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BUILDING COMPONENTS AND BUILDINGS

Policy implications of time-differentiated climate change analysis in life cycle assessment of building elements in Aotearoa New Zealand

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Abstract

Purpose Climate change policies are increasingly including time-dependent carbon targets for different economic activities. However, current standards and guidelines for climate change assessment of buildings ignore these dynamic aspects and require use of static life cycle assessment (LCA). This research investigates how to better account for the timing of greenhouse gas (GHG) emissions and removals in LCAs of buildings and construction products, using a static and dynamic LCA case study of roofs, walls and floors in Aotearoa New Zealand residential dwellings.

Methods Static and dynamic LCA methods were used to assess the climate change impact of two assemblies each for external walls, ground floors and roofs used in stand-alone residential dwellings in Aotearoa New Zealand. Each assembly was modelled for a life cycle extending from material production, through to element construction, operational use, and final end-of-life treatment. Results were calculated as total GWP100 results for each life cycle stage, GWP100 results disaggregated into time periods, and as instantaneous and cumulative radiative forcing up to year 190. Sensitivity analysis was undertaken for the building reference service life, exposure zone, location, and end-of-life treatment.

Results and discussion Four time-related aspects were found to be particularly significant as regards their contribution to the final static LCA (sLCA) climate change results:

- Inclusion versus exclusion of biogenic carbon storage in landfill
- Modelling of end-of-life recycling activities using current versus future low or net zero carbon technologies (in module D)
- Building reference service life (50 versus 90 years)
- Choice of modelling parameters for landfilled timber and engineered wood products.

Use of dynamic LCA (dLCA) enabled priorities to be identified for climate change mitigation actions in the shorter and longer term, and showed that half of the assemblies achieved net zero carbon by year 190 (timber wall, steel wall, timber floor).

Conclusions Timing of GHG emissions and removals should be included in LCAs to support decision-making in the context of achieving targets set in climate change policies. In particular, LCA results should show ongoing biogenic carbon storage in landfilled timber and engineered wood products. Carbon footprint standards, guidelines and calculation tools should be prescriptive about building and construction product reference service lives, the EofL fate for different materials/products, and modelling of forestry and landfill activities, to provide a level playing field for stakeholders.

Keywords Climate change · Dynamic life cycle assessment · Building · Construction · Time

1 Introduction

In order to move towards a more sustainable future, the climate change impact of human activities must be significantly reduced. In 2021, the operation of buildings and manufacture of construction products contributed around

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37% of global carbon dioxide emissions (UN Environment Programme 2022). In Aotearoa New Zealand, nearly 9.4% of production-based, and 20% of consumption-based greenhouse gas (GHG) emissions were building-related in 2018 (MfE 2022c, p.228; Vickers and Fisher 2018). Therefore, it is important for this sector to identify activities, design strategies, materials, technologies and behavioural changes that will both reduce GHG emissions and mitigate remaining GHG emissions via carbon sequestration. To support decision-making, information is required about the climate change impact of alternatives, and this requires assessment of both GHG emissions and carbon sequestration (Hanssen et al. 2020; Kouchaki-Penchah et al. 2023).

Life cycle assessment (LCA) has been applied for many years in the building sector globally, and there has been increasing focus, in particular, on the carbon footprint of the building and construction sector due to concerns about climate change. For example, the NZ Ministry for Business, Innovation and Employment (MBIE) has initiated a Building for Climate Change (BfCC) programme in order to reduce emissions from constructing and operating buildings, and to make sure our buildings are prepared for the future effects of climate change (MBIE 2023). The Building Research Association of NZ (BRANZ) has initiated a Zero Carbon Built Environment research programme, and the New Zealand Green Building Council (NZGBC) has increasingly incorporated recognition of LCA and carbon footprinting into its building environmental rating tools Green Star and Homestar.

Internationally, LCA studies (including those for buildings and construction products) follow the requirements in the ISO 14040 and 14,044 LCA standards (ISO 2006a, 2006b), and carbon footprint studies are additionally guided by ISO 14067 ("Greenhouse gases – carbon footprint of products – requirements and guidelines for quantification", ISO 2018). In addition, LCAs of construction products and buildings may be guided by other international and/or European standards, depending on the location in which they are carried out. For example, building LCAs carried out in North America are likely to be guided by ISO 21931–1 (ISO 2022) and construction product LCAs will follow ISO 21930 (ISO 2017). In Aotearoa New Zealand, LCAs of buildings and construction products tend to follow the European standards that are equivalent to these ISO standards, being EN15978 (CEN 2011) and EN15804 (CEN 2019) respectively. Also, EPD Australasia requires adherence to EN15804 for construction products certified through its programme. Therefore, as environmental product declarations (EPDs) are becoming more widely used, EN15804 is increasingly seen as a de facto international standard for construction product LCAs in Aotearoa New Zealand (and Australia). However, although EN15804 is aligned with ISO 14040 and 14,044, it goes beyond them in providing some detailed methodological guidance on topics of ongoing research interest, including biogenic carbon (carbon contained in biomass) storage and modelling of future recycling activities.

In the LCA research community, there has been growing interest in addressing the role of time in assessment of carbon storage and delayed emissions of GHGs, as proposed by Nebel and Cowell (2003), Clift and Brandão (2008), Müller-Wenk and Brandão (2010), and Courchesne et al. (2010). Levasseur et al. (2010) proposed a dynamic LCA (dLCA) approach to account for time in LCA, and elaborated a method for climate change impact assessment that can be applied to land use, land use change, and forestry (Levasseur et al. 2012). More recently, the dLCA method has been discussed and applied in LCAs of construction products and buildings (e.g. see reviews by Arehart et al. 2021; Hoxha et al. 2020, Su et al. 2021).

Another recent development is the increasing use of time-defined climate change targets in policymaking through establishing Nationally Determined Contributions (NDCs). For example, in Aotearoa New Zealand, the Climate Change Response Amendment Act 2019 requires the setting of emission budgets in order to meet a 2050 goal of net zero GHG emissions (except for biogenic methane which is required to reduce to 24–47% less than 2017 emissions by 2050) (New Zealand Government 2019). The emission budgets for the periods 2022–2025, 2026–2030, and 2031–2035 have been published by the Ministry for the Environment (2022c).

Therefore, considering the potential significance of the timing of GHG emissions and mitigation efforts in the context of climate change policies that include climate targets, this research sets out to investigate the use of static and dynamic LCA approaches in the building sector. In this paper, static LCA (sLCA) refers to the conventional approach in LCA where GHG emissions and removals are aggregated regardless of when they occur, and dLCA involves disaggregating these emissions and removals along time lines (after Levasseur et al. 2012; Beloin-Saint-Pierre et al. 2020). Temporal variables that may be considered in dLCA applied to buildings include changes due to: occupant behaviour, energy mix and generation efficiency, degradation of materials and devices, carbon absorption, the expected service lives of components and devices, outside temperature (due to climate change), waste recycling rates, and technological innovations (Su et al. 2021). In this paper, we mainly focus on disaggregated assessment along timelines; however, we also model future changes in electricity mix during the Use phase of buildings (Sect. 4.2.3) and future carbon absorption by concrete (Sect. 4.2.4). Furthermore, we investigate the influence of service life of buildings (Sects. 2.3 and 5.4), waste management (Sects. 2.4 and 5.5), and technological innovations (Sects. 2.2 and 5.2).

This paper firstly discusses current knowledge and practice with respect to accounting for timing of GHG emissions and biogenic carbon storage in climate change assessment of construction products and buildings (Sect. 2). A case study of three types of building construction (roof, wall, floor) used in NZ stand-alone residential buildings (Sect. 3), is then used to explore the implications for the climate change results of different time-relevant modelling assumptions (Sect. 4). Section 5 provides recommendations about climate change assessment methods to support climate change policy-making for a more sustainable building and construction sector.

