# Calling Time on the Imperial Lawn and the Imperative for Greenhouse Gas Mitigation

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## Abstract

*Non-technical summary*

As green spaces, lawns are often thought to capture carbon from the atmosphere. However, once mowing, fertlising, and irrigation are taken into account, we show that they become carbon sources, at least in the long run. Converting unused urban and rural lawn and grassland to treescapes can make a substantial contribution to reducing greenhouse gas emissions and increasing carbon absorption from the atmosphere. However, it is imperative for governing bodies to put in place appropriate policies and incentives in order to achieve this.

*Technical summary*

Mown grass or lawn is a ubiquitous form of vegetation in human dominated landscapes and it is often claimed to perform an ecosystem service by sequestering soil carbon. If lawn maintenance is included, however, we show that lawns become net carbon emitters. We estimate that globally, if one third of mown grass in cities was returned to treescapes, 310 to 1,630 million tonnes of carbon could be absorbed from the atmosphere, and up to 43 tonnes of carbon equivalent per hectare of emissions could be avoided over a two-decade time span. We therefore propose that local and central governments introduce policies to incentivise and/or regulate the conversion of underutilised grass into treescapes.


## Social Media summary

If unused lawns were planted with trees, a gigaton of carbon could be removed from the atmosphere over two decades.

## Main

Globally, mown grass is one of the most common features of our human-shaped landscapes; it is almost ubiquitous in suburban residential gardens, especially in the USA, Australia, and New Zealand (Ignatieva & Stewart, 2009). It dominates in parks (For example, 75% - 95% of the park area in Europe (Gilbert, 1989)), covers approximately 23% of urban areas (Ignatieva & Hedblom, 2018), and is common on highway margins and street verges. Mown grass is estimated to cover 16.4 Mha in the contiguous 48 states of the USA alone (Milesi *et al.*, 2005), an area which roughly equals that of England and Belgium combined. Globally it occupies 15 to 80 Mha of land within urban areas (Ignatieva & Hedblom, 2018). The imperial lawn originated from hand-cut grass in lieu of grazed pasture to demonstrate wealth among the gentry. It then became part of the order that colonists implanted on the conquered land, representing a pastoral nostalgia of the European landscape (Ignatieva & Stewart, 2009). Today a large range of lawnscapes are formed from mown grass. While some of these can have a specific purpose (such as for sport fields and recreation), often their occurrence is purely historical, lacking a rationale for their upkeep.

Mown grass has been promoted as providing important ecosystem services such as carbon sequestration, and while it may have advantages relative to impervious surfaces (Ignatieva & Hedblom, 2018; Velasco *et al.*, 2021), we believe the more apposite comparison is with trees and shrublands that would have once occupied current lawnscapes. Given the widespread nature of mown grass, and with humanity facing a catastrophic climate crisis, it is important to review the role lawnscapes play with respect to greenhouse gases. Here we review the potential of carbon storage in mown grass relative to that provided by other vegetation types. Carbon sequestration/emissions and long term storage estimates are projected over two decades, the time frame that aligns with the critical period for action on climate change. We conclude that mown grass in almost all cases makes a negative contribution (carbon release) when emissions associated with lawn maintenance are considered. Other forms of vegetation cover, such as shrubs and trees, store substantially more carbon, both below and above ground. We therefore recommend radical changes in policy settings to maximise conversion of mown grass to shrub, tree, or mixed vegetation.

