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Development of an Urban Turfgrass and Tree Carbon Calculator for Northern Temperate Climates

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Abstract: The presence of urban plants in an ecosystem are vital for processes including carbon sequestration and the type of urban plants included in urban settings affect the amount of carbon sequestered. The objective of this study is to assess the ability of urban plants to sequester carbon under a number of available management practices through the development and refinement of an accessible carbon calculator. Available urban plant data were analyzed using the calculator developed using available literature regarding carbon sequestration to determine differences between different types of plants, when hidden carbon costs (HCC) were considered. Carbon sequestration including HCC for turfgrasses could be calculated but there was a lack of information regarding HCC of urban trees and shrubs. The calculator was shown to be an effective tool for homeowners to determine viable management practices to maintain or increase carbon sequestration.

Keywords: turfgrass; urban plants; trees; northern temperate climate; hidden carbon costs; soil; carbon



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1. Introduction

Urban plants are important biogeochemically, as they cover a large portion of North America. Turfgrasses alone are estimated to cover 163,000 km² in the United States [1,2]. The ecosystem services of urban plants, including carbon sequestration, cooling effect and flood prevention, have been described in detail, advocating for the use of trees, turfgrass and shrubs in urban centres [3–5]. The primary focus of the inclusion of urban plants has centered around their innate ability to sequester carbon. The type of urban landscape design that is advantageous for the environment, especially with respect to carbon sequestration, has sparked some debate, as the general public does not perceive particular urban plants as being able to provide adequate carbon sequestration and other ecosystem services [6]. Urban plants differ from plants in rural or natural habitats due to required maintenance practices, which are necessary to promote plant health, minimize pests and grooming for utility and aesthetic purposes. For plants to sequester carbon in an urban setting the maintenance practices, or hidden carbon costs (HCC) should not exceed the carbon sequestered.

When undisturbed or with very minimal management, trees and turfgrass have been estimated to sequester soil organic carbon (SOC) at similar rates [7]. Management practices in the urban environment led to differences in carbon sinks for trees and turfgrass. Urban trees store most of their carbon in wood, which is primarily above ground [8], while turfgrasses store carbon in SOC, primarily from thatch and fine roots (<2 mm) and to a lesser extent, clippings that are converted to SOC [9]. Urban trees, which do not typically accumulate significant amounts of SOC due to the removal of accumulation components including leaves and fine woody litter that contribute to SOC in natural ecosystems [10]. Trees have fine root turnover, but the quantity is much less compared to grasses [11]. Carbon sequestration of trees and turfgrass have not been compared in the same study under the same environmental conditions, urban or otherwise, likely due

to the difficulty of comparing two different types of sequestration: (1) SOC accumulation in the soil and, (2) carbon stored in wood. Available literature for urban trees is often harder to understand, as assumptions and data from silviculture or natural forests are used for modelling sequestration in urban environments. An extensive literature review conducted by McPherson et al. [12] showed that urban tree cover across the United States and other countries across the world at similar latitude had an average carbon sequestration rate of $0.60 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and a range of 0.14 to $1.23 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. A study by McGovern et al. [2] that surveyed urban trees across Canada, found an average carbon sequestration rate of $1.62 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and a range of 1.53 to $2.51 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Both studies report similar results to those that appear in the natural forest literature, 0.19 to $0.72 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ [13] and in silvicultural plantations 0.43 to $2.73 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ [14].

The quantification of net carbon sequestration or net global warming potential for turfgrasses have been thoroughly studied [15–21]. Net carbon sequestration is a function of the gross carbon sequestration minus the carbon cost of the maintenance inputs, which include mowing, fertilization, irrigation, and pest management. It is critical to target management practices to ensure that the hidden carbon cost (HCC) of maintenance does not exceed the carbon sequestered in an urban plant system. When managed too intensely, a turfgrass system can go from a sink to a source in approximately 30 years [22]; however, in the absence of general maintenance, the process can take anywhere from 79 to 409 years [17]. Returning clippings to the turfgrass may be important for SOC accumulation and the role of clippings in SOC accumulation has differed depending on the study [9,19,20]. Qian et al. [23] used a CENTURY ecosystem model adapted and verified for use with Kentucky bluegrass grown under home lawn conditions to show that returning clippings to the home lawn could increase C sequestration in the soil anywhere from 11% to 59% increasing with high N rates. Law and Patton [20] also observed an increase in SOC accumulation when the clippings were returned when compared to when the clippings were collected.

