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Urban Equilibrium for sustainable cities and the contribution of timber buildings to balance urban carbon emissions: A New Zealand case study

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ABSTRACT

In the current study, Urban Equilibrium is defined as the situation where buildings in an urban environment act as a balancing agent for the greenhouse gas emissions of the urban area; therefore the buildings act like carbon pools. Cities contribute significantly to pollution, and the move to more, and larger, cities is increasing. The whole-of-life role of timber in future urban developments as a contributor to balance urban carbon emissions is considered here using a new concept of Urban Equilibrium. When applied to Auckland, New Zealand, as a case study, maximising the use of timber in future urban developments demonstrated that Auckland's target of a 40% carbon emissions reduction by 2040 could be achieved 20% faster than planned while still meeting the city's future growth needs. This strategy is complementary to, and easy to integrate with, other strategies and policies for greenhouse gas mitigation. However, the Urban Equilibrium concept is broader than this and can also be applied in other aspects relating to the sustainability of urban environments. Urban Equilibrium fosters a framework of urban governance that integrates environmental and social development agendas with economic development. This holistic approach takes into account the various effects that economic development can have, and re-defines the concept of growth to include a moral obligation to future generations.

1. Introduction

Cities currently occupy 1% of the earth's surface but contain 50% of the world's population, consume 75% of the world's energy and emit 80% of the greenhouse gases (GHG) (Wuppertal Institute for Climate Environment and Energy, 2009). Ideally, *urban* areas should exist in *equilibrium* with the environment to be sustainable in the long term. The phrase "*Urban Equilibrium*" has already been used in relation to urban economies, land use, transport, housing supply/demand and planning (Capello, 2013; Dai et al., 2010; De Lara et al., 2012; Kilani et al., 2010; Simmonds et al., 2013; Verhoef and Nijkamp, 2008; Wu et al., 2004) but it has not been used previously in relation to urban GHG emissions and climate change (CC).

The current study introduces a new concept where Urban Equilibrium (UE) is applied in relation to urban GHG emissions and CC with a specific definition: *where the structures that define an urban environment act as a balancing agent for the greenhouse gas emissions of the urban area; therefore the buildings act like carbon pools* (David Turner, Executive Director of Sequal Lumber Ltd. Pers comm. 2014). In this novel concept of UE, the whole-of-life role of timber in future urban developments is evaluated for its contribution in balancing out urban carbon emissions and involves three types of carbon mitigation, as defined in Equation (1):

$$\text{UE} = \text{Sequestration optimisation} + \text{Storage maximisation} + \text{Emission minimisation} \quad (1)$$

This terminology is used throughout the paper. The UE approach emphasises the role of timber in future urban developments on the basis that the environmental benefits provided by such an approach will extend synergistically to social and economic areas. However, the UE approach is broader than that, and can be applied

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to different aspects within urban environments. Ideally, it builds on the 'sustainable city concept' developed by the United Nations that provides an operational model for sustainable cities. No one size fits all so policies and management measures need to be tailor-made to take into account the challenges and opportunities driven by the idiosyncrasies of different urban environments "*to ensure solutions that are both functional and economically feasible*" (Falconer and Mitchell, 2012; United Nations DESA, 2013). Hence, UE involves a systems approach that incorporates whole-of-life thinking within an entire urban environment, with the aim of assisting urban governors to manage pollutants in an urban system. By doing this, UE provides considerable scope for more sustainable future urban developments. Urban policy makers need to respond to future growth needs in cities while addressing GHG mitigation and this study demonstrates, in particular, the benefits of greater utilisation of timber in future building construction.

Timber has various carbon-mitigation benefits: trees remove (sequester) carbon as they grow, and wood is a long-term carbon store until trees and wooden products reach the end of their useful life and are either burnt or degrade. Only then is the carbon partially released back in the atmosphere. Evaluating the environmental benefits of using timber in construction is not new, but previous studies have generally involved only single buildings. The novelty of this project, and of the proposed UE concept, is to consider the advantages of multiple timber-building developments in an urban environment. Conducting an evaluation of alternative development options at an urban scale presents many challenges, complexities and uncertainties. For example, all the buildings within a built environment would need to be individually assessed, compared and their actual timber content summed to generate the overall urban figure, but this procedure is infeasible when considering future urban growth scenarios. Instead, the objectives of this study were to: raise awareness of the underlying potential of maximising the use of timber in future urban developments by incorporating and applying the concept of UE; and assess the broader implications this potential may have for urban governors to achieve sustainable urban environments. These objectives were achieved by assessing published literature to identify appropriate data then applying these in a high-level case study within Auckland, New Zealand. Such an approach can then be applied to any developing urban environment worldwide.

New Zealand is at the upper end of the international urbanisation spectrum with over 87% of the population living in urban environments. The country is currently facing an important challenge to keep its international image of being sustainable with a healthy and socially connected population (Otago University, 2014). Auckland is the largest city in New Zealand with approximately one-third of the country's population. With 1.4M (Million) people spread over 500,000 ha and a projected 1M additional people over the next 30 years, business-as-usual urban development would result in a 39% increase in GHG emissions over the next 20 years (Auckland Council, 2014a). However, Auckland Council has set in place an alternative vision of becoming the world's most liveable city while meeting forecasted urban growth through the Auckland Plan. To accommodate the projected population growth, Auckland Council foresees "*adopt[ing] a Rural Urban Boundary in Auckland's Unitary Plan that provides for land capacity over the next 30 years for 280,000 new dwellings within the 2010 Metropolitan Urban Limit baseline, 160,000 new dwellings in new greenfield land, satellite towns and other rural and coastal towns, and at least 1400 ha of new greenfield business land.*" (Auckland Council, 2014a) Part of the Plan's implementation will require the city to reduce urban GHG emissions and increase energy efficiency, resilience and adaptation to CC.