## Carbon storage and emissions in lawnscapes

Soil organic carbon (SOC) capacity is influenced by bioclimatic conditions and increases at higher latitudes due to slow mineralisation at low temperatures (Vasenev & Kuzyakov, 2018). Across the USA, soil organic carbon stored in the top 15 cm of residential lawns averaged 45.8 t $ha^{-1}$ (Selhorst & Lal, 2013) (Table 1). In the top 30 cm of fertilised and irrigated lawn soil at a warm temperate site as much as 108 t $ha^{-1}$ has been recorded (Weissert, *et al.*, 2016). Reported annual gross carbon sequestration into lawn soils, summed over two decades, may be as high as 28 t $ha^{-1}$ (Table 1). However, although sequestration of carbon into lawn soils can occur over some years, it can be expected to asymptote to zero within 30 to 50 years, depending on climate (Lindén *et al.*, 2020; Qian *et al.*, 2003). At very slow rates of accumulation, this might extend to 100 years (Smith *et al.*, 2018), after which carbon sequestration will level off. On the other hand, climate forcing gas emissions that occur through mowing, fertilising, and irrigation are summative, and extend past periods of biological carbon sequestration into soils. Therefore, these need to be subtracted from gross sequestration to establish net carbon equivalent fluxes and pools.

The rate of carbon emissions due to mowing depends on the size and type of mower used and the regularity of mowing. Estimates range from 1.4 to 6.7 t C $ha^{-1}$ over two decades (Table 1). Given that the estimated area of mown grass in the continental USA is 16.4 million hectares (Milesi *et al*., 2005), this implies that in the USA alone 1.1 to 5.5 million tonnes of carbon are emitted every year due to mowing.

The addition of fertiliser to lawns causes emissions of $N_2O$, which has a climate forcing effect 298 times that of $CO_2$ (Townsend-Small & Czimczik, 2010a). Emissions from fertilising depend on the regularity and rate of application, but with the high rates often recommended, they can offset carbon sequestration over two decades by up to 26.6 tonnes carbon equivalent $ha^{-1}$, an amount almost equal to the highest rates of sequestration reported (Townsend-Small & Czimczik, 2010b) (Table 1).

Irrigation of lawns involves carbon emissions due to the energy required to capture, pump, and transport the water. Detailed calculations for lawns are sparse. Townsend-Small and Czimczik (Townsend-Small & Czimczik, 2010b) estimate up to 0.5 t $ha^{-1}$ $y^{-1}$ carbon emissions (10.6 tonnes of carbon per hectare over two decades). Studies of agricultural irrigation suggest similar numbers: 0.1-0.5 t C $ha^{-1}$ $y^{-1}$ (Griffiths-Sattenspiel & Wilson, 2009; Nelson *et al.*, 2009; Zou *et al.*, 2015).

Therefore, grass that is mown, fertilised, and irrigated, may produce emissions over two decades equal to as much as 43.9 tonnes of carbon equivalent per hectare. Some estimates of emissions due to lawn maintenance are as high as 126 tonnes carbon equivalent per hectare over two decades (Kong *et al.,* 2014) (Table 1). Such emission rates far outweigh the highest reported gross soil sequestration of 28 tonnes over the same timeframe. Beyond our two decade horizon, emissions from lawns will always outweigh initial soil carbon sequestration. Kong *et al.* (2014) estimated that the carbon sink capacity of the lawns they studied would be offset by carbon emissions in 5–24 years under their current management, thereby shifting them from carbon sinks to permanent carbon sources. This number is within the range of data we gathered from multiple sources (Fig. 1). Greenhouse gas emissions related to even basic lawn maintenance (i.e. infrequent mowing without fertiliser or irrigation) will eventually outweigh the carbon storage potential, transforming lawns from carbon sinks into carbon sources (Selhorst & Lal, 2013). Given that many lawnscapes are old and have been in place for many decades, most of them can be assumed to act as carbon sources.

Finally, the carbon stored above ground in mown grass is 1.0 t $ha^{-1}$ on average and 1.4 t $ha^{-1}$ below ground (Guertal, 2012) (Table 2). This is negligible compared to the potential for carbon stored in plant tissue of trees and shrubs.

