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Can future cities grow a carbon storage equal to forests?

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Keywords: residential development, wooden construction, carbon storage, forest area, urban planning

Abstract

Urban areas have experienced exponential growth since the industrial revolution and by virtue, the urban population has followed. Current projections suggest that this growth has yet to reach its peak implying that urban developments will continue to sprawl into untouched territories. This growth and subsequent sprawl will undoubtedly come at the expense of forested areas. This study presents a carbon storage factor indicator for new urban developments. It is a novel concept which integrates urban planning, land use changes and wooden construction. The factor sets a carbon storage requirement for new urban areas that are developed at the expense of forested areas. The study is conducted in four parts. First, we estimate the carbon storage potential of forest areas via existing literature and databases. Then we collect all new development and construction estimates up to the year 2050 for the whole metropolitan region in Finland. Next, we conduct scenario analyzes for different demand levels of wood in projected residential developments. Finally, we compare the carbon storage potential of the future building stock to the forest areas planned for development. The data used is provided by the regional authority. The results detail that the future residential building stock can store between 128–733 kt of carbon. The lower level implies that current construction methods can only partially preserve the carbon storage of an area in buildings. However, the higher level suggests future buildings to be able to exceed the carbon storage potential of forest areas by nearly 47 tC ha^{-1}. The study reminds that an increased use of wood is dependent on sustainable forest management practices. Furthermore, it is not our purpose to promote urban development into entirely new areas but rather encourage urban planners to consider the carbon balance when it is the only viable option.

1. Introduction

Cities have been widely considered as key components in combatting climate change. Particularly since they are large global emitters and have the most potential in decreasing their respective emissions. However, urban areas are globally experiencing an increase in population [1] which directly creates new demand for both residential and non-residential developments. These developments have been presented to burden the atmosphere with high concentrations of greenhouse gas (GHG) emissions in a short timeframe [2, 3]. It is essential to mitigate these emissions while planning new urban areas.

Research has presented multiple strategies in decreasing construction and building related emissions. These consist of, for example, a more intensive use of buildings [4], more efficient designs and material use [5], green roofs for increased energy efficiency [6], and substituting current materials with biogenic construction materials like timber [7]. The substitution option exhibits an additional benefit alongside lower embodied emissions, as wooden construction materials (WCMs) act as long-term carbon storages. The use of these materials has been suggested as a strategy to decrease the consumption of more carbon intensive materials [8–11].

Historical data presents that wood, probably due to large share of low-rise construction, has been the predominant construction material in residential buildings in North America, Africa, and Oceania [12]. Moreover, the share of WCM has been rather low in the European construction scene with a few exceptions; WCM have played a significant role in constructing detached residential buildings for example in the Nordics [13]. The market share in multistorey buildings, on the other hand, has systematically remained low regardless of many efforts. These efforts have been unsuccessful due to regulatory barriers as well as higher costs associated with wooden multistorey construction [14]. Fortunately, the public sector has widely presented high interest in increasing the share of WCM through wood encouragement policies to mitigate construction related emissions [15]. For example, the New European Bauhaus initiative considers decreasing embodied emissions through wooden construction as one key element in creating a more low-carbon future [16]. The growing interest in wood and other bio-based construction materials may be explained by the increasing awareness of associated climate benefits. But how large of a climatic impact can wooden construction create?

Research has extensively studied the climatic outcomes of WCM in urban development. Typically, these studies consider the biogenic construction materials in comparison to more conventional materials like concrete or steel. For example, the related GHG emissions have been studied on a product (e.g. [7, 17]), building (e.g. [18–20]), national (e.g. [21, 22]), and ultimately on a global level (e.g. [10, 23]). These studies present a clear trend of lower embodied emissions when using WCM. Literature, however, suggests that the carbon storage potential of WCM may be even more significant than the reduced GHG emissions. Fortunately, these two are mutually inclusive. Three separate studies [11, 24, 25] present that increasing the share of wood in urban construction can have a significant impact on reaching climate mitigation targets. In addition, research has presented opportunities in using recycled wood in construction renovation as well as insulation [26]. The use of harvested wood products has substantially increased the total carbon stock in the Nordic region [27]. On the other hand, the carbon stored in wood-based products varies widely across regions and further suggests that it may be vulnerable to economic shocks [28].

Only recently, research has suggested wooden construction to increase the necessity to expand global forest plantations [10]. However, studies that analyze the climatic impacts of wooden construction seldom consider the land that is required for new developments and the associated loss of forested areas i.e. deforestation. This study attempts to address this issue by presenting a carbon storage factor (CS-Factor) concept for urban planning. The concept introduces a carbon-based approach to urban planning.

Literature presents that new urban areas are commonly created at the expense of forested and agricultural areas [29–32]. Therefore, the study hypothesizes that the CS-Factor concept may provide urban planners necessary understanding of how to maintain or even restore the natural carbon storage in the area. The concept is comparable to the green factor tool which supports planners to increase the ecological sustainability of urban areas (See e.g. [33]). The study attempts to uncover whether the built environment can counterweigh the carbon lost from developing to forested areas. The study analyzes empirically the CS-Factors of future residential areas in the Uusimaa region, the metropolitan region with most extensive growth in Finland, between 2022 and 2050. Emphasis is specifically set here on wooden construction.

2. Methods

2.1. Study area and projected residential building growth

The Uusimaa region consists of six areas of which the largest, by population, is the Helsinki metropolitan area (HMA). The region has experienced rapid urbanization since the 1990's with the population increasing by over half a million to a total of nearly two million. By virtue, Uusimaa has and will see drastic changes in its land use since the rate of urbanization is expected to grow until 2050.

According to the Food and Agricultural Organization of the United Nations, net loss of forest land globally has been nearly six million hectares annually during the last decade [34]. Moreover, the regional authority in Uusimaa estimates that around one thousand hectares of forest areas are transformed into other land uses annually—most prominently into urban areas [35]. As a response, authorities have discovered over 100 thousand hectares of idle areas suitable for reforestation in Finland [36]. Globally the value reaches nearly one billion hectares [37]. Research has recently considered the potential of urban areas in assisting climate change mitigation through carbon storage and sequestration (CSS) methods. These methods vary from increasing the quantity of urban trees, amending urban soil with biochar, to increasing the share of urban wooden construction [38, 39]. Even though all methods of CSS can be associated with CS-Factors, this study focuses solely on the carbon storage potential of the future residential building stock through increased wood usage in the Uusimaa region.