Generally, an analysis of net carbon sequestration in trees is carried out using the amount of carbon stored in wood and taking tree decay into consideration but, does not account for management practices including pruning, fertilization and nursery production [8]. Despite there being more literature regarding HCC in turfgrass, there is significantly less literature on the life cycle of turfgrass, specifically in the context of seed production and the establishment phase, which has been studied in urban trees [24–26]. This is important because of the added environmental cost of transporting seed and sod when it is used. Hidden carbon costs of maintenance come in many forms. Most studies consider the HCC of mowing, fertilizer production, irrigation and pesticide production [16,20,21]. Mowing and fertilizer production are typically the largest contributors to the HCC of maintenance due to the relatively large amount of fuel consumed in these processes compared to irrigation and pesticide production.

Other contributions to global warming potential of urban plant systems include nitrous oxide (N_2O) emissions. Nitrous oxide is a potent greenhouse gas, with a global warming potential that is 298 times that of CO_2 and should be considered as a factor in the HCC calculation [27]. Zirkle et al. [16] considered the HCC of fertilization, mowing, irrigation and pesticides, but omitted N_2O emissions in their calculation, which can offset over 20% to 34% of the carbon sequestration of a turfgrass system [20,21]. N_2O emissions occur in non-fertilized settings as part of the standard N soil-surface fluxes, but emissions increase at high rates of fertilization [15,21]. It should also be noted that higher nitrogen rates can leach, resulting in the total amount of N_2O emissions excluded from the N_2O emission estimate [28,29]. Irrigation also can influence N_2O emissions; higher water content in soils tends to promote greater N_2O fluxes [30]. Less irrigation led to lower N_2O emissions during the high temperature months (June to August), and increased irrigation did not have an effect during low temperature months (September to May) [21]. Nitrogen will also increase the growth rate and thus, will increase the number of mowing events [21]. Trees are not free of inputs and these inputs have significant emissions during the production phase. In the production of a nursery tree, there are several HCCs including seed collection, irrigation,

fertilizer and transport [24]. Producing a nursery tree that is viable for transplanting can take over four years, and there will continue to be HCCs of maintaining the tree [25].

The HCC of maintaining urban trees is not as well documented compared to turfgrass, and has only been assessed in a few studies [31]. Nowak et al. [3] discussed how the management practices of trees can result in the trees being net emitters of carbon over the course of its lifecycle. Maintenance practices are important for ensuring survival [32]. Disposal of removed trees tends to be the largest contributor to C emissions from urban trees [32]. The C emissions of a tree largely depend on the practice used to dispose of the tree. For example, when mulched and left for decomposition, the net effect of the tree on total C throughout its life cycle is offset by decomposition, but when placed in a landfill and buried, trees lead to net positive sequestration of carbon [3].

The ability to make informed choices of urban land uses and selection of landscape plants is limited and would benefit from a tool to help make decisions maximizing societal use and carbon sequestration. The objective of this paper is to assess the ability of plants to sequester carbon in an urban setting under a variety of management practices using existing data available in the literature by developing and refining an accessible carbon calculator. Specifically, an attempt is made to compare carbon sequestration of different urban plants, turfgrasses and trees, to better understand how the mixed system present in urban environments contributes to carbon sequestration.

2. Materials and Methods

2.1. Geography

Studies were not excluded based on geography for the purpose of this carbon calculator. Carbon sequestration potential can vary across latitude [33], but there is not enough literature to satisfy the requirement of a “northern temperate climate”, representative of the environments across Ontario, Canada. Despite having varying degrees of carbon sequestration rates across latitudes, published carbon sequestration rates can vary significantly in the same region; for this reason, studies across many regions were included. For example, the carbon sequestration rate for turfgrass in Duluth, Minnesota as reported by Selhorst and Lal [17] was between $2.5 \text{ Mg C Ha}^{-1} \text{ yr}^{-1}$, while in the same study, the authors reported a C sequestration rate of $5.4 \text{ Mg C Ha}^{-1} \text{ yr}^{-1}$ for Minneapolis, Minnesota.

2.2. Turfgrass

Although NPP is highly related to the accumulation of SOC [16] and can be estimated by using 10% of NPP, the estimates are not always reliable. Studies that used NPP to estimate SOC accumulation were excluded. A similar measure, net ecosystem exchange, was excluded as it tends to overestimate carbon storage and may be appropriate for short term changes only, as there can be a significant loss of data due to environmental factors [34,35].

2.3. Trees and Shrubs

Studies which used number of trees rather than tree canopy were excluded because the size of the canopy is unknown and cannot be directly compared to other plant canopies, such as turfgrasses. There were no studies that included shrubs in the urban environment. For this study, shrubs were examined in native or restoration environments and compared to that of trees and turfgrass in the urban environment.