## Carbon storage potential from converting lawns into treescapes

The reported carbon stored in plant tissue in natural forests varies considerably but can, for example, be as much as 690 t $ha^{-1}$ in tropical Ghana (Nero *et al.*, 2017) and 360 t $ha^{-1}$ in cool temperate climates such as New Zealand (Paul *et al.*, 2021) (Table 2). Even low shrub vegetation can store quantities of carbon that are significantly higher than those in lawns. For example, native sage scrub in California contains 43 t $ha^{-1}$ of above and below ground carbon (Wheeler *et al.*, 2016). While these pristine natural forests and dense shrublands may not be compared directly to the carbon storage potential of urban treescapes, some report almost as high stores of carbon from parks: up to 420 t $ha^{-1}$ of above ground carbon in tropical Ghana (475 t C $ha^{-1}$ roots included) (Nero *et al.*, 2017) and up to 289 t $ha^{-1}$ of above ground carbon in the cool temperate climate of Leicester, England (Davies *et al.*, 2011) (Table 2). Residential trees in Florida are reported to store 63 t of above ground carbon per hectare, and in Leipzig, Germany, above ground carbon stored per hectare of tree cover in areas with multi-story houses is as high as 64 tonnes (Strohbach & Haase, 2012).

Reported above and below ground sequestration rates of carbon average 61.2 t $ha^{-1}$ over two decades in urban areas across the USA but over the same timeframe above ground carbon sequestration alone is as high as 137 t $ha^{-1}$ in Seoul urban forest (Table 2) (Lee *et al.*, 2019; Nowak *et al.*, 2013). Shrubland can sequester up to 62 t $ha^{-1}$ over two decades (Kimberley, Bergin, & Beets, 2014). However, sequestration cannot continue indefinitely and approaches zero as rates of respiration match rates of photosynthesis. For example, net carbon flux does not differ significantly from zero in natural forests across New Zealand (Paul *et al.*, 2021). In an urban context, the fate of removed biomass will be important. If the wood from felled or pruned trees is used for furniture or to replace fossil fuels the carbon balance can remain positive.

In addition to the much higher carbon storage in above and below ground plant tissue in treescapes compared to lawnscapes, the potential to store soil organic carbon must be considered. Soils under natural forests store more organic carbon than those under natural grasslands in the same climatic zones (Jobbágy & Jackson, 2000). Carbon content in soil under urban trees can be as high as 144 t $ha^{-1}$ without the addition of fertilizer or irrigation (Dorendorf *et al.*, 2015) (Table 1). Furthermore, soil organic carbon under mown grass increases with the addition of trees or shrubs in a linear relationship with aboveground tree biomass (Bae & Ryu, 2015; Huyler *et al.*, 2017; Huyler *et al.*, 2014b; Lerman & Contosta, 2019). From sites in Seoul, Bay and Ryu (2015) report 37.4 t $ha^{-1}$ of organic carbon in the top metre of lawn soil whereas carbon under urban forest was 2.4 times greater (89 t $ha^{-1}$) and that under mixed forest 2.7 times greater (101.9 t $ha^{-1}$). Linden *et al.* (2020)

found more soil carbon under shrubs than under lawns (91.5 and 73 t $ha^{-1}$, respectively, 0-60 cm depth) in Helsinki parkland. By contrast, in Auckland higher concentrations of carbon under mown grass than under urban forest have been reported (108 and 89 t $ha^{-1}$ respectively) (Weissert *et al.*, 2016). However, this difference was probably due to three out of the four mown grass sites being subject to fertilisation and irrigation, which in turn will have led to carbon emissions.

Emissions from treescapes due to trimming and other maintenance need to be considered as permanent components of their carbon balance. A study in Florida found carbon emissions due to maintaining trees of 0.04 t $ha^{-1}$ projected over two decades, a rate of greenhouse gas emission related to maintenance approximately two orders of magnitude lower than for lawns (Horn, *et al.*, 2015) (Table 1, Fig. 1).

In summary, tree cover in any form or shape presents a much greater potential for sequestering and storing carbon, both above and below ground. The mid- to long-term effects of replacing lawns with treescapes are visualised in Fig. 1, with the main advantage of trees being the much higher above ground storage, combined with the summative nature of emissions related to lawn maintenance. If urban trees that die, or need removal for other reasons, are used for timber or to replace fossil fuels, a more favourable carbon balance than shown in Fig. 1 will result.

