	10	0.8	5.4	1.3	170			
avg 10		1.0	4.5	1.0	162	0.0	0.0	121
11	1	1.3	3.9					
11	5	1.3						
11	10	1.0	3.4	1.4	161			
avg 11		1.2	3.7	1.4	198	0.2	0.1	169
12	1	1.0	5.0	3.1	285			
12	5	1.3	5.4					
12	10	0.9	4.5					
avg 12		1.1	5.0	3.1	296	0.1	0.0	242
13	1	0.9	3.8					
13	5	1.0	3.2	1.6	154			
13	10	0.9	5.6	6.4	439			
avg 13		0.9	4.2	4.0	289	0.1	0.0	243
14	1	0.7	6.8	3.5	231			
14	5	0.6	7.6	2.1	173			
14	10	0.7	4.8	2.3	156			
avg 14		0.6	6.4	2.6	187	0.0	0.0	143
15	1	0.9	2.8	1.8	143			
15	5	0.8	4.5					
15	10	1.0	4.4					
avg 15		0.9	3.9	1.8	165	0.2	0.0	154
16	1	1.1	3.8	2.4	243			
16	5	1.0	3.2					
16	10	1.3	4.2					
avg 16		1.1	3.7	2.4	246	0.1	0.0	216
18	1	1.0	2.6	2.0	169			
18	5	0.9	3.0	3.3	225			
18	10	0.7	2.9	1.3	91			
avg 18		0.9	2.8	2.2	159	0.0	0.0	110
19	1	1.0	2.8	1.5	140			
19	5	1.1	3.1					
19	10	1.0	4.2	1.4	173			
avg 19		1.0	3.4	1.5	159	0.3	0.0	150
20	1	1.0	4.3	1.8	204			
20	5	1.4	3.8					
20	10	0.9	4.0	1.0	130			
avg 20		1.1	4.1	1.4	192	0.3	0.0	182
21	1	1.0	3.6	0.8	126			
21	5	1.1	4.2					
21	10	1.0	3.6	2.1	203			
avg 21		1.0	3.8	1.4	171	0.5	0.0	166
MEAN		1.0	3.8	1.9	188	0.1	0.0	155

Standard Error		0.1	0.3	0.2	13	0.0	0.0	11

FOREST				
Site	Forest Bulk Density	C content 0-25 cm depth(%)	C content 25-75 cm depth(%)	Forest Soil C 0-75 cm (Mg C ha^{-1})
1	0.6	3.8	2.5	137
2	0.5	8.8	2.8	171
3	1.0	2.0	0.9	98
5	0.7	5.4	1.4	144
7	1.0	3.0	2.5	197
8	0.5	5.3	3.5	142
9	0.8	4.5	7.9	393
10	0.7	11.2	3.0	287
11	0.5	10.7	5.5	286
12	0.4	11.6	2.5	163
13	0.5	10.6	12.4	415
14	1.0	9.6	3.7	422
15	0.9	5.1	2.3	225
16	1.1	1.5	0.9	92
18	0.9	5.6	2.6	233
19	1.1	3.7	3.8	319
20	0.9	8.5	3.2	339
21	0.9	5.0	2.7	236
MEAN	0.8	6.4	3.6	238
Standard Error	0.2	0.8	0.6	25

* Cleared area values do not include the house footprint; they show total cleared area less the house footprint. Total cleared area=cleared area+house footprint.

Appendix A II: Soil carbon in garden samples

Site	18	20	Reference (average for all sites)
Lawn: Average C content 0-25 cm (%)	2.8	4.1	3.8
Garden: C content 0-25 cm (%)	3.5	3.9	
Lawn: Average C content 25-75 (%)	2.2	1.4	1.9
Garden: C content 25-75 (%)	n/a	1.2	

Appendix B: Biomass measurements

SITE	DBH (cm)	C in AGB (Mg)*	Average C in AGB for house lot (Mg/ha)
1	10	0.013	
	41	0.394	
	27	0.145	
Total		0.6	6
2	86	2.694	
	30	0.203	
	13	0.023	
Total		2.9	24
3	4	0.001	
	4	0.001	
	4	0.001	
	4	0.001	
	13	0.023	
	5	0.002	
	8	0.006	
Total		0.0	0
5	4	0.001	
	5	0.002	
	3	0.001	
	5	0.002	
	6	0.004	
	3	0.001	
	4	0.001	
	5	0.002	
	5	0.002	
	5	0.002	
	5	0.002	
	5	0.002	
Total		0.0	0
7	34	0.272	
	36	0.297	
	20	0.074	
	20	0.074	
	20	0.074	
	20	0.074	

	20	0.074	
	20	0.074	
	20	0.074	
	20	0.074	
	20	0.074	
Total		1.0	11
8	20	0.074	
	22	0.086	
	56	0.914	
Total		1.1	25
9	4	0.001	
	4	0.001	
	4	0.001	
	4	0.001	
	4	0.001	
	4	0.001	
	4	0.001	
	5	0.002	
	5	0.002	
Total		0.0	0
10	78	2.099	
	75	0.004	
	38	0.003	
	20	0.002	
	6	0.001	
	38	0.003	
	10	0.002	
	10	0.002	
	10	0.002	
	24	0.003	
	25	0.003	
Total		2.1	35
11	Lost record-Mean assumed		
12	Lost record-Mean assumed		
13	14	0.029	
	10	0.013	
	14	0.029	
	9	0.010	
	8	0.006	
	8	0.006	
	8	0.006	
	18	0.053	
	8	0.006	
	13	0.023	
	27	0.146	
	29	0.183	
	10	0.013	
Total		0.5	5
14	5	0.002	
	8	0.001	
	10	0.002	
Total		0.0	0
15	14	0.029	
	5	0.001	

Total		0.0	0
16	22	0.086	
	18	0.053	
	9	0.010	
	8	0.006	
	8	0.006	
	13	0.023	
	5	0.002	
Total		0.2	1
18	8	0.006	
	8	0.006	
	8	0.006	
	8	0.006	
	4	0.001	
	8	0.006	
	6	0.004	
	30	0.203	
	32	0.225	
	5	0.002	
	6	0.004	
	10	0.013	
Total		0.5	4
19	48	0.635	
	56	0.914	
	64	1.255	
	48	0.635	
	53	0.814	
	53	0.814	
	18	0.053	
	10	0.013	
	13	0.023	
	13	0.023	
	11	0.018	
	15	0.036	
Total		5.2	11
20	15	0.036	
	20	0.074	
	8	0.006	
	10	0.013	
	14	0.029	
	20	0.074	
	22	0.086	
	24	0.114	
Total		0.4	1
21	6	0.004	
	6	0.004	
	4	0.001	
	8	0.006	
	6	0.004	
	5	0.002	
	13	0.023	
	30	0.203	
	10	0.013	
	17	0.044	
	18	0.053	
	17	0.044	

Total		0.4	1
MEAN			8
SE			3

***** Based on equation Biomass=Exp(B_0+B_1 ln *dbh*) where B_0=-2.48 and B_1=2.48

Appendix C: Photograph of a typical study site