The data used in this study is provided by Uudenmaan liitto, the regional authority. It details the projected growth of both residential and non-residential buildings in square meters of gross floor area (GFA) per 250 × 250 meter grid cell to the Uusimaa region between 2022–2050. In addition, the data details the projected population growth per building type per grid cell. This study focuses solely on residential developments that are projected to entirely new areas in the region. New development areas are defined as grids where no construction activity has occurred before. Figure 1 presents residential construction to

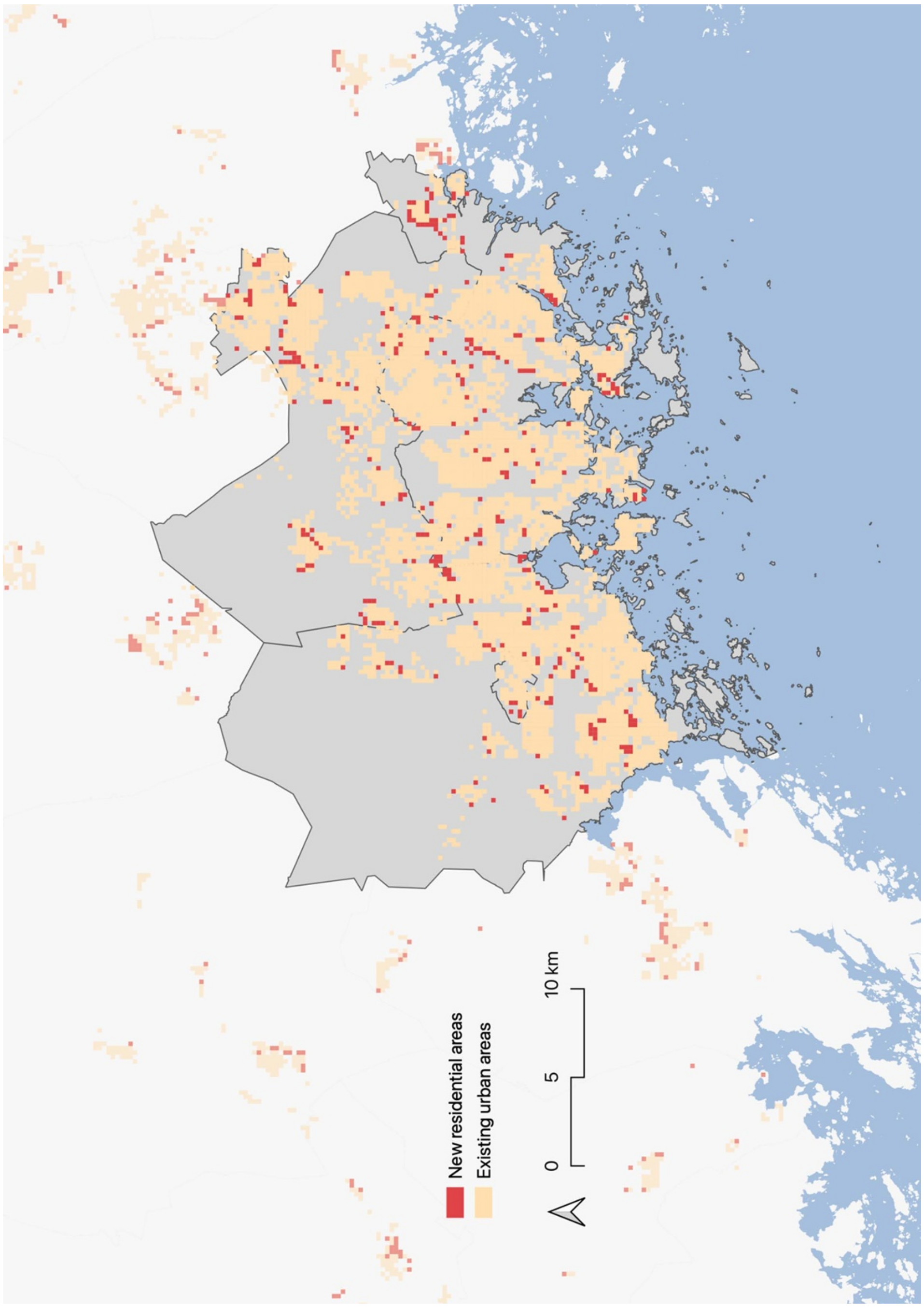

Figure 1. Snapshot of Helsinki metropolitan area and representation of the location of new residential areas ©OpenStreetMap contributors.

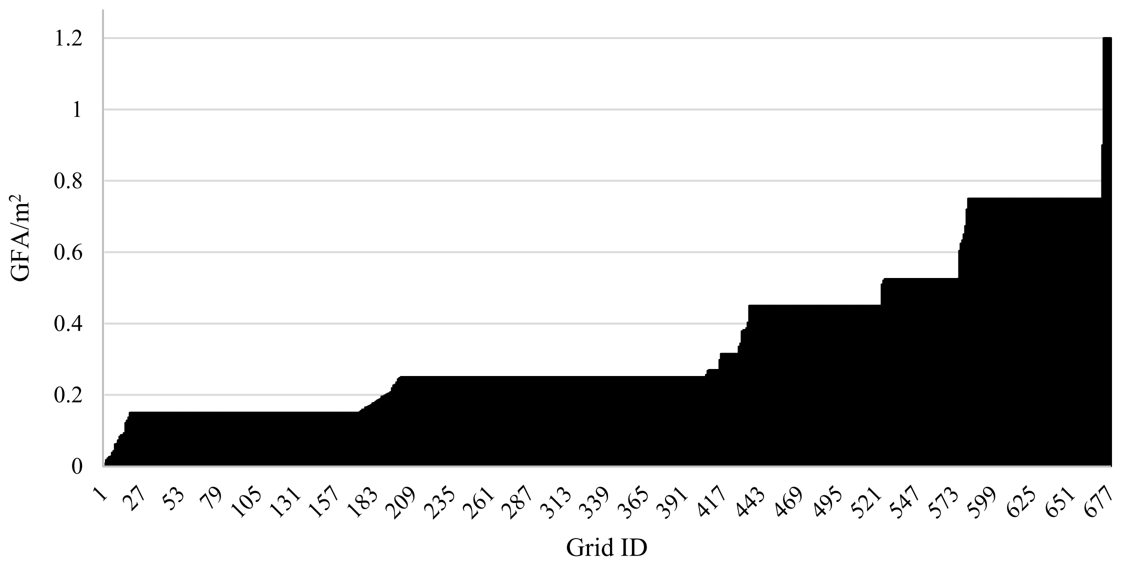

Figure 2. Projected gross built density (GFA m^{-2}) of new residential areas in Uusimaa by 2050.