2.4. Hidden Carbon Costs (HCC)

A review of research on hidden carbon costs (HCC) in urban turfgrass systems was conducted to help understand the offsetting carbon emissions caused by maintenance practices (Table 1). The HCC accounted for in the calculator were fertilizer production, fuel consumption associated with mowing, N_2O emissions, irrigation, and production of pesticides used [20,21]. N_2O -N emissions were converted to carbon (C) equivalence by converting to N_2O emissions by multiplying by a factor of 1.5711 and then using a factor

of 298 times that of the global warming potential of CO₂ for a 100-year time scale [36]. To convert CO₂ to C equivalence a factor of 0.2727 was used.

Table 1. Annual hidden carbon cost (HCC) of mowing.

Type of Management ^a	Species	Location	HCC of Mowing ^b	Mowing Events/Year	References
HL	<i>Zoysia japonica</i> Steud.	KS, USA	0.07 * (0.05 to 0.09)	18.5 * (13 to 24)	[21]
HL, MP, GC	Not specified	TN, USA	0.11 (0.10 to 0.13)	18.5 * (15 to 22)	[19]
HL	<i>Poa pratensis</i> , <i>Lolium arundinaceum</i>	IN, USA	0.05 (0.04 to 0.06)	22 * (18 to 26)	[20]
HL	<i>Poa pratensis</i> , <i>Cynodon dactylon</i> , <i>Zoysia matrella</i> , <i>Stenotaphrum secundatum</i> , <i>Agrostis palustris</i> , <i>Buchloe dactyloids</i>	Many USA sites	0.19	31	[17]
HL	Not Specified	CA, USA	0.33	n/a	[15]
HL	<i>Poa pratensis</i> , <i>Lolium perenne</i>	CO, USA	0.17	28	[18]
HL	Not specified	Many USA sites	0.17 (0.13 to 0.21)	28	[16]
Average			0.16 (0.04 to 0.33)	24.33	

^a Home lawn (HL); Golf course (GC); Municipal park (MP). ^b Measured in (Mg C/ha/year). * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

2.5. Carbon Calculator

The carbon calculator is a tool designed to inform the landscaping industry of Ontario about the C sequestration capabilities of different urban plant systems within the Ontario environment.

For this analysis, gross C sequestration is defined as the total C that is left over in the soil (for turfgrass) and in wood (for trees) after respiration and decay. Net C sequestration represents the gross C sequestration subtracting the HCC of production and maintenance practices. Currently, much of the urban tree literature uses “net carbon sequestration” to refer to the carbon that a tree intake through net primary production (NPP) minus the carbon loss due to decay, but does not take into account HCC [37]. This has also occurred in analysis of turfgrass systems, where a change in SOC is referred to as net C sequestration, and HCC are not considered [23]. Inputs such as irrigation and fertilization can lead to additional gross C sequestration, this additional C sequestration is not included in the calculator because the extra SOC sequestered is relatively small when compared to unirrigated and unfertilized turfgrass systems [21].

The carbon calculator used for the comparisons in this paper does not include carbon avoidance offsets associated with the presence of plants, such as the carbon offset of the cooling effect of urban plants. In addition, due to a lack of information regarding the carbon cost of production, transportation and establishment of urban plants was also not included in the carbon calculator [24,26].

3. Results

3.1. Gross Carbon Sequestration

The carbon calculator was created using existing information in the scientific literature. Annual gross SOC accumulation under urban turfgrasses ranged from 0.59 to 3.82 Mg C/ha/yr (Table 2). This wide range could be influenced by species, growth rate and maintenance. Some of the higher gross SOC accumulations were associated with warm season species, including *Cynodon* ssp. Additionally, *Zoysia japonica*. It is more difficult to determine the sequestration of tree and shrubs in the urban environment, as information is more prevalent for these in natural or urban forest environments compared to environments typically found in lawns and parks (Tables 1 and 3). Hidden carbon costs of mowing, for example, change with the use of the turfgrass area, the species present and the number of mowing events (Table 1). The SOC accumulation in shrubs varies

greatly across sites with one site, Saskatchewan, being over three times that of the other sites (Table 3). The summary of these numbers still allows for a carbon calculator to be populated with scientific literature-based information to give better estimations of the gross carbon sequestration potential of these components of the urban ecosystem.

Table 2. Annual gross SOC accumulation of urban turfgrass.