## The upside of treescapes

Lawns have been promoted as providing ecosystem services including carbon sequestration (Velasco *et al.*, 2021). By contrast, we demonstrate that in bioregions capable of supporting trees, mown grass represents a degraded ecosystem in terms of carbon relative to the forested land that once occupied these sites. The literature we review clearly demonstrates that treescapes not only store considerably more carbon per unit surface area than mown grass, but they remain carbon sinks for much longer time periods. Even more important than the larger carbon pools and sequestration rates offered by treescapes are the inevitable and constant emissions due to lawns, mostly caused by mowing, fertilisation, and irrigation. With the ubiquity of mown grassland (Milesi *et al.,* 2005), an opportunity exists to create alternative landscapes that not only store more carbon above ground, but also have a potential for greater below-ground storage. Although the role of urban trees in providing ecosystem services, particularly carbon sequestration, has been evidenced in many cities around the world, little work has been done to implement this knowledge into land use policies (Haase *et al.*, 2014).

Planting trees in urban environments, in addition to fixing carbon, can reduce pollution, cool summer air temperatures thereby reducing heat stress related mortality (Manickathan *et al.,* 2018; Singh *et al.,* 2012; Zölch, Maderspacher e*t al.,* 2016), raise winter temperatures (Edmondson *et al.,* 2016), mitigate stormwater runoff (O'Sullivan *et al.*, 2017), and if species native to the region are used, enhance ecological restoration. Lawns contribute to homogeneity of the landscape, and generally lack biodiversity, particularly if mowing occurs often (Ignatieva & Hedblom, 2018).

There are also social and health benefits associated with converting mown grass to trees. Increasing tree cover is usually favourable to residents for aesthetic reasons (O'Sullivan *et al.*, 2017) as well as for higher perceived safety (Mouratidis, 2019). Significant positive associations between tree cover and self-reported health of residents have been found, whereas no such benefits to health were associated with grass (Reid *et al.*, 2017). Significant improvement in cardiovascular health parameters have been found among people walking among trees in contrast to no effect achieved from city-walking (Lee & Lee, 2014).

To maximise sequestering atmospheric carbon, local and central governments need to: firstly, quantify the area of mown grass and identify the potential for carbon sequestration by conversion to treescapes. Improvements in data quality from satellite images and improved classification algorithms now allow for accurate mapping of mown grassland cover (Weng, 2012). Secondly, specific policies and plans to maximise this conversion should be introduced. We propose four types of urban and non-urban space that, prior to human occupation, would have supported forest but are now degraded to lawns: public parks and recreational reserves, highway verges, residential street berms and private gardens.

## Public parks and recreational reserves

We propose widespread re-evaluation of park management plans with the view to identifying areas to be retired from mown grass. This will require a fundamental shift in what people perceive as desirable and usable in parks. However, the climate crisis is of such magnitude that all possible options must be explored, and action taken to reduce emissions and increase carbon sequestration wherever possible. Planting approaches will need to take account of the quantity of public traffic the areas receive. We therefore propose a range of planting options, a mixture of which might be introduced into any given park. These options range from a fully tiered forest structure (canopy and emergent trees with under storey shrubs and ground vegetation such as ferns, woody shrubs, grasses and/or herbs depending on the location), to open-plan treescapes with mostly closed canopies but with an open understorey and gaps to provide spaces for people to gather for picnics and other activities, to low density treescapes with indigenous grass species that require little or no mowing (Fig. 2). Shrubland can be used where an open vista is required.