The aspirational GHG emissions target is a 40% reduction by 2040, compared with 1990 levels, while accommodating the projected (1M) additional people (Auckland Council, 2014a, b). The plan envisioned the adoption of a series of emission mitigation pathways. The contributions of the various different pathways and the expected total emission reduction for the 20 year period 2011–2031 are shown in Fig. 1. If all these actions were adopted as suggested by the plan then a 40% emission reduction by 2031 would be possible (ARUP, 2012a; b; Auckland Council, 2014b).

Auckland was chosen for the case study because its governance aims lend themselves to the implementation of additional strategies using the UE concept. The aim of the current study was to estimate at a high level the additional emission reduction achievable by including the amounts of carbon sequestered and stored, and the emissions eliminated as a result of using timber in all new buildings constructed in Auckland over the next 30 years. The analysis involved: (1) assessing published literature to obtain relevant input data; (2) designing the case study framework; and (3) calculating the carbon storage and sequestration benefits of incorporating timber into new buildings over the next 30 years.

2. Methods

2.1. Retrieval of relevant literature

Relevant literature was retrieved to obtain data regarding the environmental benefits of using timber in building construction and its effects on urban GHG emission reduction. Various keyword phrases (see Supplementary File) were searched during the period February 2014–April 2015 using Elsevier's Science Direct and Scopus databases, and also using Google Scholar.

2.2. Case study design

The basic premise of the case study was the projected need for 280,000 new dwellings within the Metropolitan Urban Limit (MUL) baseline and 160,000 new dwellings in new greenfield and satellite towns and other rural and coastal towns to be constructed in Auckland for the next 30 years (Auckland Council, 2014a).

Auckland Council expects medium-to-high rise building development to occur within the MUL and a low-to-medium rise development in the new greenfield land, satellite towns and other rural and coastal towns (Auckland Council, 2014a). In this high-level case study, the city development has been assumed to happen linearly over the 30-year time frame considered by the Auckland Council. This will result in an average of 14,660 new dwellings being constructed per year for the next 30 years of which 9330 residential units will be within the MUL (assumed 50% medium-rise and 50% high-rise), 5330 units will be other areas within the Rural Urban Boundary per year (assumed 50% low-rise and 50% medium-rise).

Supporting social infrastructure development (e.g. hospitals, courts, schools, etc) is also expected to be built or adapted (Auckland Council, 2014a). The forecast 1.7M m^2 of additional education and health floor-space development averages 55,000 $m^2\,y^{-1}$ over a 30-year timeframe (Auckland Council, 2014a). Educational buildings were used as a proxy for social infrastructure adaptation as the Plan identifies young people as a top priority. By 2040, the population of children is expected to increase by almost 100,000 (Auckland Council, 2014a), which equates to an approximate increase of 3300 students per year.

Auckland's forecasted commercial space needs shows that, by 2041, an additional 2.97M m^2 of office floor space and 1.8M m^2 of retail floor space will be needed compared to 2011 (Auckland Council, 2013). The increase equates to 99,000 m^2 of office space and 60,000 m^2 of retail floor area annually.

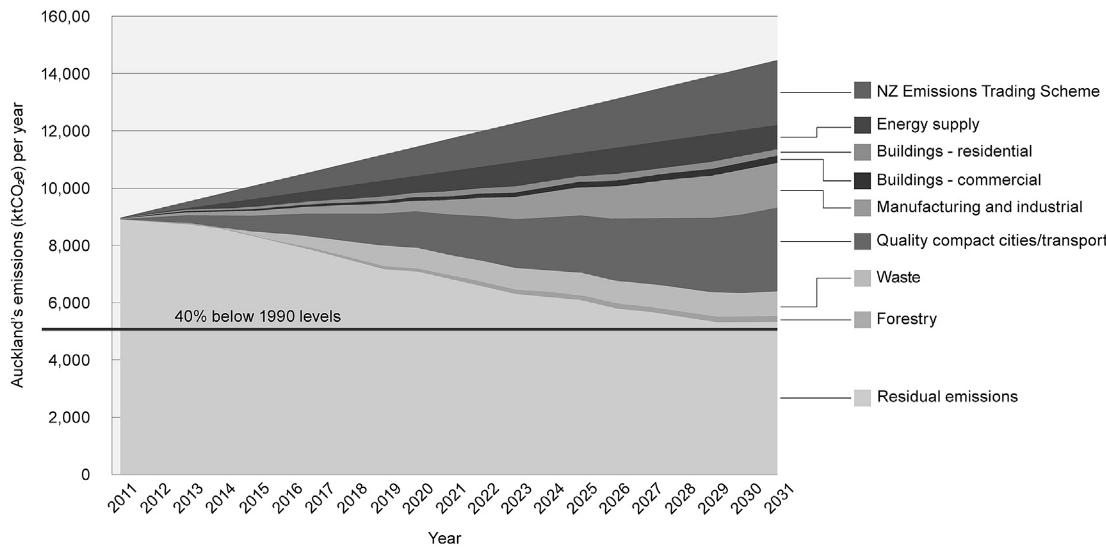

Fig. 1. The contributions of various mitigation actions envisioned in the Auckland Plan (ARUP, 2012a; b; Auckland Council, 2014b) for delivering a 40% reduction target for the period 2011 to 2031.