occur in 677 (9.6%) new development areas by 2050. The projected residential buildings are categorized into two building types: attached and detached buildings. The latter are described as single-family houses with one to two stories. Attached buildings are thus detailed as all other residential buildings. A visual representation of the building types is provided in appendix.

In the data, both building types are distinguished by their projected urban density. The density is calculated by dividing the total gross floor area of a site with the respective site area (250 × 250 m). This urban density indicator is referred to as gross built density (GBD) [40]. Figure 2 presents the projected GBD of the new development areas and assigns each development area a Grid ID. Grid IDs from 1 to 405 are primarily planned as detached building areas, and 406–677 as attached building areas. In figure 2, the values range from 0.0–1.2 GFA m^{-2} with a mean of 0.35 GFA m^{-2} and a standard deviation of 0.22. The most frequently observed value is 0.25 GFA m^{-2} with 205 observations. The data describes that nearly half of the predicted residential developments in the Uusimaa region are projected to these new development areas. These areas are expected to accommodate nearly 190 000 new urban residents by 2050, 71% in attached buildings.

2.2. Scenarios to project carbon storage potential in future building stock

This study conducts scenario analyzes for substituting conventional building materials with wooden counterparts to estimate the carbon storage potential of the future residential building stock in the study area. The scenario analyzes will assist decision-making while improving the evaluation of the environmental impacts associated with increased wooden construction [41, 42]. This method has been used in a large body of prior research (See e.g. [10, 11, 21]).

In this study, the scenario analyzes are based on the projected growth of the residential building stock in the Uusimaa region between 2022–2050. The scenarios consider two key elements in assessing the impact of increasing wooden buildings: the carbon storage potential and the expected demand of wooden buildings in the future (table 1). To determine the former, we classify wooden buildings into three carbon storage categories recommended by prior research [24]. Amiri *et al* [24] detail through an extensive literature review that wooden buildings can accommodate either a low, medium, or high carbon storage per GFA depending on building characteristics. In this study the lower and higher value categories are utilized (table 1). An example of a wooden building with lower carbon storage potential is one constructed of pole-framed elements, whereas a building with high carbon storage potential is one constructed of cross laminated timber (CLT) elements.

Table 1 presents the potential demand of wooden buildings for both building typologies in each scenario. The *Baseline* scenario projects that no additional demand will occur for wooden buildings in Finland [14, 43]. Therefore, the market share of attached buildings (5%) and detached building (85%) will stay constant over time. The second scenario, Growth 40, estimates a slight increase in demand for wooden buildings. *Growth40* uses reference values from Sweden where the market share has been roughly 10% for wooden attached buildings and 90% for detached buildings [43, 44]. The third scenario, *Growth50*, estimates a significant increase in demand where half of the projected residential building stock will be wooden. This estimation is also used in

Table 1. Market share (%) of wooden buildings per building type in each development scenario.

Scenario	Building type			Carbon storage (kgCO2-eq/m2)	
	Attached (%)	Detached (%)	Residential (%)	Building 100	Building 300
Baseline	5%	85%	34%	100	300
Growth40	10%	90%	39%	100	300
Growth50	30%	85%	50%	100	300
Growth60	46%	90%	62%	100	300

Table 2. Carbon storage of forest areas.

Source	Country	Region	Aboveground C	Belowground C	Total C	Unit
Ilvesniemi [50]	Finland	Southern, Finland	**45**	**60**	105	t ha^{-1}
Ilvesniemi [50]	Finland	Northern-Finland	30	50	80	t ha^{-1}
HSY [51]	Finland	Espoo, Uusimaa	49	95	144	t ha^{-1}
HSY [51]	Finland	Helsinki, Uusimaa	43	80	123	t ha^{-1}
HSY [51]	Finland	Vantaa, Uusimaa	43	86	128	t ha^{-1}
HSY [51]	Finland	Kauniainen, Uusimaa	44	109	153	t ha^{-1}
HSY [51]	Finland	HMA, Uusimaa	**46**	**89**	134	t ha^{-1}
Uudenmaan liitto [52]	Finland	Uusimaa	26	.	.	t ha^{-1}
Gustavsson *et al* [53]	Sweden	Kronoberg	**46**	**108**	154	t ha^{-1}
Högberg [27]	Finland	Finland	**35**	.	.	t ha^{-1}
Högberg [27]	Sweden	Sweden	**46**	.	.	t ha^{-1}
Högberg [27]	Norway	Norway	**30**	.	.	t ha^{-1}
Högberg [27]	Canada	Canada	**48**	.	.	t ha^{-1}
Högberg [27]	Russia	Russia	**37**	.	.	t ha^{-1}
Högberg [27]	US	Alaska	**35**	.	.	t ha^{-1}
Mean			41	85	126	t ha^{-1}
Std. Dev.			6.6	24.2	.	

previous studies (See e.g. [11, 21]). The fourth scenario, *Growth60*, predicts a high increase in demand for wooden residential buildings. In Growth60, the market share for wooden multistorey buildings increases according to the target set by the Finnish Ministry of Environment [45]. The study considers this scenario to be the most ambitious and thus increases the market share of detached buildings according to *Growth40*.