2 Current issues in accounting for time in building carbon footprint studies

2.1 Forestry modelling

For timber and engineered wood products, an important modelling issue concerns how to account for forestry. This requires consideration of how to model three broad pools of carbon in a forest: soil, live biomass in trees and other plants, and dead organic matter on the forest floor or in standing dead trees. In a natural forest, these pools will all be present and may be fluctuating about a steady-state carbon stock. In a new plantation forest planted onto grassland, the carbon stock in live and dead biomass will build up from a low base level, but some initial loss of soil carbon is likely (Fig. 1). At the time of harvest, some biomass leaves the forest as harvested logs and some is transferred to the dead organic matter pool as harvest residues, which then decay over time. While this decay takes place, the replanted forest accumulates carbon again in biomass.

There are (at least) three alternative methods for assessing carbon storage in a sustainably managed plantation forest that are illustrated in Figs. 1 and 2 using the example of radiata pine planted onto grassland:

1. Stand-level, historic: forest carbon is tracked from the time a forest is established on the land until the time of harvest (time = −28 to 0 years in Fig. 1, assuming the average rotation period for radiata pine in Aotearoa New Zealand). A biogenic carbon credit is associated with this cultivation, and may be associated with ongoing carbon storage in harvested timber products.
2. Stand-level, replacement: forest carbon is tracked from the time of harvest until the carbon removed from the forest as logs has been recaptured in the re-established forest (time = 0 to 28 in Fig. 1). A biogenic carbon credit is associated with this cultivation, and may be associated with ongoing carbon storage in harvested timber products.
3. Forest (or landscape) -level: this approach assumes that a forest under sustainable forest management is carbon neutral, with no net change in the carbon stored in the forest over longer timeframes (Fig. 2). As an example of this approach, Fig. 2 shows that the live biomass reaches a steady-state 'cycle' from the time of the first harvest, the soil reaches a steady-state 20 years after the second harvest ($t = 20$), and the dead organic matter continues to accumulate (although at a very low rate) even after 100 years—although it is very close to a steady-state cycle after the second harvest. Using this approach, no biogenic carbon credit is calculated for the forest plantation; however, the harvested timber may be associated with a biogenic carbon credit for ongoing carbon storage in harvested timber products.

Fig. 1 Carbon stocks in the soil, live biomass and dead organic matter in a plantation forest stand established in year −28 and first harvested in year 0

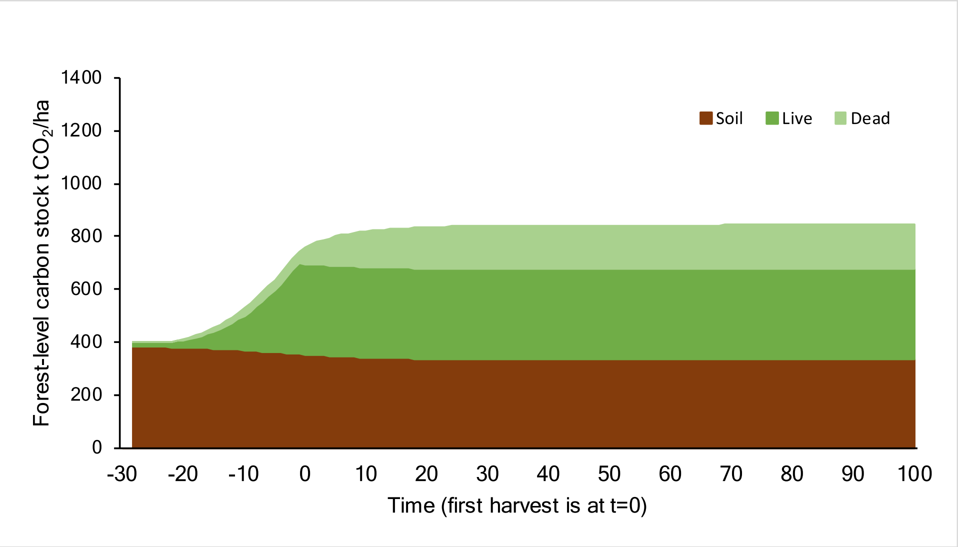


Fig. 2 Carbon stocks in the soil, live biomass and dead organic matter in a plantation forest established annually from year −28 to year 0, and first harvested in year 0 (includes stock in soil and live biomass in pre-afforestation pasture as the plantation is established)

For example, in a study of Danish silvicultural systems, Andersen et al. (2024) found that the choice of stand- versus forest-level modelling significantly influenced the embodied emissions results for the case study building (using a functional unit of 1 m^2 gross floor area) when utilising timber from clear-cut forestry systems (but not for continuous cover forestry systems). Other methodological choices discussed in the literature on climate change assessment for harvested wood include: discounting of future emissions and removals, displacement of future forest growth that would occur in the absence of human activities, and land displacement activities elsewhere due to forestry establishment in the studied area (Peng et al. 2023). The choice of one or other of any of these approaches may lead to different climate change results in both static and the dynamic LCAs due to differences in both the magnitude and the timing of biogenic carbon storage (see, for example, Hoxha et al. 2020; Head et al. 2021).

For this attributional study relating to forests planted specifically for timber production, the "stand level, replacement" approach is used following the recommendation of Hoxha et al. (2020); the influence on the dLCA results of using the "stand level, historic" approach is investigated in Sect. 5.6.3. The forest-level approach was not used because we consider it appropriate to account for this economic activity which, in Aotearoa New Zealand, only exists due to human management. No displaced land use is modelled and no discounting is applied. Furthermore, all harvested stands are assumed to be replanted, soil carbon is assumed to be in a steady-state and dead organic matter is assumed to decay aerobically, and so biogenic carbon outside the products is considered to be carbon neutral.

Regarding the issue of accounting for displacement of future forest growth in the absence of human activities (Peng et al. 2023; Maierhofer et al. 2024; Soimakallio et al. 2022; Vauhkonen 2023), in Aotearoa New Zealand radiata pine forests are commercially planted and there is a contractual requirement and/or commercial imperative to harvest them. It is unrealistic to assume an alternative future where they continue to grow and sequester more carbon in the absence of human activities. If harvesting plantation forests was not an option, the landowner would seek to earn an income from an alternative land use such as livestock farming. Furthermore, the paper examines the carbon impacts of alternative building materials, so a hypothetical scenario where there is no human activity and therefore no need for building materials is not relevant.

2.2 Modelling of future activities (modules B, C and D)

As buildings are generally long-lived product systems, there are likely to be ongoing maintenance, renovation and refurbishment, and end-of-life (EofL) activities that may occur many years after construction. It may be questioned whether these future activities should be modelled using current technologies (as specified in EN15804:A2 (CEN 2019, Sect. 6.3.5.5, Note 4; Sect. 6.4.3.3). It is (hopefully) more likely that manufacturing activities will have significantly lower emissions in future, and particularly in 50 or 90 years' time at the EofL of buildings currently being constructed. In Aotearoa New Zealand, two recent initiatives provide indicative support that this will be the case:

- Concrete NZ has published a roadmap for net zero concrete by 2050 (Concrete NZ 2023).
- The Aotearoa New Zealand government recently announced plans to partner with NZ Steel to convert its current primary steel manufacturing capability into sec-

> ondary steel production which would reduce Aotearoa New Zealand's total annual emissions by 1% (NZ Government 2023).

This raises a question about the most appropriate approach to represent modelled future activities in building carbon footprint tools.

2.3 Building reference service life

The service provided by a building inevitably requires inclusion of a time aspect. Buildings can be designed with the aim of achieving different lifetimes, according to their anticipated use (for example, hospitals and museums may be expected to have longer lifetimes). Previous Aotearoa New Zealand research estimated a residential service life of 90 years (Johnstone 1994). For LCA studies, the selected reference service life is more commonly 50 or 60 years (Potr Obrecht et al. 2019; Grant and Ries 2013). From a life cycle perspective, the choice of 50, 60 or 90 years, or some other time period, is significant when comparing alternative constructions with different lifetimes, because they are compared using a common functional unit which includes a specified time period e.g. 1 m^2.RSL or 1 m^2.year. For example, the impacts for any one year of building service life would double or halve with choice of a 50-year versus 100-year service life respectively (excluding maintenance, regeneration or refurbishment activities).