## Road verges and private gardens

Highway margins are routinely cleared of vegetation and maintained as mown grass due to a perception that it makes roads safer. On the one hand, trees in close proximity to road margins create crash hazards for drivers that lose control, but, on the other hand, they reduce driver stress, lower driving speeds and thereby reduce the occurrence and severity of crashes (Van Treese II *et al.*, 2017). There is, therefore, a case to be made for converting roadside mown verges into shrubs and trees that can contribute to carbon sequestration and remove the need for mowing (Fig. 2). In New Zealand, for example, with a population of approximately 5 million, there is 94,000 km of highway (NZTA). Assuming 1-2 m of mown grass on each side of the road, we estimate a total area of 18,800 to 37,600 ha of mown highway road margins. New Zealand native shrubs can store up to 62.2 t $ha^{-1}$ of above ground carbon after two decades of growth thereby potentially providing 1.2-2.3 Mt of above ground carbon storage over two decades (Fig. 2) (Kimberley *et al.*, 2014). Planting with trees could store more over longer timeframes. Similarly, front and back lawns and streetside berms of grass are common in many countries especially those influenced by colonisation (Ignatieva & Stewart, 2009). Some of these areas provide spaces for children to play or to access below-ground infrastructure, but many exist without a specific reason as a default setting that is seldom questioned. Much of this grass could be converted into shrubs or trees (Fig. 2).

## Recommendations and Conclusions

Central and local governments throughout the world should consider introducing policies to regulate or incentivise the conversion of treeless mown grass areas into shrublands and/or treescapes, eliminating mown grass wherever possible, and where circumstances dictate, trees with minimal grass should be retained. Such a process will reduce greenhouse gas emissions associated with maintaining mown grass and add stored carbon to the landscape. To estimate the global potential of carbon sequestration from converting mown grass into trees we use 61.2 t $ha^{-1}$ for whole tree carbon, which is the average across 50 states in the USA (Nowak *et al.*, 2013) (Table 2). Global urban lawn area is estimated at 150,000 to 800,000 $km^{2,}$ (Ignatieva & Hedblom, 2018). If 1/3rd of the lawn in urban areas could be converted to tree cover, we estimate that 0.31 to 1.63 Gt of carbon could be sequestered over two decades. The estimate might be ambitious, but even one tenth of these figures would be substantial. The rate of sequestration will accelerate in following decades, and soil organic carbon sequestration as well as emission savings due to the redundant lawn maintenance will be additional to this estimate. Finally, the many co-benefits of trees most importantly for human health and biodiversity make a strong case to reconsider urban land use.

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none


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LG wrote the first draft and edited the manuscript, SL designed the figures, contributed to writing and editing, BB contributed to writing and editing.

Table 1. A sample of publications reporting carbon equivalent emitted due to maintenance and organic carbon stored or sequestered in soil. All units are tonnes carbon equivalent ha$^{-1}$. See Supplementary Information for an extended version of table.

| **Description** | **20-year emissions due to fertiliser use** | **20-year emissions due to fuel use for maintenance** | **20-year emissions due to irrigation** | **20-year gross organic carbon sequestration in soil** | **Net 20-year organic carbon sequestration in soil** | **Reported stored organic carbon in soil** | **Location** | **References** |
|---|---|---|---|---|---|---|---|---|
| Mown lawns, low fertilizer rate (0-20 cm depth) | 4.9 | 6.7 | 10.6 | 28.2 | 5.9 | | California | (Townsend-Small & Czimczik, 2010a, 2010b) |
| Mown lawns, high fertilizer rate (0-20 cm depth) | 26.6 | 6.7 | 10.6 | 28.2 | -15.6 | | | |
| Mown lawns | 1.3 | 3.8 | | | | 45.8 | USA Average | (Selhorst & Lal, 2013) |
| Residential lawns (0-50 cm depth) | | | | 3.0 | | | Alabama | (Huyler *et al.,* 2014a) |
| Weekly mown lawns | | 3.4 | | | | | Massachusetts | (Lerman & Contosta, 2019) |
| Three-weekly mown lawns | | 1.4 | | | | | | |
| Residential lawn maintenance | | 2.8 | | | | | Florida | (Horn *et al.*, 2015) |
| Residential tree maintenance | | 0.04 | | | | | | |
| Grass (high fertiliser rate) | 13.4 | | | | | | | (Gu *et al.,* 2015) |
| Grass, push mower | | 4.29 | | | | | Singapore | (Velasco et al., 2021) |
| Parkland shrubs (0-60 cm depth) | | | | | | 91.5 | Helsinki | (Lindén *et al.,* 2020) |
| Parkland lawn (0-60 cm depth) | | | | | | 73.0 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mixed forest soil (0-1m depth) | | | | 101.9 | Seoul | (Bae & Ryu, 2015) |
| Lawn (0-1m depth) | | | | 37.4 | | |
| Urban forest (0-30 cm) | | | | 89 | Auckland | (Weissert *et al.,* 2016) |
| Lawn (0-30cm) 3/4 sites irrigated and fertilised. | | | | 108 | | |
| Lawn (0-40 cm) (100 yr old) fertilised | | | 5.96 | 29.8 | Salt Lake City | (Smith et al., 2018) |
| Forest restoration 7-8 y old (0-100 cm) | | | | 37.9-82.9 | New York City | (Downey *et al.,* 2021) |
| Park lawn C (14yrs old) (0-15 cm) | 126 * | | | 31.5 | Shenzen and Hong Kong | (Kong *et al.,* 2014) |
| lawn (high sand content) (0-10 cm) | | 4.2 | | 11.5 | Texas | (Sapkota *et al.,* 2020) |
| Dry urban forest (0-30 cm) | | | | 75.7 | Hamburg | (Dorendorf *et al.,* 2015) |
| Wet urban forest (0-30 cm) | | | | 144.3 | | |