2.3. Carbon storage in forested areas

Forested areas cover three quarters of Finland's land area, thus, this study defines all new development areas, according to the precautionary principle, as fully forested areas. Research details the carbon sequestered and stored in a forest area to vary across forest age groups [46, 47]. Repo *et al* [47] presents that younger forest areas have the highest carbon sequestration potential, but older forests to store the most carbon. The carbon sequestered is stored both aboveground and belowground, e.g. both in trees, litter, deadwood, and soil. The former can be sufficiently measured through the volume of biomass since half of the mass of wood is carbon [48]. In other words, the greater the volume of biomass the greater the aboveground carbon in a forested area. Similar measurements of belowground carbon are not as straightforward since it differs across regions, soil type, depth, and density.

Table 2 presents both aboveground and belowground carbon per hectare in forested areas according to literature and databases. The aboveground carbon ranges from 30 to 48 tons per hectare (tC ha^{-1}) with a mean value of 41 tC ha^{-1} and a standard deviation of 6.6. Less observations were found for belowground carbon, thus, presenting more variance. The values range between 60–108 tC ha^{-1} with an average value of 85 tC ha^{-1} and a standard deviation of 24.2. This study estimates the carbon storage of a forest with the mean values presented in table 2. The relative share of aboveground carbon is in line with prior research (See e.g. [49]).

2.4. CS-Factor categories and minimum requirements

The study presents three CS-Factor categories used in the analysis. The first category, CS-Factor Zero (CSF.0), illustrates a condition where the carbon storage potential of a new residential area is less than the aboveground carbon of the prior forest area. The second factor, CS-Factor One (CSF.1), details a condition where the carbon storage potential of a new residential area equals or exceeds the aboveground carbon of the prior forest area, but is less than the total. The final category, CS-Factor Two (CSF.2), describes a condition where the carbon storage potential of a new residential area equals or exceeds the total carbon storage of the prior forest area. Depending on the development scenario, these categories are then

Table 3. Gross built density (GFA m^{-2}) requirements to meet CS-Factor conditions in Uusimaa.

	CSF.1 (>41 tC ha^{-1})		CSF.2 (>126 tC ha^{-1})		
	Wooden building category:				
Share of WCM	Building 100 (100 $kgCO_2$ m^{-2})	Building 300 (300 $kgCO_2$ m^{-2})	Building 100 (100 $kgCO_2$ m^{-2})	Building 300 (300 $kgCO_2$ m^{-2})	unit
5%	3.00	1.00	9.27	3.09	GFA m^{-2}
10%	1.50	0.50	4.63	1.54	GFA m^{-2}
20%	0.75	0.25	2.32	0.77	GFA m^{-2}
30%	0.50	0.17	1.54	0.51	GFA m^{-2}
40%	0.37	0.12	1.16	0.39	GFA m^{-2}
50%	0.30	0.10	0.93	0.31	GFA m^{-2}
60%	0.25	0.08	0.77	0.26	GFA m^{-2}
70%	0.21	0.07	0.66	0.22	GFA m^{-2}
80%	0.19	0.06	0.58	0.19	GFA m^{-2}
90%	0.17	0.06	0.51	0.17	GFA m^{-2}
100%	0.15	0.05	0.46	0.15	GFA m^{-2}

appointed to the projected residential development areas in the Results section.

Table 3 showcases the minimum GBD requirements for the new development areas to meet the conditions set for CSF.1 and CSF.2 respectively. The table details the minimum requirements for two wooden building categories under multiple market share conditions. The density values are calculated by dividing the mean values of aboveground and belowground carbon (C m^{-2}) with the share of carbon in projected wood construction (C/GFA). The table illustrates that density requirements decrease when the relative share of WCM increases. The values presented in table 3 cannot be extrapolated to other global regions as such since the aboveground and belowground carbon volume varies widely across regions. The concept, however, can be generalized under correct circumstances. A detailed discussion of the applicability is presented in section 4.

3. Results

This section presents the carbon storage potential of the new residential development areas in Uusimaa by 2050. Figure 3 details the carbon storage potential through 'Building 100′ -categorized wooden structures whereas figure 4 through 'Building 300′ -categorized wooden structures. Associated CS-Factor conditions are highlighted as dotted lines in both figures.

Figure 3 details that the *Baseline* scenario cannot reach CSF.2 in any development area. However, the scenario exceeds the CSF.1 threshold in 221 areas (32%). These areas are entirely projected for detached building developments (GBD $\geqslant$ 0.18). The carbon storage potential in the development areas range between 0.4–57.9 tC ha^{-1}. The average value, 30.4 tC ha^{-1}, does not exceed the average value set for either CS-Factor. The scenario has a total carbon storage potential of 128 810 tC. This equals nearly half a million cubic meters (Mm^3) of WCM and roughly 6 306 hectares of designated forest plantations by 2050.

Furthermore, *Growth40* similarly does not reach CSF.2 in any development area. Figure 3 details that the scenario achieves CSF.1 in 223 areas (33%). As per *Baseline* scenario, these areas are projected only for detached building developments (GBD $\geqslant$ 0.17). In *Growth40* the carbon storage potential in the development areas range between 0.76–61.3 tC ha^{-1}. The average value, 35.2 tC ha^{-1}, does not exceed the average value set for either CS-Factor. The scenario has a total carbon storage potential of 148 869 tC. This equals 0.53–0.57 Mm3 of WCM and roughly 7 288 hectares of designated forest plantations by 2050.

Figure 3 presents that *Growth50* can neither equal the threshold of CSF.2 in any development area. However, the figure illustrates that *Growth50* achieves CSF.1 in 375 areas (55%). The results dictate that both building types can achieve CSF.1. Attached buildings exceed the threshold in 41% of these development areas (GBD $\geqslant$ 0.51). The results regarding detached buildings are the same as in the *Baseline* scenario. In *Growth50* the carbon storage potential in development areas ranges between 0.78–98.1 tC ha^{-1}. The average value is 46.1 tC ha^{-1} which exceeds the threshold set for CSF.1 by 5.3 tC ha^{-1}. The scenario has a total carbon storage potential of 195 122 tC. This equals 0.70–0.75 Mm^3 of WCM and roughly 9 553 hectares of designated forest plantations by 2050.