Firstly, the amount of carbon stored within a timber building was calculated from the volume of timber used to construct it. The amount of carbon stored within the future urban environment was then estimated by assuming the number of new buildings required within the given timeframe. Furthermore, knowing the amount of timber used within the urban environment, the same amount of carbon was conservatively assumed to be sequestered from the atmosphere by new trees replanted in sustainable forests to replace the ones harvested from existing forests to manufacture timber construction products. Carbon sequestered previously by harvested forests was excluded from this calculation.

Representative international mass-timber buildings made from engineered wood products (EWP) (e.g. Cross Laminated Timber, Glulam and Laminated Veneer Lumber) were chosen as exemplars to quantify the carbon benefits generated by the greater use of timber and EWP in the building and construction industry. There is a paucity of relevant empirical data and much of what does exist comes from reports and overseas analyses. Ideally, all the timber used in a complete building should be accounted for but, in many cases, available data were limited to structural timber. The following examples of different types of building were chosen:

- **Low-rise residential**: Bourne House Lane (185 m^2, 3 bedrooms, single family house in Kent, UK). Built using 50 m^3 timber in the structure. (Nash Baker Architects, 2011; Stora Enso, 2013b).
- **Medium-rise residential**: Fairmule House (a 5-storey solid-timber construction, incorporating 11 flats and 7 office units in London, UK). Built using 360 m^3 of timber in the structure. (CEI bois, 2011; Quai 2c Ltd, 2010; Zumbrunnen and Fovargue, 2012);
- **High-rise residential**: Bridport House (8 storeys containing 41 social housing apartments in London, UK). Built using 1576 m^3 of timber in the structure (Stora Enso, 2013a; Zumbrunnen and Fovargue, 2012);
- **School**: Cherry Hinton Junior School (2-storey school accommodating 210 students in South Cambridgeshire, UK). Built using 622 m^3 of timber in the structure (B&K Structures, 2014); and
- **Office** and **retail**: Canterbury University Biological Sciences Building (6-storey 4247 m^2 gross floor area building in Christchurch, NZ). Building design used 950 m^3 of timber by maximising the use of this material (John et al., 2009).

Note: The open-plan floor layout of the Canterbury University Biological Sciences Building is considered to allow for both office and retail (e.g. shop in shop) uses.

Based on these exemplars, a low-rise residential dwelling was defined as 1 building unit, medium rise as 11 building units, and high rise as 41 building units. Also, a school was defined as accommodating 210 students and office and retail building providing 4247 m^2 of gross floor area.

The specified volume of timber used for the construction of the building was used to calculate the long-term stored amount of CO_2 for each exemplar building. A CO_2 conversion rate of 1 m^3 of timber to 0.915 tCO_2 was assumed considering New Zealand grown *Pinus radiata* D.Don timber with a density of 500 kg/m^3 at 10% humidity (Nebel et al., 2009). The amount of carbon sequestration, carbon storage and GHG emissions reduction through the use of solid-timber technologies were then derived.

2.2.1. *Key assumptions*

The case study aims to demonstrate at a high level that future urban growth can be undertaken in an environmentally sustainable manner and moreover become a resource for GHG mitigation. Such an analysis involves many complex parameters, and data were sourced from existing buildings where possible or from peer-reviewed studies. The assumptions used are explicit (see list below) and the calculations are presented in detail so that alternative scenarios outside the scope of the current study can be explored. A conservative approach was taken to ensure the overall figures were representative.

For example, constant growth and sequestration rates for sustainably managed forests were assumed for their planting-growth-harvest-replanting cycles. However, in reality, it is acknowledged that the rate of carbon sequestered from the atmosphere by growing trees changes over time with natural variations in growth, sequestration and timber volume that depend on forest type, local climate, soil factors and management (Johnson and Coburn, 2010; Lippke et al., 2011). Also, we conservatively chose to consider only those the timber quantities that were transformed into long-term timber building products and the additional GHG mitigation benefits from the use of timber in short-term products or use of timber waste were not included. One of the objectives of this study was to raise awareness of the underlying potential of maximising the use of timber in future urban developments so it was assumed that 100% of forecasted Auckland building growth would be achieved using timber.

Type of timber:	*Pinus radiata*
Forest rotation:	30 years in New Zealand (Maclaren, 1993)
Tree growth rate:	constant over the entire rotation period
Timber density:	500 kg/m^3 at 10% humidity (Nebel et al., 2009)
Annual development demand:	100% of new buildings per annum as forecasted by the Auckland Plan of which: Low-rise dwellings: 2665 Medium-rise dwellings: 7330 High-rise dwellings: 4665 School students: 3300 Office area: 100,000 m^2 Retail area: 60,000 m^2
Volume of timber per building:	Low-rise residential: 50 m^3 Medium-rise residential: 360 m^3 High-rise residential: 1576 m^3 School: 622 m^3 Office and retail: 950 m^3
Carbon conversion rate:	m^3 of timber equals 0.915 t CO_2 (Nebel et al., 2009).
Carbon sequestration rate:	Constant throughout the tree-growth cycle

3. Results

3.1. Assessment of published literature

The literature was analysed in terms of the three components of UE: (carbon) sequestration optimisation, storage maximisation and emission minimisation (Equation (1)).

3.1.1. Sequestration optimisation and storage maximisation

A number of published studies have concluded that carbon storage in harvested wood products (HWP) is an additional benefit to the carbon sequestration provided by sustainably managed forests, and its role in mitigating CC should be enhanced. It is widely known that trees remove carbon from the atmosphere, accumulating it in the biomass until approaching maturity. Felling trees from sustainable forests before their growth and carbon sequestration rates slow down optimises the carbon sequestration. The sequestered carbon can then be stored long term by making long-life wood products from the felled timber such as construction timber products (European Commission, 2004, 2013; Grêt-Regamey et al., 2008; Lippke et al., 2010, 2011; Perez-Garcia et al., 2005; US EPA, 2002). Such long-life wood products delay the re-emission of sequestered carbon back into the atmosphere.