* Emissions associated with mowing, fertilising, irrigation, and pesticide application.

Table 2. A sample of publications reporting carbon stored and sequestered in urban vegetation: tonnes of carbon per hectare of vegetation cover and per hectare of land. AG = above ground stems, BG = below ground roots. See Supplementary Information for an extended version of table.

| **Description** | **20-year carbon sequestration per hectare of cover** | **Stored carbon per hectare of cover** | **Stored carbon per hectare of land** | **Location** | **References** |
|---|---|---|---|---|---|
| Natural forest (AG) | | | 19.8 | Barcelona | (Chaparro & Terradas, 2009) |
| Natural forest (AG & BG) | | | 690.4 | Kumasi | (Nero *et al.,* 2017) |
| Natural forest (AG & BG plus litter) | | | 144-360.5 | Auckland | (Paul et al., 2021) |
| Public owned sites (AG) | | | 288.6 | Leicester | (Davies *et al.,* 2011) |
| Urban trees (AG & BG) | 61.2 | | | Average across 50 states | (Nowak *et al.,* 2013) |
| Urban Forest (AG) | 136.8 | | 63.19 | Seoul | (Lee *et al.,* 2019) |
| Natural urban forest AG & BG to 10 cm depth) | | 263.04 | | New York | (Pregitzer *et al.,* 2021) |
| Urban dry forest (AG & BG) | | | 123.2 | Hamburg | (Dorendorf et al., 2015) |
| Forest park (AG & BG) | | | 262.4 | Almada | (Mexia *et al.,* 2018) |
| Park trees (AG & BG) | | | 474.7 | Kumasi | (Nero *et al.,* 2017) |
| Domestic garden trees | | 28.6 | | Leipzig | (Strohbach & Haase, 2012) |
| Domestic garden trees (multi-story houses) | | 63.8 | | | |

| | | | | | |
|---|---|---|---|---|---|
| Residential trees | | | 63.0 | Florida | (Timilsina, *et al.,* 2014) |
| Mixed shrub species (AG) | 62.2 | | | New Zealand | (Kimberley *et al.,* 2014) |
| Sage scrub (AG & BG to 10 cm depth) | | 43 | | California | (Wheeler *et al.,* 2016) |
| Grass (AG) | | 1.0 | | Average reported from 2012 literature review | (Guertal, 2012) |
| Grass (BG) | | 1.4 | | | |