Type of Management ^a	Species	Location	Average SOC Accumulation ^b	References
GC	<i>Poa pratensis</i> , <i>Lolium perenne</i>	CO, USA	1.05 * (0.90 to 1.20)	[23]
GC	<i>Zoysia matrella</i>	KS, USA	1.01 * (0.98 to 1.05)	[21]
GC	<i>Agrostis stolonifera</i>	NC, USA	0.59	[38]
HL	Not specified	MN, USA	5.10	[39]
HL	<i>Poa pratensis</i> , <i>Lolium arundinaceum</i>	IN, USA	1.52 * (1.41 to 1.63)	[20]
HL	<i>Cynodon dactylon</i> (L.) Pers. × <i>Cynodon transvaalensis</i> Burtt Davy, <i>Zoysia</i> spp.	AL, USA	3.82 * (2.09 to 5.54)	[40]
GC	<i>Agrostis stolonifera</i> , <i>Poa annua</i> , <i>Poa pratensis</i> , <i>Lolium perenne</i>	CO and WY, USA	0.95 * (0.90 to 1.00)	[41]
GC	<i>Agrostis stolonifera</i> , <i>Poa pratensis</i> , <i>Festuca</i> spp.	NE, USA	0.59 * (0.32 to 0.78)	[42]
HL	<i>Poa pratensis</i> , <i>Cynodon dactylon</i> , <i>Zoysia matrella</i> , <i>Stenotaphrum secundatum</i> , <i>Agrostis palustris</i> , <i>Buchloe dactyloides</i>	Many USA Sites	2.80 (0.90 to 5.40)	[17]
GC	Not specified	OH, USA	3.10 * (2.64 to 3.55)	[22]
MP, HL	Not specified	CA, USA	1.40	[15]
GC	<i>Poa annua</i>	New Zealand	0.69	[43]
HL	Not specified	Many USA Sites	0.87 * (0.46 to 1.27)	[16]
Average			1.85 (0.32 to 5.54)	

^a Home lawn (HL); Golf course (GC); Municipal park (MP). ^b Measured in (Mg C/ha/year). * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

Table 3. Annual rate of carbon sequestration in shrubs **.

Type of Management ^a	Species/Forest Type	Location	Average SOC Accumulation ^b	References
NE	Caragana shelterbelt, SRC shrub willow	SK, Canada	3.98 * (1.31 to 6.64)	[44]
NE	<i>Coprosma</i> spp., <i>Corokia cotoneaster</i> , <i>Cytisus scoparius</i> , <i>Ozothamnus</i> spp., Several other species	Oxford, New Zealand	1.15 (0.17 to 3.23)	[45]
NE	<i>Zizyphus xylopyra</i> , <i>Mallotus philippinensis</i> , <i>Eriolaena hookariana</i> , <i>Butea superba</i> , <i>Lantana camara</i> , <i>Smilax macrophylla</i> , Several other species	Chhattisgarh, India	1.14 * (0.71 to 1.57)	[46]
Average			2.09 (0.15 to 6.64)	

^a Natural Environment (NE). ^b Measured in (Mg C/ha/year). * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used. ** No literature is available on shrubs in the urban environment, all values of SOC accumulation are of shrubs in the natural environment.

3.2. Hidden Carbon Costs

A number of studies have calculated the HCC of turfgrasses and provide information on mowing averaging 0.16 Mg C/ha/yr (Table 1), nitrogen escape averaging 0.19 Mg C/ha/yr (Table 4), fertilizer production averaging 0.21 Mg C/ha/yr (Table 5) and irrigation averaging 0.15 Mg C/ha/yr (Table 6). Nitrogen escape appeared to be highest in lawns with warm season grasses despite a lower nitrogen application rate and nitrogen application rate did not seem to affect the nitrogen escape measured from home lawns (Table 4). The average HCC of fertilizer production was directly associated with applica-

tion rate as standard values are typically used in calculating fertilizer production costs (Table 5). This amount of detail in the literature allows for an accurate assessment of the HCC and therefore leads to a robust carbon sequestration calculation for turfgrasses in the urban environment. The information available for HCC of urban trees and shrubs (Table 7) is lacking, with only three studies found and an assumption of very little maintenance, making it difficult to calculate realistic HCC for these systems.

Table 4. Annual hidden carbon cost (HCC) of nitrogen escape.

Type of Management ^a	Species	Location	HCC of N ₂ O ^b	Nitrogen Rate ^c	References
HL	<i>Zoysia japonica</i> Steud.	KS, USA	0.22 * (0.14 to 0.29)	0.00 to 0.98	[21]
HL	<i>Zoysia japonica</i> Steud.	KS, USA	0.30 * (0.25 to 0.35)	0.00 to 0.98	[21]
HL	<i>Lolium perenne</i>	KS, USA	0.13 * (0.13 to 0.21)	0.50 to 2.50	[47]
HL, MP, GC	Not specified	TN, USA	0.18 * (0.06 to 0.29)	0.52	[19]
HL	<i>Poa pratensis</i> , <i>Lolium arundinaceum</i>	IN, USA	0.14	1.42	[20]
HL	<i>Lolium perenne</i>	ON, Canada	0.14 (−0.02 to 1.03)	1.50	[48]
HL, MP	Not specified	CA, USA	0.17 * (0.08 to 0.25)	1.00 to 7.50	[15]
HL	<i>Poa pratensis</i> , <i>Lolium perenne</i>	CO, USA	0.24 * (0.08 to 0.40)	1.10	[18]
Average			0.21 (−0.02 to 1.03)	1.40	

^a Home lawn (HL); Golf course (GC); Municipal park (MP). ^b Measured in (Mg C/ha/year). ^c Measured in kg 100 m² year^{−1}. * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

Table 5. Annual hidden carbon cost (HCC) of fertilizer production.