When considering carbon sequestration and storage from a life-cycle perspective, clearly a portion of the stored carbon will return to the atmosphere when products reach the end of their useful life and are either burned or sent to landfill. However, this process will be avoided or mitigated if timber products are recycled or reprocessed. Using old timber for energy production will return carbon to the atmosphere but will displace the use of fossil fuels and will, therefore, offset GHG emissions (Grêt-Regamey et al., 2008; Lippke et al., 2010; US EPA, 2002). In the New Zealand context, John et al. (2009) reported that landfilling waste timber would provide a net permanent storage of 44% of the original carbon while energy conversion would result in 35% avoided emissions for energy production.

3.1.2. Emission minimisation

Timber products have another benefit in addition to carbon sequestration and storage. The manufacture of some building materials involves higher levels of carbon emissions than others. Wood products present lower embodied energy from their manufacturing processes compared with other building materials (e.g. concrete and steel). Substituting these other materials with sustainably harvested wood typically reduces GHG emissions (Buchanan et al., 2012; Buchanan and Levine, 1999; Burnett, 2006; CEI bois, 2011; Gustavsson et al., 2010, 2006a, 2006b; Institute of Foresters of Australia (2011); Levine et al., 2007; Lippke et al., 2010, 2011; mgb Architecture+Design et al., 2012; Perez-Garcia et al., 2005; Sathre and O'Connor, 2010; Zumbrunnen and Fovargue, 2012). For example, an analysis by Buchanan and Levine (1999) showed that a 17% increase in wood usage in the New Zealand building industry could result in a 20% reduction in carbon emissions from the manufacture of all building materials, with a corresponding decrease in total national fossil fuel consumption.

Timber construction technologies are suitable for prefabrication and modular construction approaches, which contribute reducing overall wastage in both construction time and materials, and allow for more efficient future maintenance and refurbishment. Furthermore, prefabrication and modular construction also contribute to the lowering of a building's embodied energy and consequent carbon emissions (Lehmann, 2013; Peris Mora, 2007). A New Zealand study by Burgess et al. (2013) comparing four different construction approaches for a single storey 120 m^2 house found that cradle-to-site GHG emissions can be reduced up to 13% by using prefabricated panels compared with onsite construction. They concluded that "*enhanced environmental sustainability is a key reason to use prefabricated construction*".

3.1.3. Combining the benefits

Timber cannot completely replace other building materials like steel and concrete but the sustainability of future developments can be improved by maximising the use of timber in combination with other materials and components. Buchanan et al. (2012) compared concrete, steel, and timber construction materials for a three-storey building and showed that the GHG emissions for the timber option were 91%–96% lower than for concrete and 93%–97% lower than for steel due to carbon sequestration. Similarly, John et al. (2009) compared four building designs options: timber; steel; concrete; and TimberPlus (maximising the use of timber) for the construction of a new University of Canterbury laboratory building in Christchurch, New Zealand. The results showed that the global warming potential (GWP)[1] of the building materials required for the timber design was 38% lower than for concrete and 40% lower than for steel. Using a TimberPlus approach resulted in 64% less GWP than concrete and 65% less GWP than steel, without accounting for the carbon sequestered in the timber in either case. Furthermore, the extensive use of timber stored more carbon over the building's life-cycle than that was emitted during the manufacturing of all the other building materials (assuming 100% of the carbon was permanently stored in timber and EWP).

This analysis of published literature identified appropriate data that were then applied to a high-level case study that estimated the effect of timber building construction on the carbon balance in Auckland, New Zealand.

[1] Expressed in tonnes of CO_2 equivalent (tCO_2e).

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Table 1
Annual long-term carbon storage potential (*YBS - Yearly Building Storage*) using EWP to meet Auckland's building demand.

Building type	Development demand	No. units per building	Volume of timber (V) per building (m^3)	Number of buildings	Volume of timber (V/a) (m^3)	*YBS* Stored carbon [(V/a)*0.915] (tCO_2e)
Low-rise residential	2665 dwellings	1 dwelling	50	2665	133,250	121,924
Medium-rise residential	7330 dwellings	11 dwellings	360	666	239,760	219,380
High-rise residential	4665 dwellings	41 dwellings	1576	114	179,664	164,393
School	3300 students	210 students	622	15	9330	8537
Office	100,000 m^2	3,563m^2 floor space	950	28	26,600	24,339
Retail	60,000 m^2	3,563m^2 floor space	950	17	16,150	14,777
Total *YBS*						**553,350**

3.2. Case study analysis

3.2.1. Data inputs

Key data used for determining the potential long-term carbon storage in products for the construction of buildings are given in Table 1.

3.2.2. Carbon storage and sequestration calculations

The annual long-term carbon storage potential (*YBS - Yearly Building Storage*) is calculated from estimates of the quantity of timber required for each of the different annual building type development scenarios. *YBS* is then compared to Auckland's 2009 total GHGs emission.

The annual residential long-term carbon storage (505,697 tCO_2e) using EWP represents 5.7% of Auckland's 2009 total GHG (8.9M tCO_2e) (ARUP, 2012b). Additionally, the annual schools' contribution represents 0.1% of Auckland's total GHG emissions in 2009, the annual commercial buildings contribution (office and retail) forms 0.4%. Thus, long-term storage accounts for a 6.2% reduction in carbon emissions per year.