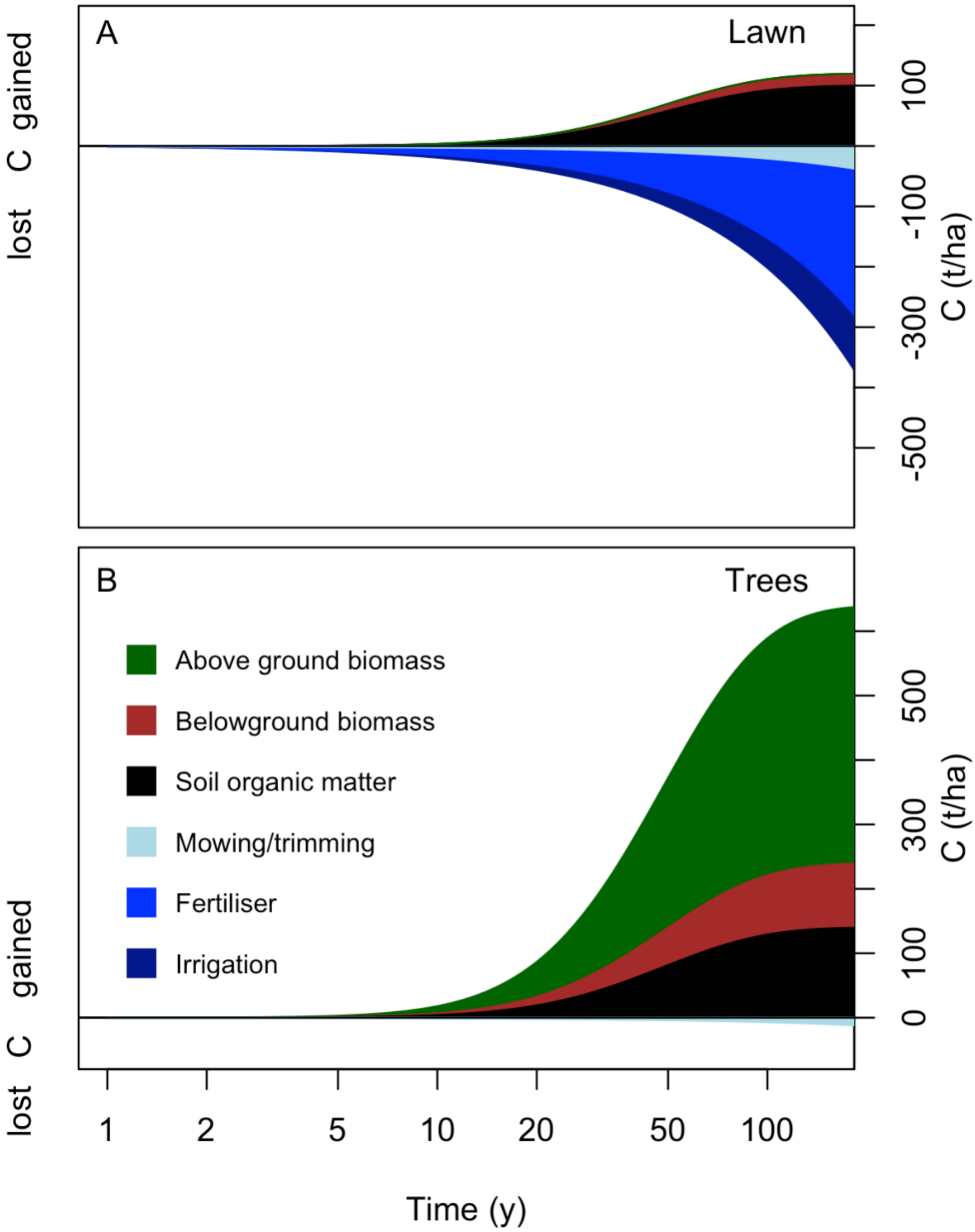


Figure 1. Cumulative carbon sequestration/emissions over time (log scale) for lawns and treescapes with the assumption of starting at zero carbon content both below and above ground at year 1. Note that carbon gains level off after about 50 years for grass, and after about 100 years for trees. Conversely, carbon losses associated with mowing, fertilising, irrigation, and trimming are constant and quickly outweigh potential carbon gains in grass soils. The ‘carbon compensation point’ (where

emissions equal sequestration) occurs as early as after a few years in lawns but may never occur in forest or treescapes. If older trees are removed and either used to replace fossil fuel, or as construction timber, then the carbon balance looks even more in favour of trees. Coloured bands represent a range of values sourced from Tables 1 & 3.