EN15804:A2 provides guidance about setting the RSL for construction products but does not specify a required construction product or building RSL. The NZ Building for Climate Change programme specifies a lifetime of 50 years shall be used in climate change assessment of a building (MBIE 2022b, Sect. 4.2).

2.4 Landfill modelling for timber

In Aotearoa New Zealand, burning of painted or treated timber is discouraged or banned because it typically contains chromate copper arsenate (CCA) or other chemicals. However, it may be burned in industrial facilities that have obtained resource consent approving its use, and that have demonstrated no adverse environmental effects. For example, Golden Bay utilises construction and demolition timber waste as an energy source in its cement kiln (Golden Bay 2024).

When timber or an engineered wood product is landfilled, the majority of its biogenic carbon continues to be stored over long time periods; smaller amounts are degraded which results in carbon dioxide and methane emissions. There is relatively little research on timber degradation rates in actual landfills or laboratory simulations, and the tree species included in studies are not always relevant to Aotearoa New Zealand, where over 90% of annual production is from radiata pine plantations. Wang et al. (2011) estimated a Degradable Organic Carbon fraction (DOCf) for untreated radiata pine timber of 0.001 in a reactor study that included other species. This value is used in Aotearoa New Zealand EPDs. Wang and Barlaz (2016) estimated DOCf values for *Pinus taeda* and *Pinus strobus* branches of 0 and 0.045 respectively, while Ximenes et al. (2018) provided DOCf values ranging from 0.006 to 0.09 for particleboard, MDF and plywood products excavated from landfills. These three studies are cited as the basis for the IPCC default DOCf value of 0.1 (IPCC 2019). Ximenes et al. (2019) suggested that an appropriate combined species DOCf for Australian landfills was 0.014; values for treated and untreated radiata pine were given as 0.0098 and 0.0015 respectively.

For landfill emissions in Aotearoa New Zealand, the Ministry for the Environment (2022a) provides parameter values for timber in managed landfills including for the DOCf and recovery efficiency. Table 1 shows that these values are quite different from the IPCC default values (IPCC 2019) and those used in published NZ EPDs, and that the MfE (2022a) values vary considerably between managed and non-managed landfills.

However, the latest version of EN15804 (2012 + A2:2019, hereafter EN15804:A2) (CEN 2019) takes a different approach, and specifies that degradation of biogenic carbon reaching a solid waste disposal site is to be modelled "without time limit" and that any remaining biogenic carbon is "treated as an emission of biogenic CO_2 from the technosphere to nature" (EN15804:A2, Sect. 6.3.5.5, Note 4). This contrasts with the previous version of EN15804 (EN15804:2012 + A1:2013, hereafter EN15804:A1) (CEN 2013) which was not prescriptive about how to model GHG emissions from landfill.

Table 1 Examples of parameters used to calculate landfill gas emissions from landfilled timber in various sources

	IPCC default values	NZ GHG Inventory (MfE 2022a)—managed landfill	NZ GHG Inventory (MfE 2022a)—non-municipal landfill	NZ EPDs (e.g. Abodo 2020; Carter Holt Harvey 2023a,b; Red Stag 2022a,b; WPMA 2019)
DOCf	0.1	0.14	0.5	0.001
Recovery efficiency, R	20%	68%	0%	40%

3 Use of static versus dynamic LCA

In a static LCA (sLCA), GHG emissions and removals are (usually) assessed over a fixed 100-year time horizon from the point of emission/removal. Thus, for example, an emission of 1 kg carbon dioxide during building construction (year 0) is assessed for its contribution to climate change up to year 100. And an emission of 1 kg during building demolition in, say, 50 or 90 years' time is assessed for its contribution to climate change up to year 150 or year 190 respectively. This means that there is an inconsistency in the time boundaries used for the assessment of the GHG emissions for product systems (such as buildings) that emit GHGs at various times over longer time periods (Levasseur et al. 2010). Moreover, in the sLCA method, all GHG emissions in CO_2eq are aggregated into one single value, which does not allow differentiating between shorter- and longer-term impacts.

In recognition of these variable timescales when using sLCA, it has been suggested that dLCA may be more suitable for assessment of product systems with long lifetimes and to account for the benefits of temporary carbon storage (Brander and Broekhoff 2023; Fouquet et al. 2015; Levasseur et al. 2010, 2012). In a dLCA, there is no fixed time period under consideration. This means that the climate change impact of different GHG emissions and removals can be assessed over different time horizons according to the needs of decision-makers. Dynamic LCA results are measures of radiative forcing (Watts per square metre, W/m^2) over time, as opposed to climate change impact measured in kg CO_2eq.; the radiative forcing (RF) can be reported as instantaneous RF or cumulative RF. An increasing number of studies are using dLCA to assess the climate change impacts associated with buildings (Su et al. 2021).

Thus, dLCA provides information about the timing of climate change impacts that is absent from sLCAs, and that is arguably becoming more relevant as countries increasingly adopt time-dependent climate change targets.

4 Case study of building assemblies

4.1 Goal definition and scoping

In this study, two assemblies each for external walls, ground floors, and roofs used in Aotearoa New Zealand stand-alone residential buildings, were assessed. Each assembly was modelled for a building reference service life of 50 years (and 90 years at sensitivity analysis), and extended from material production, through to element construction, operational use (including the Use energy difference between any pair of assemblies, see Sect. 4.2.3), and final end-of-life treatment. The constructions were assumed to be located in exposure zone C (inland coastal); exposure zones B (inland) and D (coastal) were modelled at sensitivity analysis. The zones relate to the severity of exposure to wind-driven salt, with B being low risk, C medium risk and D high risk (BRANZ 2023a).

For the floors, the unit of analysis was 1 m^2 of ground floor, with an area/perimeter ratio (A/P) of 2.5. For the walls, the unit of analysis was 1 m^2 of wall, assuming a clear wall construction (i.e. assuming no window or door openings, and no junctions with other building elements). For the roof, the unit of analysis was 1 m^2 of horizontal ceiling projected up through the roof. For all the assemblies, replacement of any materials with a service life shorter than the building reference service life was included in the study if it was required. Maintenance was not included in any of the constructions; repainting of the walls and ceiling takes place every few years but as this was common to all the wall and roof constructions it was omitted.

Data for constructions were adapted from the BRANZ CO_2RE tool (BRANZ 2023b) and are provided in the Supplementary Materials (SM1). In addition, SM1 provides detailed information on the approach taken for modelling energy use, where relevant to the study, and modelling of landfill processes.

At impact assessment, the climate change impact was assessed using the IPCC's GWP100 characterisation factors in the sLCA, and the dynamic characterisation factors provided by Levasseur et al. (2010) and updated from Myhre et al. (2013) for the dynamic LCA. For the dynamic LCA, results were calculated and presented for a time period of 190 years; this represents the longest service life modelled in the study plus 100 years. This is analogous to the approach taken in sLCA where the climate change contribution of different GHGs is assessed over 100 years from the point of emission.

4.2 Inventory analysis

4.2.1 Roof assemblies

The roof assemblies are a timber frame with a corrugated steel profile cladding (Fig. 3a) or concrete tiles (Fig. 3b). The assemblies have R7.0 glass wool insulation on top of the plasterboard ceiling between trusses and squashed into the perimeter (averaging R5.4 in the edge area due to some compression of the insulation). At an A/P ratio of 2.5, this should achieve a construction R value of around R6.8.