The *Yearly Building Storage (YBS)* was used to calculate the *Total Buildings' Storage at year y (TBSy)*; *Yearly Regrowth Sequestration at year x (YRSx)*; *Total Regrowth Sequestration at year y (TRSy)*; and the *yearly benefits from mitigation (YBFMx)* using the assumptions detailed above and the procedure detailed below.

The case study is based on a linear building-development scenario. For this reason, the annual carbon stored in timber products calculated above, *YBS* (553,350 tCO_2e), is a constant value (k). The total carbon stored in any one year of a linear new building-development scenario can be determined as follows:

$$YBS = k \times 1 \tag{2}$$

Therefore, the total carbon stored in buildings after y number of years since the first application of the proposed UE strategy of maximising the use of timber in construction (considering all the previous years of development), would be:

$$TBSy = k \times y \tag{3}$$

where:

TBSy = Total Buildings' Storage at year y;
k = YBS;
y = number of years occurred since the first application of the strategy.

So, when y=30 (the number of years of building development considered by the Auckland Council), the total buildings' storage *TBSy* would be:

$$TBSy = 552,592 \times 30 = 16,577,760\ tCO_2e$$

By assuming constant growth and sequestration rates, the carbon sequestered from the atmosphere throughout the planting-growth-harvest cycle can be calculated. At a specific year x, *YRSx* (*Yearly Regrowth Sequestration at year x*) for timber products used in one year of new building development would be:

$$YRSx = (k/n) \times x \tag{4}$$

where:

k is the annual carbon storage in products used for the proposed constant annual building development, which also equals the quantity of carbon sequestered by the considered forest at its harvest time; and
n is the forest growth time between re-planting and harvest.

Therefore, the forest storage pool at a specific year y *TRSy* (*Total Regrowth Sequestration at year y*) is the sum of the *YRSx* from the considered year and the *YRSxx* from the previous years' replantation (on-going yearly sequestration) i.e.:

$$TRSy = \sum_{i=1}^{y}((k/n) \times i) \tag{5}$$

where:

i is the number of years between the start and the end of the proposed development strategy (year 1 with $i = 1$) and the year y considered.

When this is applied to Auckland, using the calculated k value of 553,350 tCO_2e and a 30-year urban-development cycle time (y) proposed by the Auckland Plan as well as an average New Zealand plantation-forest rotation cycle for radiata pine of 30 (n) years (Maclaren, 1993), *YRSx* would be:

$$YRSx = (553,350/30) \times 30 = 552,592\ tCO_2e$$

and *TRSy* would be:

$$TRSy = \sum_{i=1}^{30}((553,350/30) \times i) = 8,565,176\ tCO_2e$$

Therefore, at the thirtieth year of development, the considered scenario would provide a forest-pool (carbon sequestration) benefit of 553,350 tCO_2e, which is equivalent to 6.2% of Auckland's 2009 emissions level. Continuation of the scenario after the thirtieth year with further urban development and forest replantation would result in the forest sequestration and storage benefits accumulating with time.

This high-level case study show that applying the UE strategy of maximising the use of timber to address Auckland's forecasted future growth would provide a yearly carbon-mitigation benefit through the combination of forest growth and long-term timber-product carbon pools. Their yearly mitigation benefits (*YBFMx*) at a year x would be equal to the sum of Equation (2) and Equation (4):

$$YBFMx = YBS + YRSx \quad (6)$$

For example, in the twentieth year would be:

$$YBFMx = 552,592 + 368,635 = 921,227 \ tCO_2e$$

with $x = 20$

while at the thirtieth year of urban development the *YBFMx* benefit would be:

$$YBFMx = 552,592 + 552,592 = 1,105,184 \ tCO_2e$$

with $x = 30$. At this time, the combined benefit (*YBFMx*) is equivalent to 12.4% of Auckland's 2009 emissions level.

YBFMx would be an additional mitigation benefit to the ones achievable with the "abatement pathway" strategies set by the Auckland Plan presented in Fig. 1 as shown in Fig. 2. *YBFMx* is represented by the lower two bands in Fig. 2 and is the sum of the additional annual carbon-storage potential in solid-timber buildings (*YBS*) and the additional annual forestry sequestration potential from the forests used to source the construction timber (*YRSx*). Incorporation of *YBFMx* into the Auckland Plan would result in attainment of the reduction target of 5.3M tCO_2e total emissions per annum (ARUP, 2012a) occurring 20% earlier than planned (in 2027 instead of 2031).

3.2.3. Emission minimisation calculations

In addition to the calculated carbon sequestration and storage benefits, using timber building materials and construction technologies enable emission-minimisation benefits to accumulate, which is the third component of Equation (1). By assuming the findings obtained by John et al. (2009) would be the same at an urban scale as for a single building then these same numbers can be transferred to the current study. Therefore an estimated 38%–65% of cradle-to-gate carbon emissions in manufacturing building materials could be saved by substituting high with low-carbon footprint materials. Similarly, assuming and transferring the results reported by Burgess et al. (2013) would generate 13% savings in construction GHG emissions by using prefabricated solid-timber building technologies as an alternative to the business-as-usual scenario of using onsite construction approaches.

Furthermore, various emission-minimisation scenarios are available at the end of a building's life. Recycling and reprocessing materials/components would elongate the lifespan of the carbon storage while landfilling and fossil fuel displacement would release back in the atmosphere only part of the carbon previously stored. Assuming and transferring findings of John et al. (2009) show that either a permanent carbon sink representing 2.7% of Auckland's 2009 GHG emissions or avoided emissions of 2.2% through fossil-fuel substitution could be generated when dismantling the buildings considered within this case study. These UE outcomes are summarised in Fig. 3.