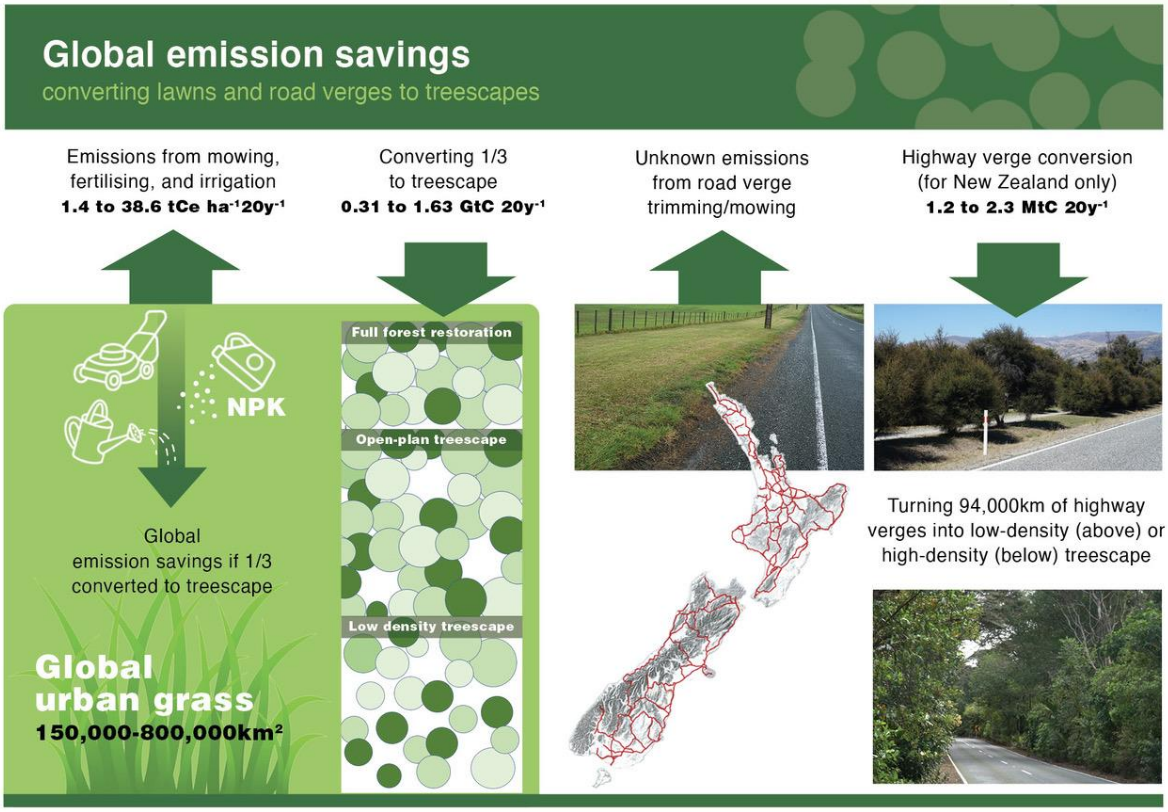


Figure 2. Left hand side: potential impact on the global carbon cycle if 1/3 of urban lawns are converted into treescapes globally. The model calculation is based on an average of three different planting regimes: restoration of a full forest ecosystem; open-plan treescapes with light gaps, and low density treescapes. On the right hand side, a model calculation for New Zealand highway verges is shown, assuming a highway network of 94,000 km (not including minor roads), a verge of 1-2 m, and a mix of low- and high-density plantings. Over two decades, this conversion would result in carbon storage of 1.2-2.3 Mt C $20y^{-1}$.

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