The external wall assemblies are for a 90-mm timber frame (Fig. 3c) and steel frame (Fig. 3d), both with a bevel backed timber weatherboard cladding. Both options have

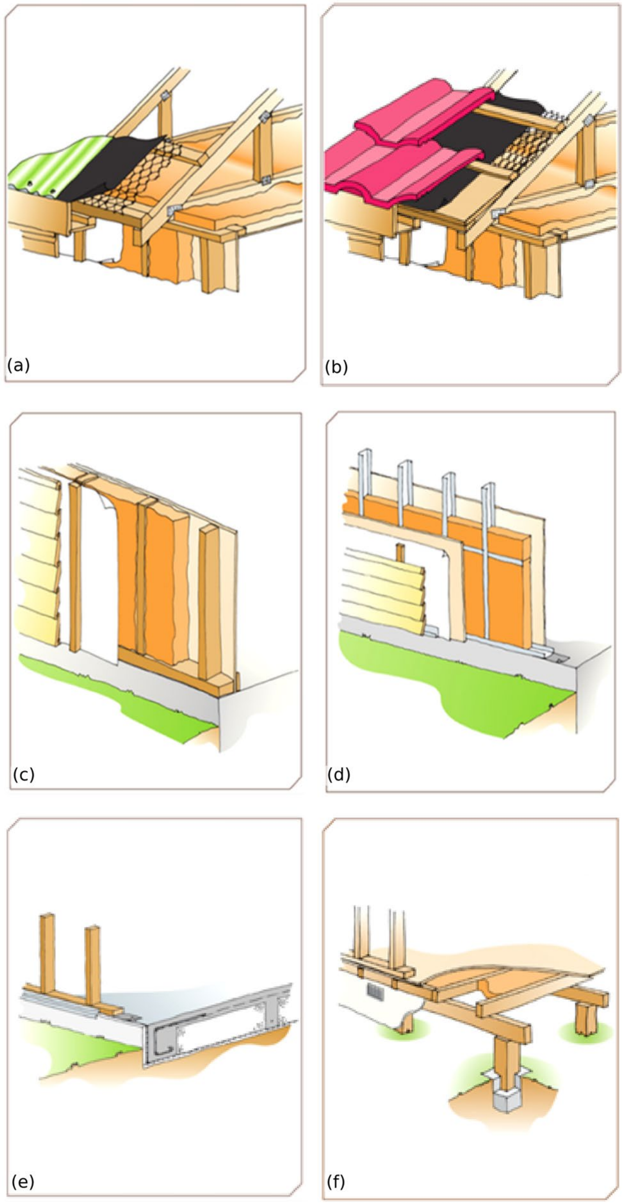


Fig. 3 (**a**) Roof assembly with steel cladding; (**b**) roof assembly with concrete tiles; (**c**) wall assembly with timber frame; (**d**) wall assembly with steel frame; (**e**) floor assembly using a concrete floor slab; (**f**) floor assembly using suspended timber floor. Colour key: brown=timber framing, yellow=timber weatherboard cladding, orange=insulation, black=roof underlay and mesh, green=steel cladding, red=concrete tiles, white=building wrap, grey=concrete. [Images sourced from BRANZ (2023e)]

material quantities based on 1 m^2 of external "clear wall" area, with a framing ratio of 14% (in contrast to measured built framing of 34% caused by, for example, presence of window openings and junctions (Ryan et al. 2019)). The construction features R2.8 Pink Batts glass wool insulation between the framing, providing an R2.0 construction *R* value.

The ground floor assemblies are an unheated concrete slab floor (Fig. 3e) and a suspended timber floor (Fig. 3f). The concrete floor assembly has an R1.6 construction *R* value. Concrete used in the construction is assumed to contain Ordinary Portland Cement (OPC) supplied by Golden Bay Cement and contains no secondary cementitious material (SCM) content. The suspended timber floor option includes materials below the floor level, including an enclosed sub-floor perimeter, timber piles and concrete pile bases. The suspended timber floor has a construction *R* value of R3.4.

4.2.2 Materials used in assemblies

Table 2 provides the quantities of different materials and construction products used in the assemblies, and Table 3 gives the replacement times for specific components in each assembly for different exposure zones and building RSLs.

For forestry, the stand-level replacement approach was followed (Sect. 2.1) and it was assumed that the forest was in a longer-term steady state as regards soil carbon and dead organic matter, i.e. an established forest not in its first rotation. A steady-state assumption is considered appropriate for Aotearoa New Zealand's moist temperate conditions where dead organic matter decay is relatively fast and soil carbon is not expected to accumulate under a constant land use (MfE 2021). Data on forestry activities, harvesting and post-harvest processing (modules A1–A3) were taken from New Zealand EPDs (see SM1 for data sources). The total amount of carbon stored in the timber used in the assemblies was also taken from these EPDs for different timber products, and used to calculate the biogenic carbon storage credit in the results. For the dLCA, carbon sequestration in the forest was allocated across the different cultivation years in proportion to the sequestration rate for growing trees in a yield table published by MfE and used for GHG inventory reporting under the United Nations Framework Convention on Climate Change (MfE 2022b).

For the main steel products in the assemblies (corrugated steel for steel roof, steel framing for steel wall, reinforcing steel for concrete floor), data were based on manufacture at New Zealand Steel's Glenbrook plant (and, additionally, Pacific Steel's Ōtāhuhu plant for the latter) in Auckland. They included a mix of published EPD data and updated unpublished EPD data (provided by NZ Steel) (see SM1 for data sources). Data for other minor steel materials included in assemblies (such as fixings, for example) were based on overseas manufacture (see SM1 for data sources). To back-calculate the disaggregated carbon dioxide, methane and nitrous oxide emissions from the aggregated EPD results, the relative GHG contributions to corresponding processes in the ecoinvent 3.7 (cut-off) datasets were utilised.

Table 2 Different materials used in assemblies (kg per m2)

Material	Truss roof [1]				External wall [3]				Ground floor			
	Steel cladding	Notes	Concrete tiles	Notes	Timber frame	Notes	Steel frame	Notes	Suspended timber	Notes	Concrete slab	Notes
Timber / engineered wood	9.8		13.3		25.8	4	19.2	4	35.0	6	0.5	7
Steel	4.5		0.3		0.5		3.9		0.6		6.2	
Concrete (in-situ)	0.0		0.0		0.0		0.0		32.9		372.3	
Insulation	4.3		4.3		1.1		2.5	5	2.6		2.2	
Plasterboard	9.8		9.8		7.7		7.7		0.0		0.0	
Concrete tiles	0.0		52.5	2	0.0		0.0		0.0		0.0	
Other	0.1		0.2		0.3		0.3		4.2		374.3	8
Total	**28.5**		**80.4**		**35.3**		**33.6**		**75.3**		**755.5**	

Notes

1. Represents 1 m^2 of horizontal ceiling area
2. Includes underlay and battens
3. Based on a clear wall construction (14% framing ratio)
4. Includes bevel back weatherboard cladding
5. Includes XPS thermal break strips
6. Includes particleboard floor
7. Includes plywood formwork and pegs
8. Includes basecourse and sand blinding

Table 3 Timing of replacement of products in assemblies over 50 and 90-year service lives (year from year 0)

Service life (years)	Exposure zone	Wall (wood)	Wall (steel)	Roof (steel)	Roof (concrete)	Floor (wood)	Floor (concrete)
50	B (inland)	-	-	-	-	-	-
	C (inland coastal)	-	-	30	-	-	-
	D (coastal)	-	-	20,40	-	-	-
90	B (inland)	60	60	$45^{\#}$	75	-	-
	C (inland coastal)	60	60	30,60	75	-	-
	D (coastal)	60	60	20,40,60,80	75	-	-

$^{\#}$ A replacement is not modelled in this study as the 45-year service life is sufficiently close to the 50 year building reference service life that it can be assumed not to take place

For concrete manufacture, in situ concrete is present in the concrete slab and suspended timber floors (in the latter case, in the timber pile bases). It is additionally present in a precast form in the concrete tile truss roof construction. Data for in situ concrete production were based on cement made in Aotearoa New Zealand by Golden Bay Cement (see SM1 for data sources). For this study, use of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS) and fly ash, as cement replacements, was not considered. Generic ecoinvent (version 3.1) data was used to represent manufacture of concrete roof tiles, adapted with Ordinary Portland Cement (OPC) made in Australia (see SM1 for data sources).