4. Discussion

Various approaches have been proposed to reduce GHG emissions at an urban scale (Marshall, 2008). For example, carbon neutrality commonly involves measuring carbon emissions, undertaking emission reduction actions and offsetting residual emissions (Ministry for the Environment, 2007). In urban environments, this approach commonly focuses on the cost-effective reduction of emissions (e.g. waste minimisation, transport and new and existing buildings energy performance) and offsetting residual emissions by utilising some form of certified emission reduction credits from some other location (Marshall, 2008). The uniqueness of the proposed UE approach is that carbon-emission mitigation opportunities come from the use of materials and technologies that provide direct carbon sinks and carbon substitution. This occurs in addition to traditional from energy-efficiency and energy-sourcing strategies for a building where other concepts like Net Zero and Energy-Positive Buildings represent best practice. Technologies providing carbon sinks and carbon substitution can be successfully integrated with already-established mitigation practices considered by these other concepts. Moreover, UE can be applied to an urban scale, thus future urban developments can be considered as a resource for carbon mitigation. In this way, UE supports the establishment of an efficient and sustainable carbon pool that directly links forests regrowth to new urban development.

The high-level assumptions in the case study served to manage the many variables involved in the long-term timeframe and highly complex nature of future multiple-building developments at an urban scale. Even so, the results demonstrate that substantial additional benefits can be obtained by applying the UE approach to the Auckland Plan. Indeed, the values calculated above are likely to be conservative since the only carbon counted as a benefit was that in the long-term products constituting the building exemplars. Perez-Garcia et al. (2005) suggested that roughly 50% of the forest carbon in a harvest becomes timber and, therefore, available for long-term products like EWP for building construction. The remaining 50% of carbon that was not accounted for here is contained in short-term products or is landfilled. The use of short-term products might provide additional benefits depending on their use, life span and end-of-life scenarios. Hog fuel, for example, might be used for the production of energy thus avoiding carbon emission through substitution of fossil fuels. Alternatively, landfilling and decay would provide a permanent sink for some of the stored carbon (Lippke et al., 2010, 2011; Perez-Garcia et al., 2005). Consequently, the accounted amount of CO_2 sequestered from the atmosphere by new tree growth (forest storage pool) was related only to the volume of wood transformed into long-term products used in the construction-development scenario.

The current study built upon earlier work by John et al. (2009) and Buchanan et al. (2012) who showed that constructing buildings using timber generated far fewer GHG emissions than either concrete or steel. However, the current study was also conservative in focusing primarily on structural timber. In contrast, John et al. (2009) demonstrated that maximising the use of timber throughout a building can reduce the GWP of the building even further. Also, Burgess et al. (2013) demonstrated additional benefits from using prefabricated construction panels that have not been taken into account in the current study. Ultimately, such data will always be generalised since it is impractical to empirically calculate the amount of timber actually used in each future new building.

The high-level case study considered only the contribution of timber and EWPs as an additional strategy to the one considered by the Auckland Plan to reduce urban GHG emissions. In reality, the environmental benefits provided by such a strategy are likely to extend synergistically to social and economic areas, although these synergies and their relative benefits were not considered here. At the macro-scale, emissions associated with transport, waste disposal and industry all occur and move within city boundaries. Therefore, an urban environment could not be considered carbon neutral just because all the buildings within it are "zero carbon" (Riedy et al., 2011). To be truly comprehensive, the different characteristics and peculiarities of each urban environment must be considered when using a systems-integration approach to reducing GHG emissions at an urban scale and addressing CC.

Trees remove carbon from the atmosphere as they grow and

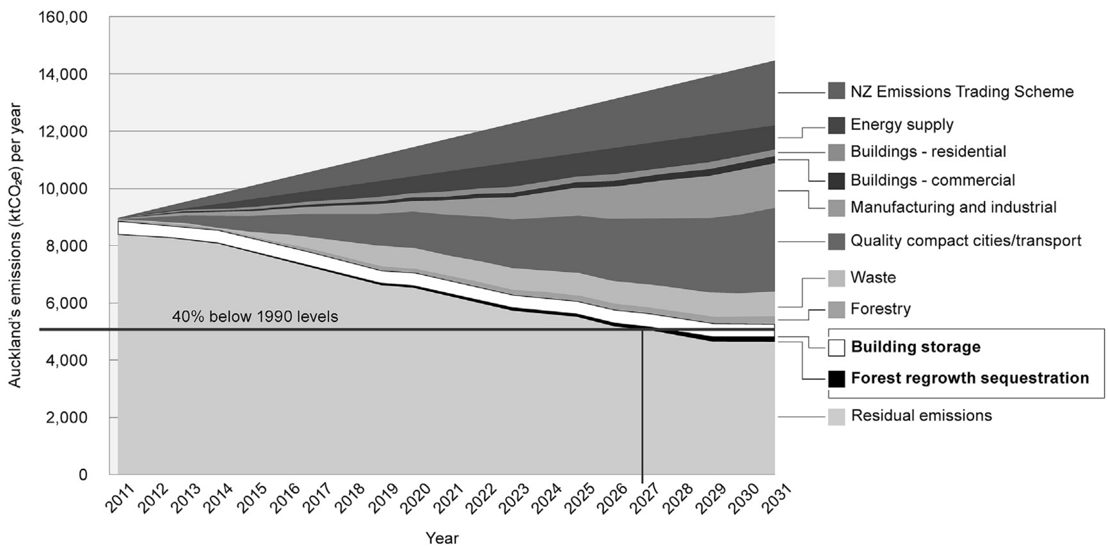

Fig. 2. The additional benefits of implementing an Urban Equilibrium strategy to the existing eight potential scenarios shown in Fig. 1. The vertical line shows that the goal of 40% reduction compared with 1990 levels is attained four years earlier when the Urban Equilibrium strategy is applied.