Type of Management ^a	Species	Location	HCC of Fertilizer ^b	Nitrogen Rate ^c	References
HL	<i>Zoysia japonica</i> Steud.	KS, USA	0.06 * (0.00 to 0.13)	0.00 to 0.98	[21]
HL, MP, GC	Not specified	TN, USA	0.06 (0.00 to 0.12)	0.52	[19]
HL	<i>Poa pratensis</i> , <i>Lolium arundinaceum</i>	IN, USA	0.20 * (0.14 to 0.27)	1.42	[20]
HL	<i>Poa pratensis</i> , <i>Cynodon dactylon</i> , <i>Zoysia matrella</i> , <i>Stenotaphrum secundatum</i> , <i>Agrostis palustris</i> , <i>Buchloe dactyloids</i>	Many USA sites	0.06	0.49	[17]
HL, MP	Not specified	CA, USA	0.52 * (0.12 to 0.92)	1.00 to 7.50	[15]
HL	Not specified	Many USA sites	0.25 * (0.00 to 0.50)	0.00 to 2.50	[16]
Average			0.19 (0.00 to 0.92)	1.44	

^a Home lawn (HL); Golf course (GC); Municipal park (MP). ^b Measured in (Mg C/ha/year). ^c Nitrogen fertilization rate measured in kg 100 m² year^{−1}. * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

Table 6. Annual hidden carbon cost (HCC) of irrigation in turfgrass.

Type of Management ^a	Species	Location	HCC of Irrigation ^b	References
HL	<i>Zoysia japonica</i> Steud.	KS, USA	0.04 * (0.03 to 0.04)	[21]
HL, MP, GC	Not specified	TN, USA	0.01 (0.00 to 0.02)	[17]
HL, MP	Not specified	CA, USA	0.53	[15]
HL	<i>Poa pratensis</i> , <i>Lolium perenne</i>	CO, USA	0.19 * (0.13 to 0.25)	[18]
HL	Not specified	Many USA sites	0.01 * (0.00 to 0.02)	[16]
Average			0.15 (0.00 to 0.53)	

^a Home lawn (HL); Golf course (GC); Municipal park (MP). ^b Measured in (Mg C/ha/year). * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

Table 7. Annual hidden carbon costs of trees and shrubs.

Plant System Type	Location	Maintenance Type	Total HCC ^a	References
Urban trees	FL, USA	Leaf blower, chainsaw, burning of removed biomass	0.0019 (0.0009 to 0.0028)	[31]
Urban shrubs	FL, USA	Hedge trimmer	0.0033 (0.00016 to 0.0040)	[31]

^a Measured in (Mg C/ha/year).

3.3. Carbon Calculator

To best understand the role of urban plants in the urban environment, the best, used value and worst-case scenarios for net carbon sequestration were calculated using different values available in the literature. Turfgrass, when over fertilized, resulted in maximized N₂O release and maximized the need for fertilizer production and mowing due to increased growth rate, which can result in a negative carbon sequestration rate (Table 8). The more likely scenarios show turfgrass being a net sink for carbon in the urban environment, sequestering 1.24 Mg C/ha/yr. There is not enough evidence to carry out an analysis of the HCC of the different management practices associated with urban trees and shrubs, however. When comparing the different urban landscapes, trees are estimated to have a net carbon sequestration of 1.81 Mg C/ha/yr and shrubs 2.01 Mg C/ha/yr (Table 9). Based on the ranges in the literature, it is difficult to conclude what landscape is most efficient as a carbon sink due to a lack of information surrounding the HCC of trees and shrubs.

Table 8. Best Case Scenario, Worst Case Scenario and Used Value for urban turfgrass systems.

	Best Case Scenario	Worst Case Scenario	Used Value
	(Mg C/ha/year)		
Gross C Sequestration	5.54	0.32	1.85
HCC of Mowing	0.16 *	0.21	0.16
HCC of N ₂ O Emissions	0.21 *	1.02	0.21
HCC of Fertilizer	0.19 *	0.92	0.19
HCC of Irrigation	0.15 *	0.53	0.15
Net C Sequestration	4.92	−2.37	1.14

* Since gross C sequestration is unlikely under minimal maintenance practices the average of each HCC was used in the Best Case Scenario.

Table 9. Average scenario for net carbon sequestration in turfgrass, trees and shrubs.