Data for other materials in constructions, for example glass wool insulation and plasterboard interior linings used in wall constructions, were mainly obtained from EPDs. Sources are provided in SM1. Build ups were selected to represent current New Zealand construction rather than investigating less commonly used alternatives, for example, wood fibre insulation or plywood interior wall linings.

4.2.3 Use energy

The assemblies were selected to achieve (at least) updated minimum construction *R* values from the 5th edition of H1/AS1 (MBIE 2022a) in climate zones 1 (Auckland) and 5 (Christchurch), as follows:

- Roof: R6.6 in climate zones 1 to 6
- Wall: R2.0 in climate zones 1 to 6
- Floor: unheated concrete slab on ground R1.5 in climate zones 1 to 4, R1.6 in climate zone 5 and R1.7 in climate zone 6. Other floors (including suspended timber floors) R2.5 climate zones 1 to 3, R2.8 climate zone 4 and R3.0 climate zones 5 and 6.

Where there were differences in thermal mass and/or construction R values between each of the roof, wall or floor assemblies, an energy simulation (using EnergyPlus v22.1.0 (NREL 2023)) was carried out to account for additional energy demand due to heating and cooling in one assembly, compared to the other assembly (SM3). For the roofs, there was no difference in Use energy between the two assemblies.

For the walls, the timber wall was used as a baseline, and the difference in Use energy compared with the steel wall was added to the steel wall results. For the floors, the concrete floor was used as a baseline, and the difference in Use energy compared with the timber floor was added to the timber floor results.

Use energy was modelled based on Aotearoa New Zealand electricity, using the life cycle method and model developed by Bullen (2020) and provided in the BRANZ module B6 datasheet (BRANZ 2021). The Reference scenario from the MBIE Electricity Demand and Generation Scenarios report (MBIE 2019) was used, assuming a Use phase starting in 2025, and using the 2050 emissions per kWh for the years beyond 2050 (as post-2050 emissions were not modelled in the MBIE report). The time-differentiated ("consequential") impact factors were used because they attribute the impacts of constructing new electricity generation infrastructure to the year it is commissioned, rather than assigning a portion over the life of the asset. Therefore, no impacts are assigned to generating and transmission infrastructure that already exists, as the emissions have already occurred.

4.2.4 Concrete carbonation

Concrete carbonation can occur in module B1 (Use stage), module A5 (beginning in year 1 if concrete material becomes waste during construction and is sent to landfill), module B4 (if replacement includes concrete as a new installation and/or as a waste stream), and module C4 (beginning the year after the service life ends if concrete goes to landfill). The method follows that described by Elliot et al. (2024a) which is an LCA approach based on the work of Souto-Martinez et al. (2017, 2018). This allows for the calculation of the depth of carbonation front over time, and thus the change in concrete carbonation each year. Furthermore, this method incorporates detail of exposure conditions based on Monteiro et al. (2012), allowing for the different rate of carbonation between waffle slab floor and roof tiles. Therefore, it was used in this study (see SM2).

4.2.5 End-of-life management

Waste is generated during construction, replacement of parts, and at EofL. For the three main materials used in the assemblies, Table 4 lists the modelled proportions wasted at construction site and their fates, and Table 5 shows end-of-life treatments modelled for replacements and at building demolition.

For landfill emissions, we accounted for timber products (sawn timber, plywood, particleboard), and for carbonation of landfilled concrete products (SM2). Other landfilled materials were treated as insignificant from a climate change perspective in module C4 and not modelled. For landfilled

Table 4 Construction site waste scenarios used in the study (BRANZ 2023c)

Life cycle stage	Timber	Steel	Concrete
Construction waste (module A5)	10% wasted at construction site: 85% goes to landfill, and 15% is recycled (displacing primary timber production)*	1% wasted at construction site: 100% displaces primary steel production in a blast furnace*	4% wasted at construction site: 90% goes to landfill and 10% is washed and the aggregate recycled (displacing primary aggregate production)

*Updated from BRANZ (2023c)

Table 5 End-of-life modelling of building demolition waste (BRANZ 2023d)

Life cycle stage	Timber*	Steel	Concrete
End of service life	100% to landfill	85% recycled which displaces primary steel production in a blast furnace 15% landfilled	80% landfilled 20% recycled by crushing to create secondary aggregate (displaces primary aggregate production) and steel reinforcing sent to recycling (displacing primary steel production in a blast furnace)

* Sawn timber, plywood, particleboard

timber, the approach for calculating landfill methane emissions in MfE (2022a) was followed using the MfE parameter values for timber in managed landfills (SM4). A sensitivity analysis was undertaken for use of alternative DOCf values (Sect. 4.3.3). For the dLCA, methane emissions from timber decay in landfill were modelled following Wilson et al. (2020).

All waste was modelled as travelling 48 km to a landfill using the heavy truck emission factor in MfE (2022a). For the Auckland and Christchurch scenarios, the distances were 30 and 65 km respectively.

4.2.6 Modelling module D

The module D results were modelled assuming displacement of equivalent primary material production based on current average technologies:

- Timber (only relevant for the small amount of timber recycled/reused from the construction site, see Table 4): the recycled/reused timber was modelled as a biogenic carbon emission in module A5 (following EN16485, Fig. 1, Fig. 2), and a net zero (or near to net zero) biogenic carbon saving in module D. The module D calculation assumes displaced sustainable forest which is offset by the biogenic carbon credit associated with the recycled timber being used in a subsequent system.
- Steel: recycled steel was represented as displacement of blast furnace steel production plus recycling in an electric arc furnace (as commonly done in existing steel EPDs).
- Concrete: recycling into secondary aggregate was represented as displacement of primary aggregate production (crushing of the EofL concrete to produce secondary aggregate omitted in this study due to its relative insignificance compared with other concrete-related activities).

As a simplification, materials were modelled as having reached their "end-of-waste state" without modelling processes that may be necessary (in module A5 or C3) to reach this point. For example, washing of uncured concrete (module A5) to recover aggregate, and crushing of cured concrete (module C3), were omitted from the analysis. These are activities with relatively small climate change impacts compared with other activities in the life cycle of concrete, and so their omission would not affect the conclusions of the study.

4.3 Impact assessment results

The baseline results presented in Sects. 4.3.1 (sLCA) and 4.3.2 (dLCA) are for the assemblies with a 50-year building RSL, using average NZ transportation distances, and assuming an exposure zone C (inland coastal) location. The results are shown including a credit for continued biogenic carbon storage in landfilled timber i.e. following EN15804:A1. Section 4.3.3 shows the sLCA results when various parameters are changed.

4.3.1 Static LCA climate change results

The sLCA climate change results for the concrete roof, timber wall, and timber floor have the lowest baseline climate change results when using sLCA (Table 6). The **net biogenic carbon storage** contribution is relatively large for all the assemblies except the concrete floor; this is due to the storage of biogenic carbon in the timber in the assemblies and subsequently in landfill. The **module D** results are relatively significant for four of the six assemblies; for the timber wall and timber floor the smaller contribution is due to the negligible recycling activities associated with these assemblies.