accumulate it as biomass until they approach maturity. This process is achieved sustainably by harvesting wood from a sustainably managed forest before tree growth slows down and using it in various timber products. In addition to those inherent removal and storage benefits, timber sourced from sustainably managed forests is a preferable building material because it can be used as a substitute for other materials that have higher embodied carbon footprints. At a systems level, using wood products generated from sustainably managed forests provides not only a stable and regenerating forest-carbon pool but also a growing (long-term) HWP-carbon pool that contributes to reducing and substituting GHG emissions. For these reasons, the UE concept proposes to maximise timber use in the construction of new buildings as part of future urban development as a strategy to mitigate urban GHG emissions and CC.

Within the UE approach, striving towards equilibrium is considered an essential precursor to achieving sustainability. This can be transferred to any level of decision making by the many stakeholders within an urban environment (e.g. planners, developers, governments and communities). Urban Equilibrium requires consideration of the urban landscape as an aggregate of structures that constitute an urban ecology that must exist, and therefore be designed, in equilibrium. There are many studies showing that urban governors/planners have a primary role in enabling cities' transformative change towards sustainable future developments through policy making and management (Hamann and April 2013; McCormick et al., 2013; Puppim de Oliveira, 2013). The key elements required to move towards a sustainable city include: political commitment; timing; financial aspects; physical qualities; stakeholder involvement; and environmental planning (Bayulken and Huisingh, 2015a). Accelerated desirable urban transformations also require an inclusive process utilising analysis, education, experimental urban development models, monitoring and consensus building among all the stakeholders

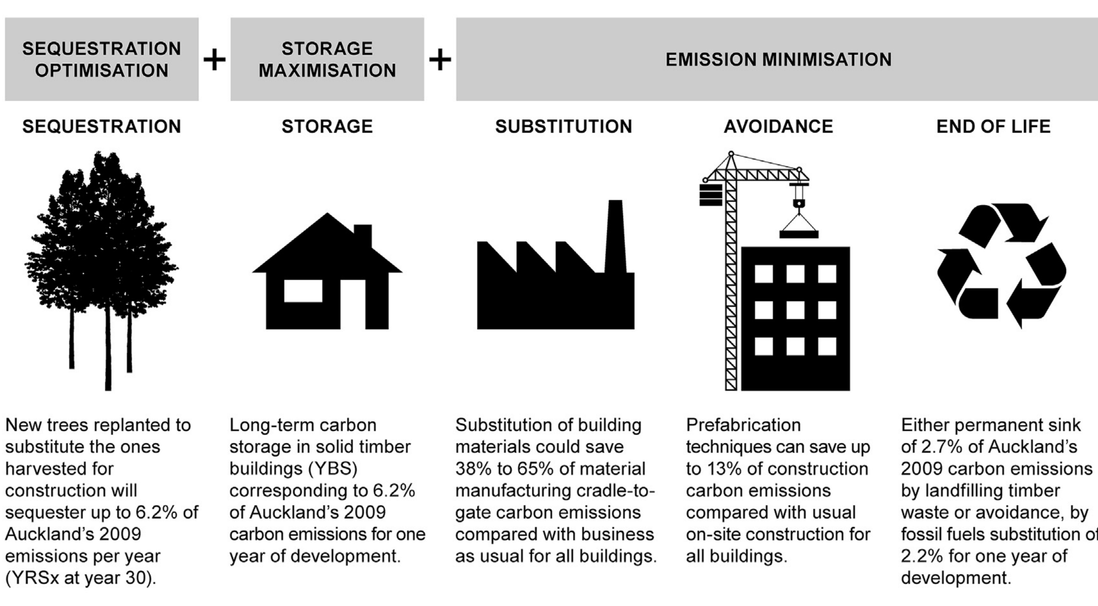

Fig. 3. Greenhouse gas mitigation benefits of applying Urban Equilibrium strategy for the Auckland City case study.

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(Bayulken and Huisingh, 2015b). Urban Equilibrium provides a framework for urban governance and decision making that includes an economic and social-development agenda while reinforcing good environmental management. Urban Equilibrium proposes an operational model for sustainable cities where the four pillars (economic and social development, environmental management and urban governance) of the United Nations sustainable city concept shown in Fig. 4 work synergistically together.

The integration of the four pillars fostered by UE generates the alignment shown in Fig. 5. Therefore, in UE economic development enhances social development to reinforce environmental management within a supportive urban governance framework. Such an approach requires urban governors to utilise an economic development agenda that considers the boundaries allowed by the natural environment's capability to support activities and development.

Analysis of the effects of decision making on each of the elements in Fig. 4 forms part of the UE approach at the urban level. For each proposed development, urban governors consider the effects on the elements and they are then better able to decide on appropriate courses of action. The outcome of applying the UE approach is a sustainable city represented by the pyramid in Fig. 6 where all four fundamental pillars (and implicitly all their elements) are key components of the structure. In this view, removing one component would cause the structure to collapse, or reducing one or more would unbalance the whole system. Therefore, a sustainable city operating within the symmetry of Fig. 6 can be considered as being in a state of UE.

The premises for achieving UE are:

- The achievement of balance requires a sequence of processes integrating the elements of the framework in Fig. 4;
- The four sides (Pillars) are equally important and imbalances need to be promptly rectified; and
- UE is a gradual process and is achieved by giving interventions time to show their effects.