Finally, figure 3 illustrates that 473 development areas (70%) can achieve either CS-Factor in Growth60. The scenario exceeds the CSF.2 in only five areas (GBD $\geqslant$ 1.20). In *Growth60*, over half of the development areas that achieve CSF.1 are projected for attached building developments (GBD $\geqslant$ 0.33). The results for detached buildings are the same as in *Growth40*. The carbon storage

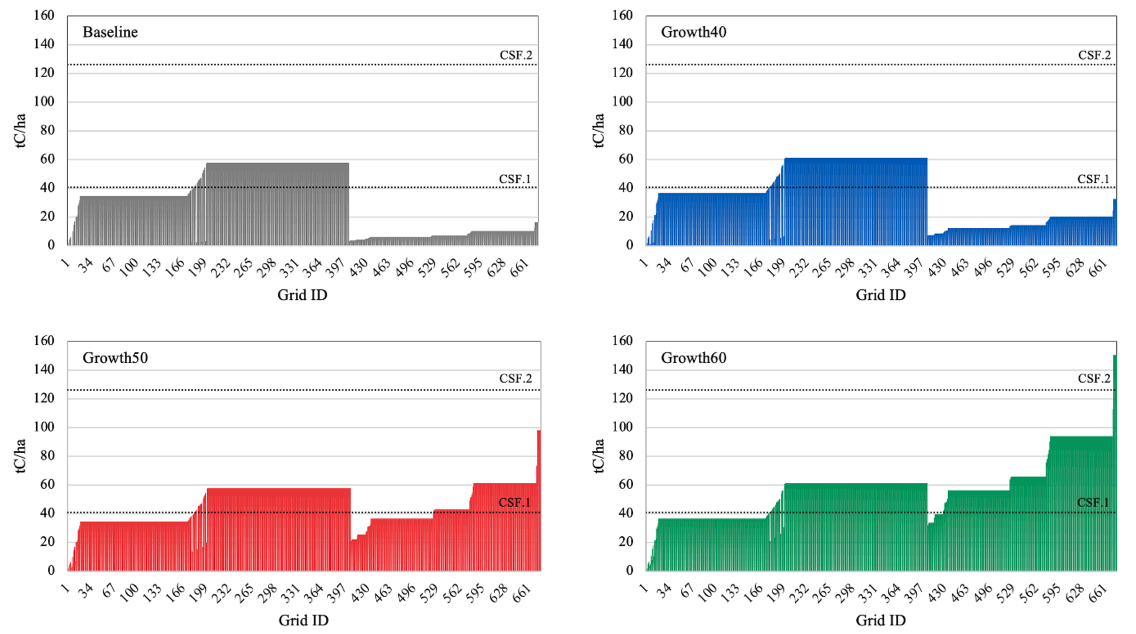

Figure 3. Carbon storage potential and CS-Factors of new residential areas with Building 100.

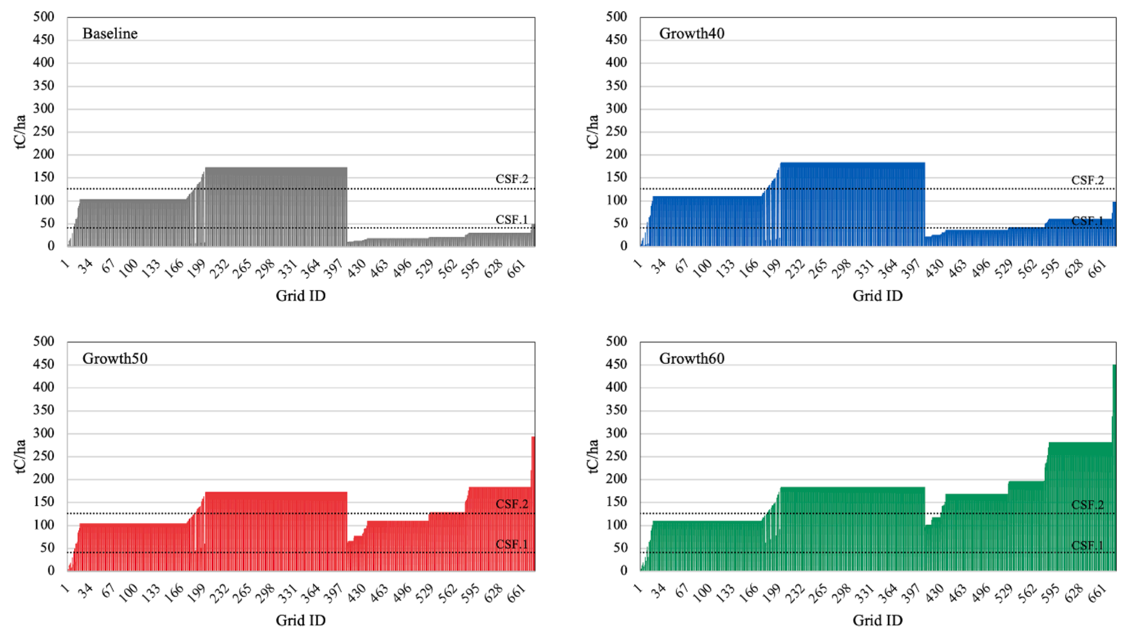

Figure 4. Carbon storage potential and CS-Factors of new residential areas with building 300.

potential in *Growth60* development areas ranges between 0.83–150.4 tC ha^{-1}. The average value per grid cell is 57.8 tC ha^{-1} which exceeds the CSF.1 threshold by over 17 tC ha^{-1}. The scenario has a total carbon storage potential of 244 360 tC. This equals 0.87–0.94 Mm^3 of WCM and roughly 11 964 hectares of designated forest plantations by 2050.

Figure 4 presents the carbon storage potential of the scenarios per development area with 'Building 300′. In the *Baseline* scenario, CSF.2 is accomplished in 218 development areas which equals nearly a third of the study area. These areas are all projected for detached building developments (GBD $\geqslant$ 0.18). Furthermore, the *Baseline* scenario achieves CSF.1 in 178 areas (26%) of which only a minority is projected for attached building developments. The carbon storage potential in the development areas range between 1.3–173.7 tC ha^{-1}. The average value per area is 91.3 tC ha^{-1} which exceeds the threshold set for CSF.1 by 50.5 tC ha^{-1}. The scenario has a total carbon storage potential of 386 249 tC. This equals 1.38–1.49 Mm^3 of WCM and roughly 18 919 hectares of designated forest plantations by 2050.