	Turfgrass	Urban Trees	Shrubs
	(Mg C/ha/year)		
Gross C Sequestration	1.85	1.80	2.01
Total HCC	0.68	0.0019	0.0033
Net C Sequestration	1.17	1.80	2.01

4. Discussion

All plant systems utilized in this study had equivalent rates of gross C sequestration (Table 9). The difference observed between plant systems is the result of hidden C costs associated with maintenance emissions. The greater HCC associated with turfgrass resulted in less net C sequestration compared to urban trees and shrubs, which is consistent with findings published by Horn et al. [31]. This is expected in this analysis, as the HCC for trees is incomplete in the literature, but well defined in turfgrass literature. The overarching theme was that all plants showed positive outcomes with respect to carbon balance in an urban environment, where different plant types added unique ecosystem and societal benefits.

Age of a turf stand is important with respect to C sequestration, as data suggest that turf stands sequester the majority of C within the first 30 years of its establish-

ment [41,49]. The sink for a turf system can reach saturation within 30+ years of establishment [17,22,23,50] and in some cases perhaps even sooner [51]. However, the soil sink capacity is not considered. Assuming that a turf system reaches C storage capacity after 30 years, beyond this time frame, a turf system would be rendered a net source of C due to emissions resulting from maintenance practices. Models show that turfgrass systems can be net sources of C even before the sink reaches saturation due to excessive maintenance practices [17,51].

Sequestration of carbon by trees tend not to be limited by the saturation of soil sinks as they tend to sequester their carbon in wood and not in the soil; thus, the C sequestration potential of trees is related to their longevity in the urban environment. Around 25% of urban trees planted die within one to five years and 50% within 36 to 40 years of being planted [52]. For this reason, trees must be selected for their ability to survive the stress of an urban environment. The sequestration potential is highly dependent on the production and establishment HCC, which are unaccounted for due to a lack of data in the literature.

Further, the literature does not appear to differentiate between “urban forests” and “landscape trees”. Many studies look at urban forests (Table 10), which would resemble their natural environment much more than the presence of trees on home lawns or in parks. Survival of trees in a home lawn or park setting would almost certainly be less than that of trees planted in an urban forest setting due to lack of physical protection and heat island effect [52]. The C sequestration values for shrubs may be over-estimated, due to the absence of quantifying the C sequestration capacity of shrubs in the urban environment (Table 3). This should be considered because the calculator is designed for making informed decisions for these specific uses.

Table 10. Annual rate of carbon sequestration in urban trees.

Management Type ^a	Species/Forest Type	Location	Average SOC Accumulation ^b	References
UF	<i>Quercus laurifolia</i> , <i>Pinus elliotti</i> , <i>Pinus taeda</i> , <i>Melaleuca quinquinervia</i> , <i>Quercus virginiana</i> , <i>Rhizophora mangl</i> , several other species	Gainesville and Miami, FL, USA	1.05 * (0.88 to 1.22)	[53]
UP	<i>Abies holophylla</i> , <i>Acer palmatum</i> , <i>Chionanthus retusus</i> , <i>Cornus officinalis</i> , <i>Ginkgo biloba</i> , <i>Pinus koraiensis</i> , <i>Prunus armeniaca</i> , <i>Prunus yedonensis</i> , <i>Taxus cuspidate</i> , <i>Zelkova serrata</i>	Seoul, Korea	3.50 (1.20 to 8.40)	[54]
UF	<i>Populus canadensis</i> , <i>Salix matsudana</i> , <i>Ulmus pumtla</i> , several other species	Shenyang, China	2.84 (1.16 to 4.78)	[55]
UF	<i>Lagerstoremia</i> spp., <i>Quercus phellos</i> , <i>Pinus taeda</i> , <i>Magnolia grandiflora</i> , <i>Quercus lyrata</i> , several other species	Alabama, USA	1.02 (0.29 to 1.76)	[56]
TUTCC	Not specified	Many Canadian Sites	1.63 * (1.53 to 2.51)	[2]
UF	Not specified	Many USA Sites	2.80 (1.28 to 4.01)	[8]
UST	<i>Sophora japonica</i> , <i>Broussonetia papyifera</i> , <i>Sabina chinensis</i> , <i>Ginkgo biloba</i> , <i>Fraxhus</i> spp., <i>Populus</i> spp., <i>Firmiana platanifolia</i>	Beijing, China	1.30	[57]

Table 10. Cont.

Management Type ^a	Species/Forest Type	Location	Average SOC Accumulation ^b	References
UF	<i>Sophora japonica</i> L., <i>Populus tomentosa</i> Carr., <i>Robinia pseudoacacia</i> L., <i>Fraxinus chinensis</i> Roxb.	Beijing, China	0.38	[58]
UF	<i>Pinus massoniana</i> and tropical pines, C. Lanceolata forests, Combined Evergreen and broad-leaved forests	Hangzhou, China	1.66 (0.82 to 3.02)	[59]
Average			1.80 (0.29 to 8.40)	

^a Urban forest (UF); Urban street trees (UST); Urban park (UP); Total urban tree canopy cover (TUTCC).