The contributors to a sustainable city (see Fig. 4) of utilising a holistic UE approach are:

Fig. 5. Urban Equilibrium governance model for sustainable cities.

- Economic development: green productive growth; technology and innovation; production and distribution of renewable energy; and creation of decent employment;
- Social development: green housing & buildings; green energy access; education and health; and decent employment access;
- Environmental management: adaptation to and mitigation of CC; waste and recycling management; and air quality conservation;
- Urban governance: planning and decentralisation; and support of local and national links.

5. Conclusions and recommendations

Historical approaches for sustainable urban development have considered only the financial benefits of economic development without regard for the environment and the inequitable legacy for

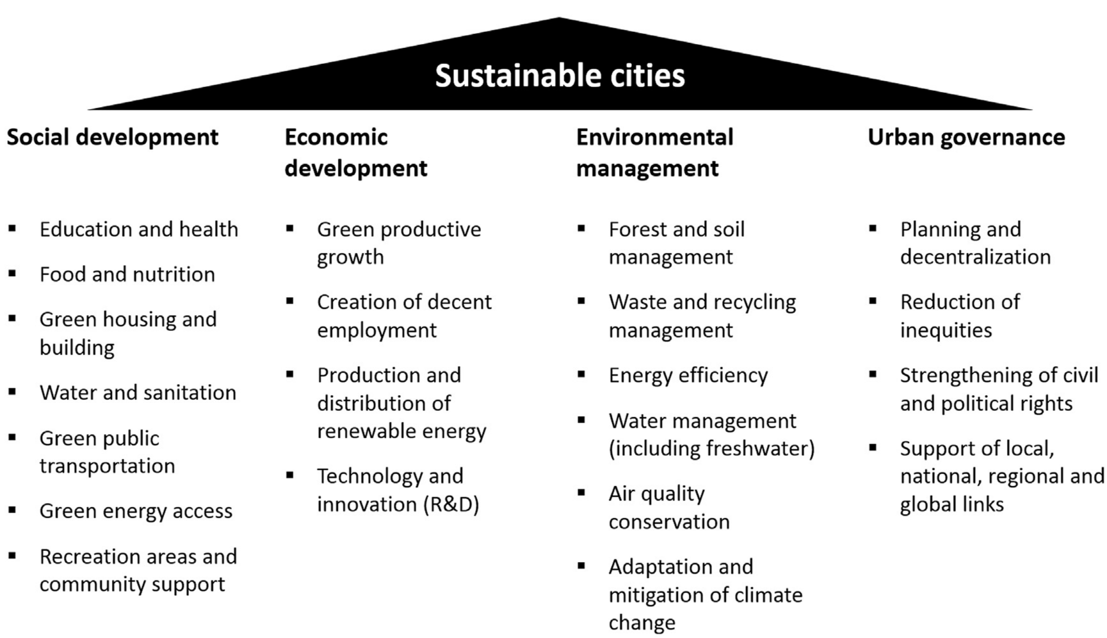

Fig. 4. Pillars and elements for achieving sustainability of cities. Source: United Nations DESA (2013).

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Fig. 6. Sustainable city model in state of Urban Equilibrium.

future generations. In contrast, the holistic UE approach contributes to achieving urban environmental sustainability by not only accounting for the various negative effects that economic development can have but also by re-defining the concept of growth to include a moral obligation to future generations. Carbon sequestration, storage and emission minimisation via substitution, avoidance, and end-of-life strategies are key components applied within the proposed UE approach for GHG emission and CC mitigation by future urban developments. The utility of this approach is the ease with which estimated benefits can be generated.

Applying an UE strategy of maximising the use of timber in future urban developments specifically to Auckland using empirical data, showed that:

- Auckland's 2009 carbon emissions could reduce over time: at the 30th year after the implementation of the strategy a yearly reduction of 12% of which 6.2% would be achieved if all new buildings were constructed using timber and 6.2% would be made achieved by the regrowth of trees in sustainable managed forests used to source the timber;
- Auckland's target of 40% carbon emissions reduction could be achieved 20% faster or 4 years earlier than planned;
- Putting waste construction timber in landfills provides a permanent carbon storage that is the equivalent of 2.7% of GHG emissions or to avoid emissions of 2.2% through fossil fuels substitution at the buildings' end of life; and
- GHG emissions could be decreased by 35–65% through appropriate design, material and construction process selection for new buildings.

These results provide a useful initial benchmark against which other scenarios can be compared. However, as with any complex model, the results from the current study could be refined in the future by using different assumptions. Although the case study was based in Auckland, this approach can be transferred and used to evaluate potential GHG mitigation benefits to any fast-growing urban environment worldwide. The UE strategy of considering future urban developments as potential carbon pool is complementary and easy to integrate with other strategies and policies for GHG mitigation.

All stakeholders in a building's life-cycle (e.g. developers, constructors, designers and owners) can ultimately embrace UE by fostering the use of materials and technologies that provide carbon storage, substitution and emissions reduction. However, urban governors have a primary role in managing cities and planning future developments through policy making. Urban Equilibrium requires them to utilise an economic development agenda that considers the boundaries allowed by the natural environment's capability to support activities and development. As a consequence, within UE, economic development enhances social development to reinforce environmental management within a supportive urban governance framework.

Urban Equilibrium provides a useful approach for increasing urban GHG mitigation while meeting a city's future growth needs. It uses the structures that define an urban environment as a balancing agent for urban GHG emissions by fostering the use of timber as a preferable building material. Thus, new urban developments act as carbon pools.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.12.020.

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