Growth40 achieves either CS-Factor in over 80% of the study area. The threshold for CSF.2 is surpassed in 222 areas (33%). These areas are all projected for detached building developments (GBD $\geqslant$ 0.18). Furthermore, this scenario accomplishes CSF.1 in 323 development areas. Nearly half of these areas are projected for attached building developments (GBD $\geqslant$ 0.51). CSF.1 is achieved in detached areas already with a GBD $\geqslant$ 0.06. The carbon storage potential in *Growth40* development areas range between 2.3–183.9 tC ha^{-1}. The average carbon storage per development area is 105.5 tC ha^{-1} which exceeds the limit of CSF.1 by over 150%. The scenario has a total carbon storage potential of 446 608 tC. This equals 1.60–1.72 Mm^3 of WCM and roughly 21 865 hectares of designated forest plantations by 2050.

Figure 4 presents that *Growth50* exceeds the carbon storage potential of either CS-Factor in 667 development areas (98.5%). CSF.2 is accomplished in 371 areas (55%) of which 41% are projected for attached building developments (GBD $\geqslant$ 0.52). The CSF.1 threshold is surpassed in in the remaining 296 areas. The share of CSF.1 areas projected for attached building developments is 42% (GBD $\geqslant$ 0.16). The results for detached buildings are the same as in *Baseline* scenario since the WCM market share is the same. Figure 4 highlights the carbon storage potential in the development areas to range between 2.3–294.3 tC ha^{-1}. The average value in a grid cell is 138.3 tC ha^{-1} which exceeds the CSF.2 threshold by 12.1 tC ha^{-1}. The scenario has a total carbon storage potential of 585 368 tC. This equals 2.09–2.25 Mm^3 of WCM and roughly 28 659 hectares of designated forest plantations by 2050.

Finally, *Growth60* achieves either CS-Factor in 667 development areas (98.5%). The scenario surpasses the CSF.2 threshold in 471 areas (70%). Over half of these areas are projected for attached building developments (GBD $\geqslant$ 0.34) while the other half are projected for detached buildings (GBD $\geqslant$ 0.18). The remaining 196 development areas (29%) achieve the requirements presented for CSF.1 of which attached buildings comprise 13%. In total, the carbon storage potential in the development areas range between 2.5–451.2 tC ha^{-1}. The average value per area is 173.3 tC ha^{-1} which exceeds the threshold presented for CSF.2 by 47.0 tC ha^{-1}. The scenario has a total carbon storage potential of 733 080 tC. This equals 2.62–2.82 Mm^3 of WCM and roughly 35 891 hectares of designated forest plantations by 2050.

4. Discussion

The study focuses on the projected residential developments in the Uusimaa region between 2022–2050. The growth projections suggest that the urban structure of Uusimaa will sprawl into a plethora of currently forested areas. This study calculates and compares the carbon storage potential both gained and lost through future developments projected to these new areas. The study aims to develop a policy tool called CS-Factor, a novel concept which aims to improve carbon neutral urban planning. This concept can provide planners knowledge on how to maintain or even restore the natural carbon storage in an area. In this study specific focus is set on wooden construction.

The results illustrate that the projected residential developments can partially or even fully equal the carbon storage potential of forested areas in Uusimaa by 2050. However, the results depend on the urban density, wooden construction design, and quantity of WCMs used. As detailed in the results, current construction practices can equal the carbon storage potential of forests only in areas projected for detached buildings. This is due to the high share of wood typically used in the building type. The finding is troublesome since the current trend in urban development strongly favors multistorey buildings, i.e. attached buildings in utilized database. If the market share of wooden attached buildings remains stagnant, this result may further polarize the on-going public discussion between the two building types.

The study highlights that increasing the market share of wooden attached buildings generates more possibilities for the built environment to equal or exceed the carbon storage potential found both aboveground and belowground in forested areas. This result is in line with previous research which details the carbon storage potential to increase in urban areas when more wood-based materials are used [11]. However, the results detail the significance of the wooden construction design used in comparison to simply the quantity of wooden buildings [24]. For example, the *Baseline* scenario with Building 300 (e.g. typical CLT multistorey building) achieves a higher carbon storage potential in the study area than *Growth60* with Building 100 (e.g. typical Pole-framed element house).

The results suggest that carbon regenerative planning for residential developments is not dependent on the building typology (attached vs. detached) if the market share of wooden attached buildings increases significantly. In Finland, for example, there are ambitious governmental programs assisting the growth of wooden attached building developments in the public sector. However, only one in ten of all residential developments in Finland are developed by public actors [45]. Thus, a significant increase in the private sector is also required to provide the projected development areas more opportunities at the proposed CS-Factors.

Expanding the carbon storage of urban areas with wooden buildings, however, comes at a cost. It directly increases or potentially deviates the current consumption patterns of natural materials, i.e. trees. Previous studies imply that an increased consumption requires context to sustain future production

Table 4. Gross built density requirements to meet CSF.1 conditions with building 100 globally.

Share of WCM	Uusimaa study area	Applicable regions			Unclear applicability	Non-applicable regions		unit
		AS [60–62]	EU [63]	OC [64]	NA [65, 66]	AF [67, 68]	SA [69]	
10%	1.50	3.50	2.47	2.15	2.83	5.66	4.59	GFA m^{-2}
25%	0.60	1.40	0.99	0.86	1.13	2.26	1.84	GFA m^{-2}
50%	0.30	0.70	0.49	0.43	0.57	1.13	0.92	GFA m^{-2}
75%	0.20	0.47	0.33	0.29	0.38	0.75	0.61	GFA m^{-2}
100%	0.15	0.35	0.25	0.21	0.28	0.57	0.46	GFA m^{-2}

[54]. Forests, in and of itself, are considered crucial components in mitigating climate change. Therefore, increased wooden construction can lead to weak rather than strong sustainability outcomes if the production of the natural material is not sustained [55, 56]. The sustainability of wooden construction is thus highly dependent on forest management practices where reforestation is a mandatory action after felling, i.e. regeneration obligation in the Finnish Forest Act [57]. This necessity is commonly discussed in prior research [10, 11, 24].