The results are shown in Fig. 4 as bar charts, highlighting the different life cycle stages that contribute to the respective climate change results. The total net impact for each bar, including module D, is indicated with a black dot; the total net impact excluding module D is indicated with a black cross (corresponding to the "Total" columns in Table 6). The majority of the fossil climate change result is contributed by modules A1-A3, and B4 for replacement of the steel roof, and there is a smaller contribution by modules A4-A5. The contribution due to differences in Use energy (module B6) between pairs of assemblies is 5% of the module A1-C4 fossil climate change result for the wall assemblies (steel

Table 6 Whole-of-life climate change result (kg CO_2eq/m^2) by greenhouse gas for each assembly accounting for biogenic carbon storage

Assembly	Total net CO_2*	Total net CH_4 (CO_2-eq)*	Total net N_2O (CO_2-eq)*	Total net climate change impact (CO2-eq)*	Total net biogenic contribution ($CO_2 + CH_4$) (CO_2-eq)	Net biogenic carbon storage (CO_2 only) (CO_2-eq)	Additional module D contribution (CO_2-eq)
Roof (steel)	24.33	6.52	0.26	31.10	-12.91	-16.44	-8.21
Roof (concrete)	0.00	6.37	0.16	6.52	-17.20	-21.98	-2.85
Wall (timber)	-28.71	10.40	0.16	-18.15	-32.84	-42.13	-0.12
Wall (steel)	-6.54	8.87	0.22	2.55	-24.69	-31.64	-2.91
Floor (timber)	-18.32	16.05	0.30	-1.96	-39.04	-51.87	-1.40
Floor (concrete)	77.70	6.42	0.42	84.54	-0.49	-0.65	-8.96

* Total net climate change impact includes both fossil and biogenic GHG emissions, and biogenic carbon storage (from atmospheric CO_2), but excludes module D.

higher than timber wall), and 19% of the module A1-C4 fossil climate change result for the floors (timber higher than concrete floor). Counteracting these contributions, carbonation of concrete is equivalent to 10.3%, 1.9% and 2.6% of the total A1-C4 modules climate change (excluding biogenic carbon storage) result for the concrete roof, timber floor, and concrete floor respectively.

Figure 5 shows the same results as those in Fig. 4 but disaggregated to identify the time period in which emissions occur. The negative biogenic carbon bar (coloured red) in years 1–28 for all the assemblies except the concrete floor is due to carbon sequestration in the growing forest, and the smaller positive values from year 51 onwards are due to methane and carbon dioxide emissions from timber degradation in landfill. Note that, for concrete that goes to landfill, there are carbonation climate change results from year 51 through to the point that maximum carbonation is reached or year 190 — whichever comes first — but the small values mean they cannot be seen on all the graphs. In general, the graphs show that the majority of the fossil climate change result is related to activities occurring in year 0, except for the steel roof where replacement occurs at year 30. The majority of the biogenic climate change result is due to the forest cultivation in years 1–28, and there are smaller contributions in years 50 onwards due to landfill emissions. The module D contributions are accounted at year 50 (and are due to recycling activities).

4.3.2 Dynamic LCA results

In Fig. 6, the instantaneous results show the change in RF associated with each pulse emission in each year up to year 190. As the majority of each gas is emitted in year 0, this is the largest instantaneous impact. For the assemblies containing significant quantities of timber (i.e. all the assemblies except the concrete floor), the instantaneous curves decrease due to forest sequestration up to year 28, then increase at year 50 due to landfill emissions, and then decline up to year 120 as these landfill emissions decrease.

For the assemblies containing significant quantities of steel as well as timber (steel roof, steel wall), additionally there is a decrease in the instantaneous curve at year 50 due to recycling activities for the results including module D. For the steel roof, there is an increase at year 30 due to replacing the steel cladding.

For the assemblies containing significant quantities of concrete (concrete roof, concrete floor), the results vary depending upon the assembly. For the concrete roof, there is a decrease in the instantaneous curve up to year 28 due to forest sequestration for timber used in the framing, and degradation or removal from the atmosphere of GHGs emitted during construction activities. There is a small drop at year 50 due to displaced primary aggregate manufacture, and then an increase due to landfill emissions associated with the landfilled timber frame. For the concrete floor, the decrease from year 1 to year 50 is due to the declining contribution of GHGs emitted primarily during construction activities.

The cumulative impact results show that the assemblies containing most timber (timber wall, timber floor) become net carbon negative within the building service life. For the other assemblies, their cumulative RF results continue to increase up to year 190 (steel roof, concrete floor), or slowly decline up to year 190 (concrete roof, steel wall), depending upon the relative contributions from GHG emissions, carbonation, and biogenic carbon storage in timber and/or engineered wood products.

4.3.3 Sensitivity analyses

Sensitivity analyses were conducted to investigate the importance of parameters that may vary under different building contexts in Aotearoa New Zealand:

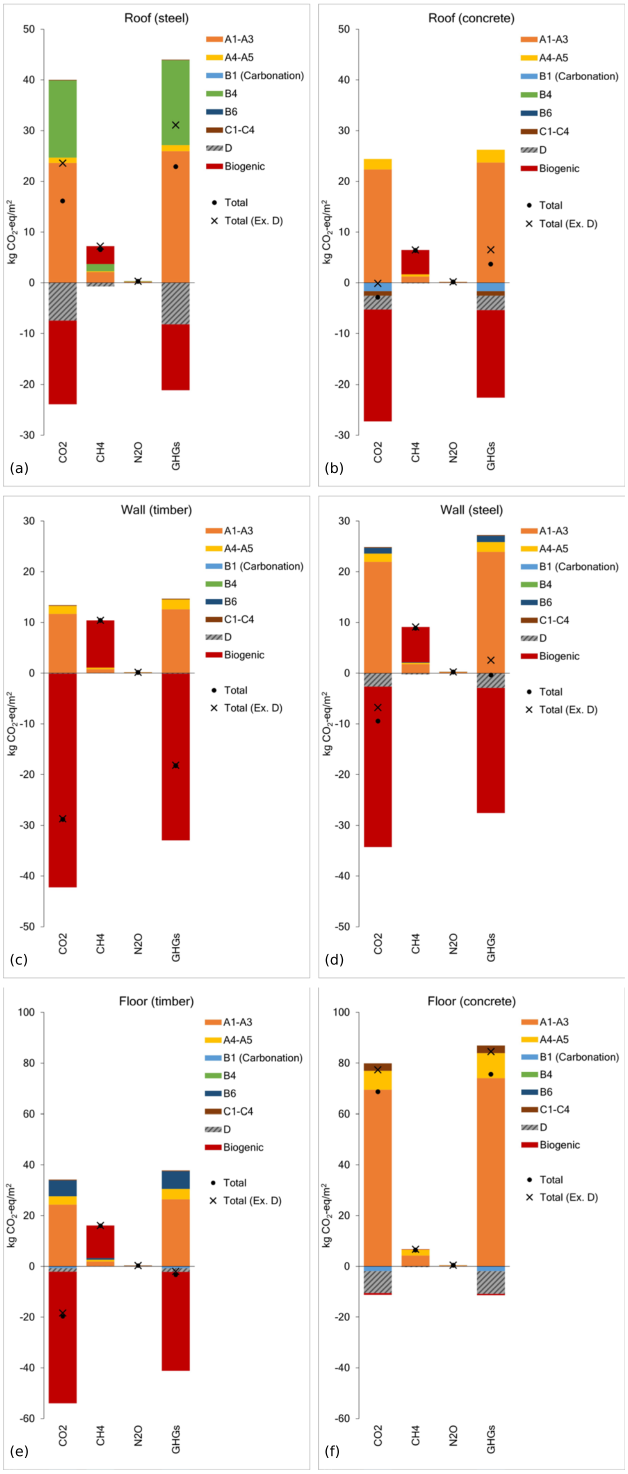


Fig. 4 sLCA climate change results

- SA1: 90-year reference service life
- SA2: exposure zones B (SA2.1) and D (SA2.2)
- SA3: role of location—investigated by modelling different distances, Use energy, and landfill-specific characteristics for assemblies in Auckland (SA3.1) and Christchurch (SA3.2)
- SA4: End-of-life parameters: IPCC values used in landfilling calculations (SA4.1); NZ EPD values (SA4.2); direct release of landfill methane (SA4.3); non-municipal landfill (SA4.4); incineration instead of landfilling at timber end-of-life (including displaced heat from natural gas as per current NZ EPDs) (SA4.5).