^b Measured in (Mg C/ha/year). * Averages followed by an asterisk (*) are cases where no average was listed in the study, an average of the minimum and maximum of the range were used.

Hidden carbon costs for urban trees are not widely available in the literature as they are for turfgrass. The scope of the study only includes the HCC of maintenance practices including N₂O emissions, but will not include the HCC of establishment or decommissioning of the ecosystem or machinery, including mulching of trees and fate of lawnmowers, among others.

4.1. HCC of Mowing

The hidden carbon costs of mowing have been highly debated in papers [15–17]. Townsend-Small and Czimczik [15] claimed that the SOC sequestered by turfgrass would be completely offset by the fuel consumed carbon costs of mowing. They included the fuel consumed for transportation of equipment to the mowing sites and blowing of leaves. These practices are not significant for many turfgrass operations, and in particular, home lawns, which make up the majority of turf area in the urban environment. In addition, the blowing of leaves is not turfgrass management but rather management of the urban tree and should be included in the HCC, as it is necessary to maintain the utility of the urban greenspace.

The HCC of mowing reported by Townsend-Small and Czimczik [15] exceeds 4 Mg C ha^{−1} yr^{−1}, which is several times the HCC reported by others assessing the HCC of mowing [16,17,19–21]. However, Townsend-Small and Czimczik [15] made a correction in light of the overestimation of the global warming potential (GWP) of fuel consumed during mowing, which changed the HCC of mowing from 4.01 Mg C ha^{−1} yr^{−1} to 0.33 Mg C ha^{−1} yr^{−1}. This realigned the findings of Townsend-Small and Czimczik [15] with previous papers (Table 1) [16,17,19–21]. Law and Patton [20] stated that mower efficiency can vary significantly, and reported an HCC of mowing between 0.044 and 0.060 Mg C ha^{−1} yr^{−1}. Braun and Bremer [21] also calculated HCC of mowing in a similar range comparing “low management” (0.049 Mg C ha^{−1} yr^{−1}) and “high management” (0.087 Mg C ha^{−1} yr^{−1}). Mowing should be reduced as much as possible to reduce CO₂ emissions [15,20,21]. The HCC of maintaining a lawn is several times that of maintaining shrubs and trees (Table 9) [31]. The implementation of electric mowing equipment may have potential to reduce the HCC of mowing for turfgrass systems.

Golf course management for fairways and greens is more intensive, and additional practices including aeration and topdressing likely lead to more HCC than that of a home lawn [60]. For this reason, golf courses are likely to become a net source of C much faster than home lawns and parks. Bartlett and James [61] observed the net carbon balance of two golf courses in the United Kingdom, Parkland, where 48% of the trees sequestered C at a rate of 1.17 Mg C ha^{−1} yr^{−1} and Links, where only 2% of the trees had a neutral C balance. The authors of the paper argued that adding more trees to the golf course would reduce the amount of maintenance practices while increasing the amount of C sequestration [61].

4.2. HCC of Fertilization

Fertilization affects the HCC of a turfgrass system through the energy consumed to produce, transport and apply fertilizer along with the potential loss of nitrogen-based greenhouse gasses. Fertilizer application can represent the largest fraction of HCC in a turfgrass system, where the majority can be attributed to nitrogen application [62]. The HCC of fertilization under normal rates of N application can range from 0 Mg C ha⁻¹ yr⁻¹ (unfertilized) to 0.50 Mg C ha⁻¹ yr⁻¹ (2.5 kg N 100 m⁻² yr⁻¹) (Table 5). The highest HCC of fertilization was 0.92 Mg C ha⁻¹ yr⁻¹ observed in the study by Townsend-Small and Czimicik [15], where an abnormally high N rate of 7.5 kg N 100 m⁻² was applied, which is unlikely in any setting. Zhang et al. [18] recommended reducing N rate over time with the intention of maintaining positive net carbon sequestration, similar to that stated in Frank et al. [28] whereby reduced nitrogen losses because N mineralization contributed to the growth of the turfgrasses [63].

The Used Value for turfgrass based off the academic literature results in positive net C sequestration (Table 8). The Worst Case Scenario is likely unrealistic due to an abnormally high fertilizer application (7.5 kg per 100 m²), leading to very high HCC of fertilizer and N₂O emissions. For the Best Case Scenario, the HCC from the Used Value was used because maximum C sequestration is unlikely to occur under minimal to no management practices [16]. The literature for HCC of urban trees and shrubs was extremely limited, and due to this, we were unable to draw up similar situations for these urban plant systems (Table 7).