The carbon storage potential of the development scenarios roughly translates to a required rate of 0.5–3.0 Mm^3 of WCMs by 2050. These volumes are feasibly achieved considering the annual raw timber material streams in Finland [58]. The material stream presents that over 13 Mm^3 of raw timber was consumed for energy purposes in 2021. Furthermore, we estimate that roughly 6000–36 000 ha of designated forest plantations are required to satisfy the different demand levels presented in the development scenarios. FAO [34] details that nearly 2 M ha of new forest areas were planted annually in the past decade. Furthermore, roughly 100 thousand hectares of idle areas suitable for reforestation have been recently discovered in Finland [36]. This implies that the increased demand for new wood-based structures is feasible to achieve. However, the estimation of land area presented in this study does not consider the increased risk of abiotic and biotic disturbances [59]. Therefore, the required rate of designated forest areas may be greater.

The findings presented in this study are directly applicable to the Uusimaa region in Southern Finland. We consider that the results are not necessarily applicable to other regions since the carbon storage of forested areas varies widely across the globe. However, we argue that the concept can be applied to all global regions under appropriate circumstances. The applicability is directed primarily to regions where forest areas experience positive annual net growth. These regions are Europe (EU), Asia (AS), and Oceania (OC) [34]. Table 4 presents the minimum urban densities required to meet CSF.1 conditions in all global regions with Building 100 - wooden buildings. The table details that less WCMs are required in regions with high projected densities and vice versa. For example, Oceania can meet CSF.1 conditions with less WCMs than Asia. Therefore, the research considers the projected urban density to play a key role in reaching CS-Factor conditions across global regions. Hence, the requirements to meet CS-Factor conditions can be roughly estimated through population densities. For example, the Uusimaa area is projected to accommodate nearly 4500 residents per square kilometer in the new urban areas. This equals the population density of the city of Berlin, but it is four times greater than in the entire Berlin-Brandenburg metropolitan area. This suggests that a greater volume of WCMs is required in these, less dense, areas of a city to achieve proposed CS-Factors.

The study emphasizes that the CS-Factor concept should not be considered as promoting urban development to forested areas but rather if deforestation occurs due to urban development. Moreover, the CS-Factor should not be interpreted as a concept which compensates for all ecosystem services provided by a forest area. For example, urban settlements can neither fully compensate for potential biodiversity loss, provisional services nor the natural water retention provided by forest areas. Urban areas can only attempt to mimic these features through green infrastructure like urban parks and yards. However, we consider that the CS-Factor concept is increasingly relevant for urban planners in developing urban areas. The relevance develops in accordance with the increasing demand for urban land which prompts for continued urban sprawl into new territories. Future research should, thus, develop the CS-Factor concept by adapting other CSS strategies. Prior research details a plethora of CSS strategies [38, 39] and showcases their positive climate effects in urban settlements [70].

Moreover, this study does not consider the carbon uptake lost due to urban expansion but instead relied on the assumption of all forested areas to be fully grown. The potential loss of carbon uptake depends a lot on the age of the forest [47]. The lost carbon uptake potential is greatest if urban development occurs in a young, forested area. This perspective should be incorporated in future urban planning as well as research when analyzing the effects of land use change.

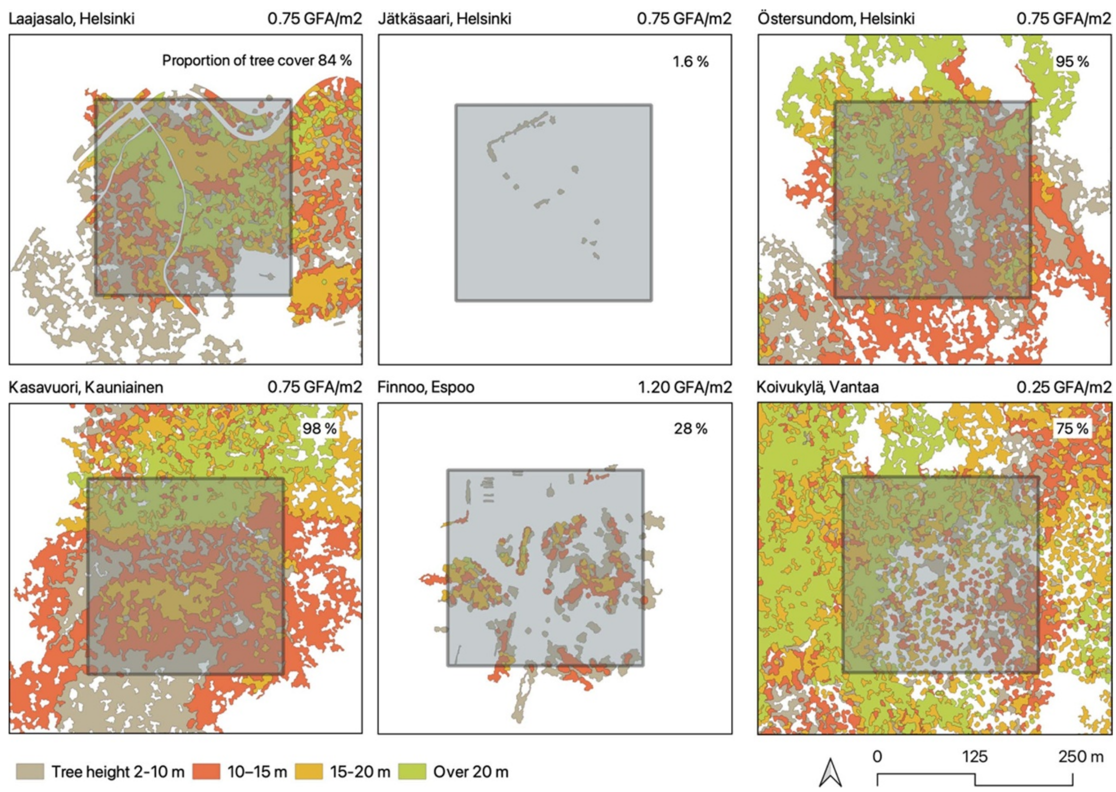

Figure 5. Location, projected density, and current proportion of tree cover in example development areas in study area ©OpenStreetMap contributors.