SA4.1 and SA4.2 investigate the influence of using IPCC and typical NZ EPD waste wood decay parameters instead of the MfE parameters used in the baseline. SA4.3 calculates the results assuming 100% direct release of GHGs from the landfill, compared to the baseline which assumed 68% landfill gas recovery. SA4.4 models the situation with a non-municipal landfill (using MfE parameters). SA4.5 calculates the results if end-of-life timber is burned in an industrial facility, displacing use of natural gas (as modelled in existing NZ EPDs, e.g. Abodo 2020; Carter Holt Harvey 2023a, b; Red Stag 2022a, b; WPMA 2019). Further details can be found in Sect. 2.4 and SM4.

Each sensitivity analysis was undertaken independently by varying one or more parameters in the baseline results. The sLCA results are presented in Fig. 7 as the net climate change impact values (modules A–D total) for each scenario per assembly (see SM5 for table of results), and in Fig. 8 as the net climate change impact values but excluding module D.

Figure 7 shows that the different scenarios cause up to a nine-fold difference in climate change results across five of the six assemblies. For the sixth assembly, the concrete floor, there is little variability between the scenario results because there is no replacement of the concrete floor when the service life is extended to 90 years, it is not affected by the exposure zone, and both the location-based variability and changes in landfill parameters have a negligible effect on the overall climate change results. For the results excluding module D, Fig. 8 shows that all the results increase due to removal of the module D credits; SA4.5 now has the highest result for five of the six assemblies as the displaced natural gas is no longer credited to the assemblies.

5 Discussion

5.1 Modelling of landfilled biogenic carbon storage

As noted in Sect. 2.2, the latest version of EN15804 (CEN 2019) requires modelling of all landfilled biogenic carbon as an emission of biogenic carbon dioxide. This is not representative of the Aotearoa New Zealand situation where a significant proportion of discarded timber and engineered