Nitrogen fertilization leads to increase SOC accumulation in no till agricultural settings, which would be more similar to the conditions of a turfgrass setting than rototilled agricultural fields [64]. N availability is likely important for C sequestration for two reasons: (1) N limits net NPP in most terrestrial ecosystems and, (2) soil microbes tend to require N for conversion of C into stable SOC [65]. Inputs can possibly increase the carbon sequestration potential of urban plants [66]. For example, fertilization can greatly increase the carbon sequestration potential of turfgrasses; however, it has a high HCC [16,20]. Fertilization of grasslands also increased carbon stocks similar to turfgrasses [67]. NPP can be used as an indicator of SOC sequestration with the assumption that 10% of dry plant biomass of turfgrasses being added to the soil as SOC [16]. The increase in biomass increases contribution of SOC to the soil, but the addition of N increases the humification rate of dry biomass [68]. Braun and Bremer [21] found fertilization and irrigation had no impact on the gross SOC sequestered contrary to the impacts of additional N found by previous studies. In a golf course setting, nitrogen fertilizer did not increase SOC content of the soil independent of a PGR, paclobutrazol [69]. A study of home lawns by Huyler et al. [70] surveyed homeowners on their maintenance practices and then measured the SOC of home lawn. The authors concluded that yard maintenance (fertilization and irrigation) had no effect on SOC in home lawns regarding age of the system [70]. A similar study conducted by Campbell et al. [71] found a different conclusion; fertilization at an increased frequency resulted in a higher C content in home lawns. It should be noted that increasing the carbon sequestration from year to year is not beneficial because the literature indicates that the sink is limited, and increasing the rate of sequestration would only lead to faster saturation of the sink.

N₂O emissions can range between −0.02 and 1.02 Mg C ha⁻¹ yr⁻¹ dependent on the N application and type of N application (Table 4). Emissions of N₂O can be reduced by using slow-release fertilizers [15,48].

4.3. HCC of Irrigation

The HCC of pumping irrigation water can fall in the range of 0.22 to 0.83 Mg C ha⁻¹ yr⁻¹, was used by Townsend-Small and Czimicik [15]. The HCC of pumping irrigation in a home lawn setting is considerably higher than other papers published in the literature (Table 6). Pumping of irrigation water typically represents one of the smallest components of hidden carbon costs [16,19–21]. In the scope of carbon emissions irrigation

causes minimal CO₂ emissions, and the argument against irrigating lawns should not be fixated on this, rather the waste of fresh water.

4.4. Soil Building Potential of Urban Plants

One component of urban plants that is potentially overlooked is the ability to build soils. Home lawns overtime tend to rise over time most likely due to organic matter being added to the system. If the lawn is rising then the sink capacity must also be increasing. For example, Qian et al. [23] took samples to 11.4 cm depth and observed a sink saturation of SOM after about 30 years, but if the sink was being increased and saturated every year then this method would not be able to observe the addition SOM being deposited, it would appear that SOM has remained stable despite additional SOC being sequestered into the system.

Turfgrasses, trees and shrubs provide a temporary carbon sink (30 to 400 years), until it is saturated. Once saturated, urban plant systems will not continue to act as a sink due to required maintenance processes. Trees can provide a longer-term carbon sink compared to turfgrass, assuming the tree survives. Once the tree is dead and mulched, that carbon is no longer stored long term unless it is buried or utilized in a permanent store, such as a building material [72]. For these reasons, the utility of urban plants should not be measured by their ability to sequester C. The same way agricultural and forestry lands do not sequester carbon over the long term (over 100 years). Although maintaining SOC of our soils is very important, depending on our soils as a sink for C in a significant way is likely not viable [73]. Urban plants should also be compared by the ecosystem and societal services they provide rather than solely by their ability for C sequestration. Urban plants are typically planted in mixtures with turfgrasses often making a significant portion of the area under the urban tree canopy. We should also investigate combining urban plants to get a compounding effect. For example, trees in combination with an understory of grass, as seen in parks, can have an additional effect of cooling in urban environments than either plant system on its own [74].

5. Conclusions

To ensure urban plant systems remain carbon sinks, maintenance practices need to be efficient and set to maintain the function of the landscape [21]. A carbon calculator can be used as a tool to help educate homeowners, contractors and businesses make informed decisions about how their maintenance practices influence the carbon sequestration potential of urban plant systems. After extensive review of the available literature and building a carbon calculator for an urban plant system, all plant systems had a positive carbon balance when considering the HCC available in the literature. The extensive work on turfgrass instills confidence with respect to the estimation of maintenance costs; however, the lack of available information regarding tree maintenance and the production and installation of any urban plant system limits the ability to make strong comparisons between different landscape plants. In the future, an urban plant system calculator on a global scale should be developed and reviewed.

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