Figure 5 presents six example areas in the study region that are projected for residential development. The figure details the location, projected urban density by 2050, and the height and proportion of tree cover [71] in the area. Based on the varying height and proportion of tree cover in each area, we reflect that the volume of aboveground carbon, and potentially belowground carbon also, is overestimated in the study. Furthermore, the urban densities presented in the figure suggest that not all areas would be entirely developed, i.e. some tree cover would remain. This positively contributes to the CS-Factor estimations; however, they were not in the scope of this study. Nonetheless, we encourage planners to favor more dense urban development, with low building site coverage ratios, in areas that have greater volumes of tree cover. This can result in more beneficial outcomes from a climate change perspective.

There are currently many initiatives globally that advocate for increasing the relative share of wood use in future construction [15]. For example, France and Japan have applied national level wood encouragement policies whereas Tasmania in Australia and the British Columbia in Canada have implemented regional encouragement policies. Each of these encouragement policies share common themes in reducing construction related emissions and promoting local economies [15]. These policies are seldom seen in countries without economically significant forest sectors. A recent study [72] argues that regions that have yet to adopt wood encouragement policies should conduct cost-benefit analyses to evaluate the feasibility of the renewable, low-carbon material.

5. Conclusions

In this study, we present a novel concept called CS-Factor. The concept advocates for a carbon-based approach in future urban planning. The research focuses on currently forested areas that are projected for residential development in the Uusimaa region between 2022–2050. This study aims to quantify the carbon storage potential of future residential buildings through scenario analyzes and compare it to the carbon storage found in the forested areas. The concept can improve the knowledge in urban planning to maintain or restore the carbon storage of a forested area projected for urban development. In this study specific focus is set on wooden construction.

The research presents that the carbon storage potential in the projected residential building stock ranges from 128–733 thousand tons. The findings illustrate that with current construction practices, a third of the projected residential development areas can fully restore the carbon storage potential of forested areas. These areas, however, are planned to only accommodate detached building developments. This finding is troubling from a carbon balance perspective since most of the projected development is focused on attached buildings. The study, however, highlights that the building typology lacks to play a difference when the market share of wooden attached buildings increases to a sufficient level. In the most ambitious wood-use scenario, the planned residential areas can exceed the carbon storage potential of forested areas by 47 tC ha^{-1}. This suggests a 37% net carbon storage increase in the studied region by 2050. The increase translates to a total of 729 ktCO2e which is the equivalent to over five years of electrical heating emissions in the HMA [73]. The study emphasizes the importance of design and construction technology used in wooden residential buildings to maximize the carbon storage potential.

The study suggests that a higher relative share of WCMs is required in low density areas to meet the CS-Factor conditions. We argue that the carbon-based approach in planning can have a direct impact on urban development practices in regions where forested areas are projected for urbanization. The study, however, reminds that the results cannot be extrapolated to all regions since wooden construction should only be considered as a viable technology in regions that have access to sustainable forest management practices. Increasing the consumption of wood requires careful planning to guarantee strong sustainable outcomes.

The concept presented in this study highlights the novel opportunities that wooden construction can present while pursuing UN Sustainable Development Goals (no. 9, 11, 12, 13). Future research should improve the CS-Factor concept by incorporating other methods of CSS. The study highlights a need for research to quantify the potential carbon uptake lost from forested areas that are projected for urban development. This can assist policy makers to direct new developments to areas where less negative climate impacts could occur.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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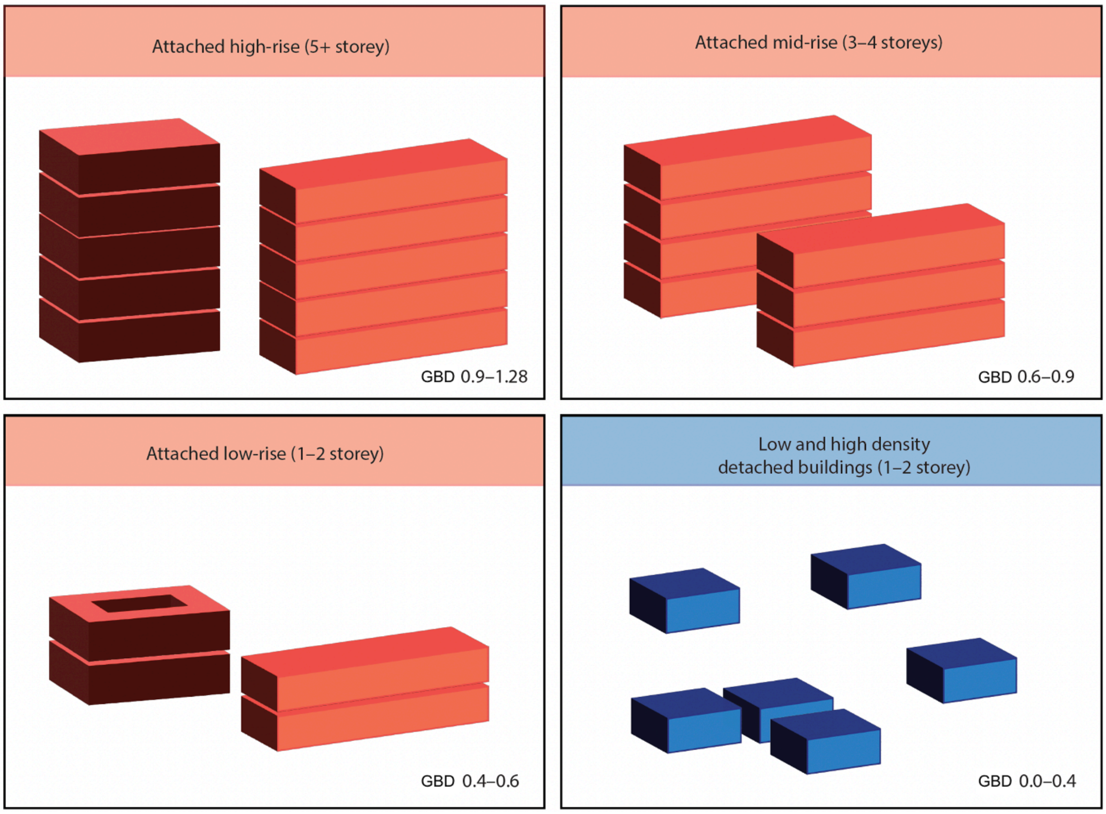
Appendix. A schematic representation of potential building typologies.



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