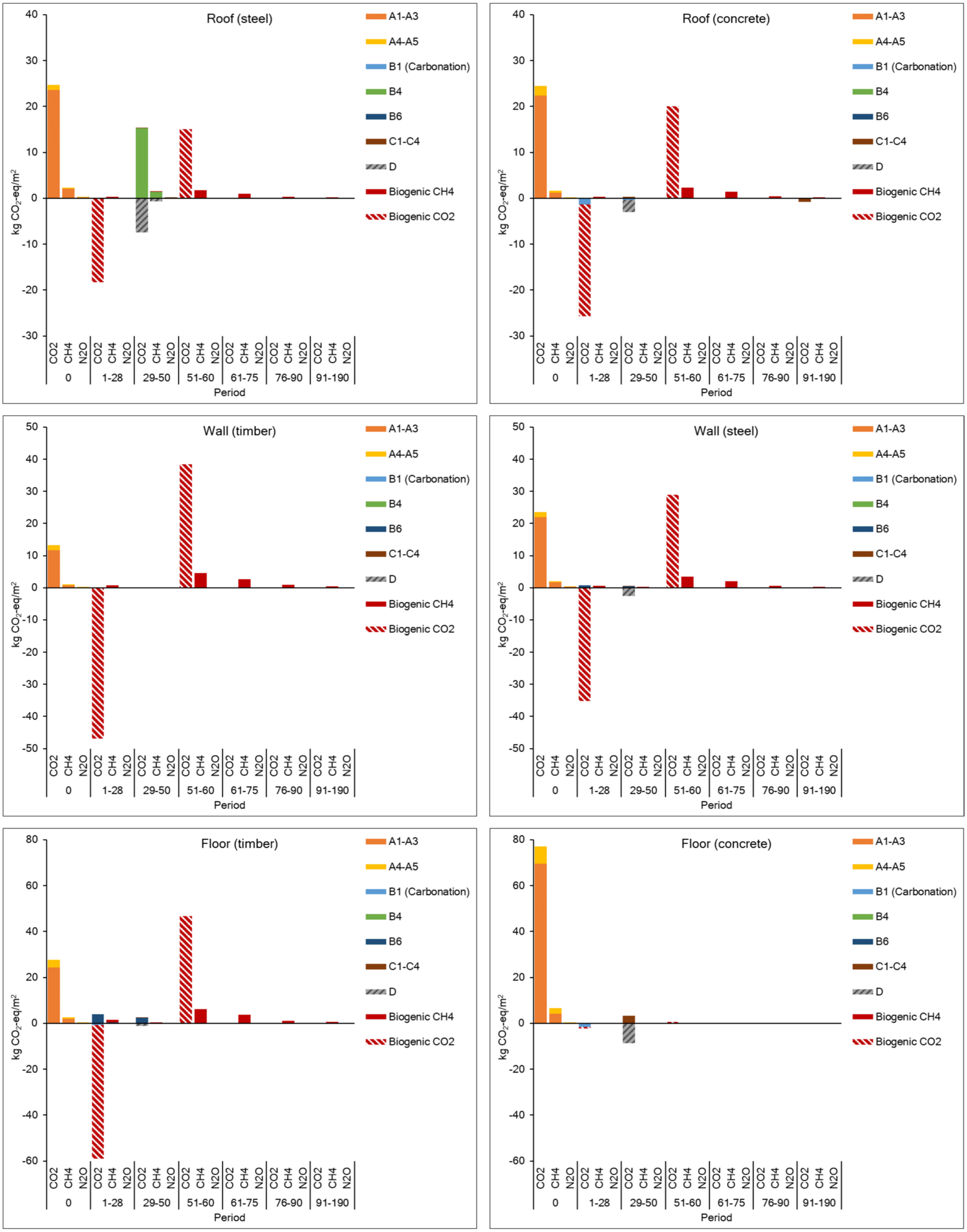


Fig. 5 Disaggregated sLCA climate change results

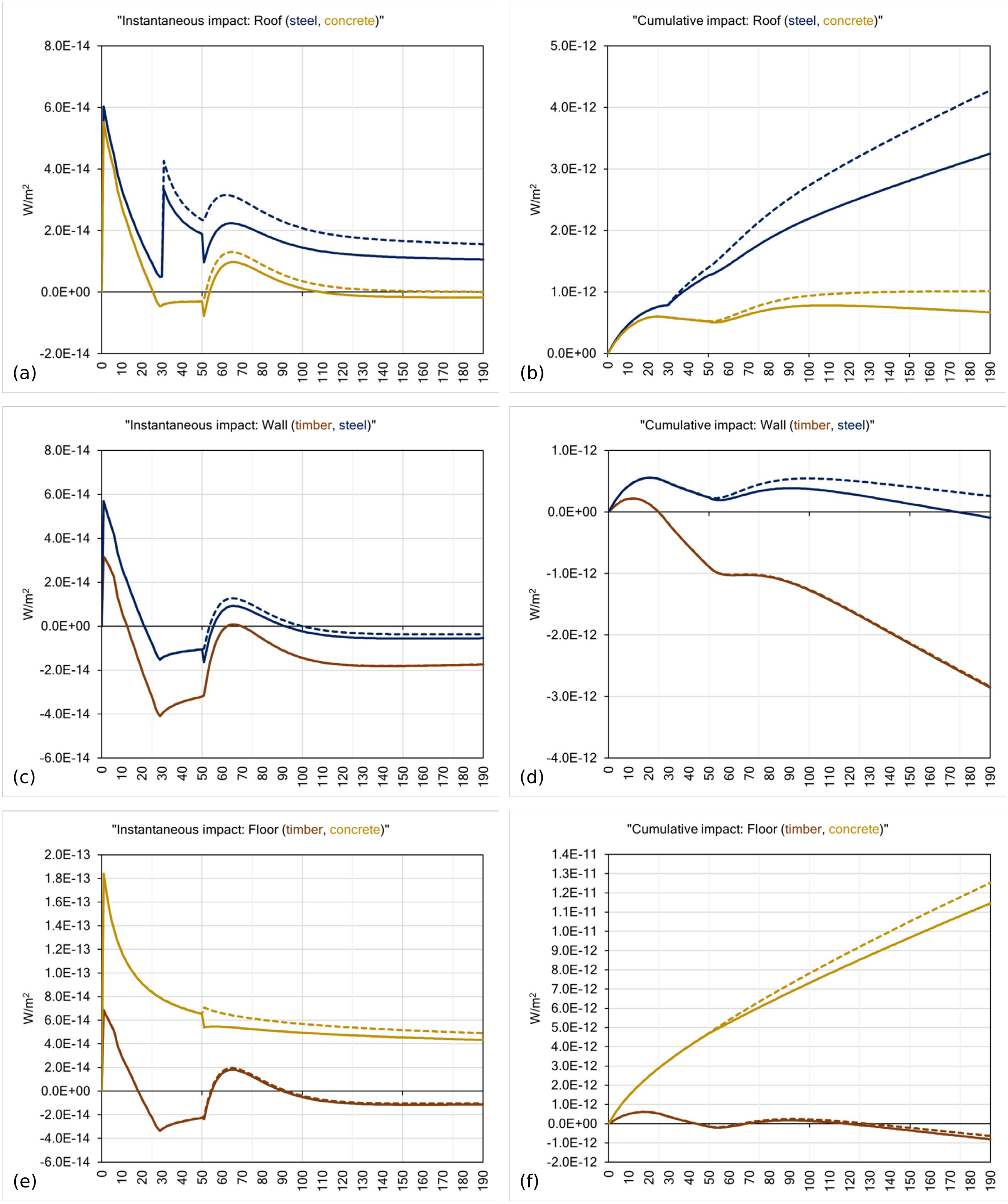


Fig. 6 Dynamic LCA climate change results: instantaneous (**a**, **c**, **e**) and cumulative (**b**, **d**, **f**), solid lines include module D and dotted lines exclude module D

wood products are landfilled (Nelson et al. 2022) — and degrade very slowly over long periods (Sect. 2.4).

Figure 9 shows the climate change results including and excluding biogenic carbon storage in landfill. These results include the landfill degradation emissions and module D results, i.e. they are equivalent to modelling following EN15804:A1 and EN15804:A2, respectively. A decision to include or exclude this biogenic carbon storage changes the results by more than 70% in four of the six assemblies. The relatively smaller changes for the steel roof and the concrete floor are explained by the smaller quantities of timber/engineered wood products used in these two assemblies — and the higher climate change impacts of the other materials and activities in the life cycle of these assemblies (see Tables 2 and 3).

Government climate change policymaking is generally focused on time horizons of 100 years or less. Over this time period a substantial proportion of the biogenic carbon in the landfilled timber and engineered wood products is stored and not emitted as biogenic carbon dioxide. Therefore, this should be represented in the climate change impact calculations (Cardinal et al. 2024) — albeit recognising that there are different perspectives on the relevant time frame for assessment (Brunner et al. 2024).

The treatment of recycled timber (and/or engineered wood products) is also an issue when timing of emissions is a consideration. EN16485 (2014, Fig. 1, Fig. 2) requires the biogenic carbon content of recycled timber to be modelled as a carbon dioxide emission from the system under analysis, and then a biogenic carbon credit can be claimed by a subsequent system using the recycled timber. This means that no biogenic carbon credit is associated with the current system. Instead, a biogenic carbon dioxide emission is modelled to occur at year 0, during refurbishment or at EofL if timber offcuts are recycled—although in reality this does not happen because the timber is recycled into another system. An alternative modelling approach is needed that better represents this ongoing biogenic carbon storage (Elliot et al. 2024b; Meyer et al. 2024).

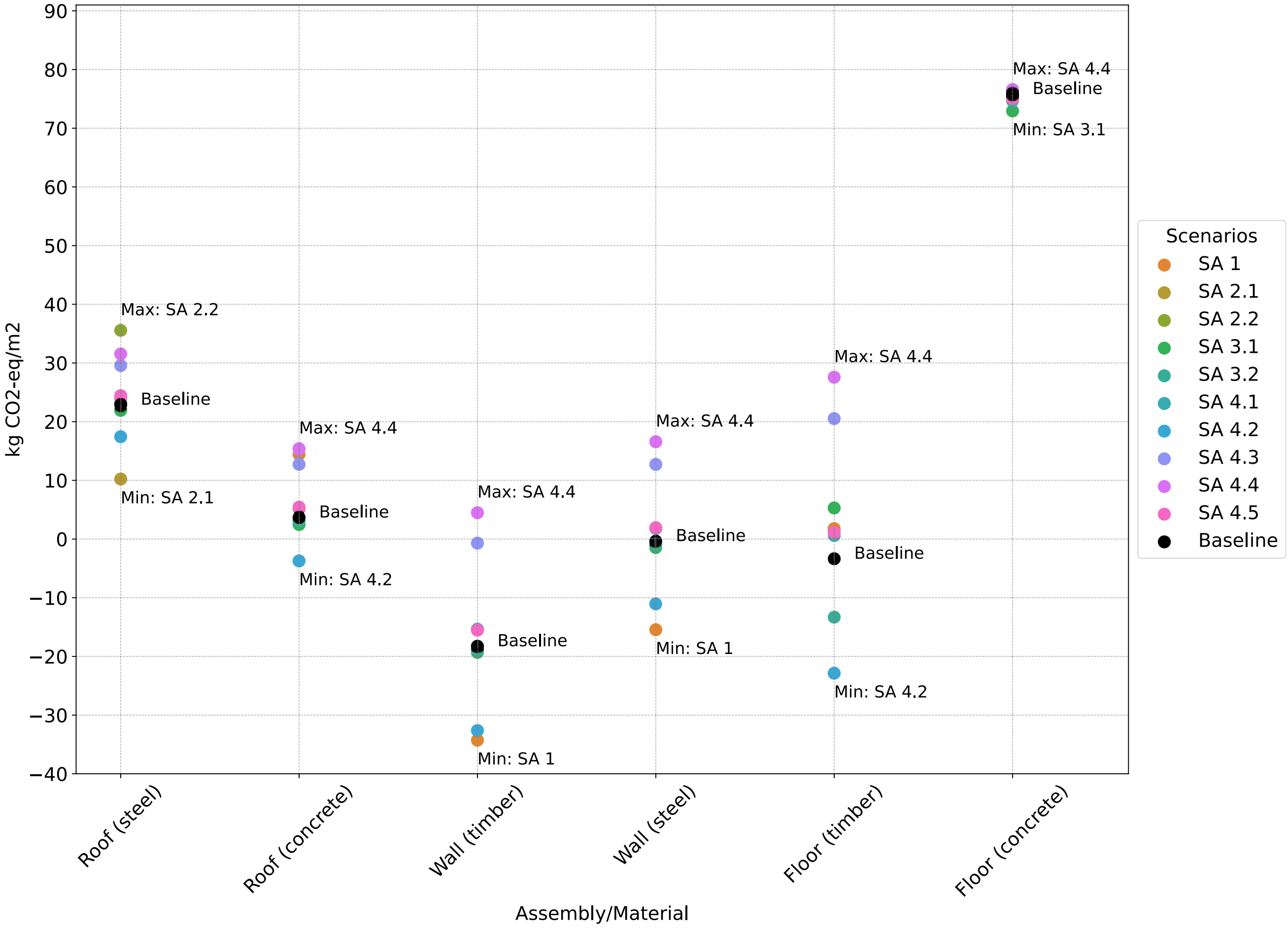


Fig. 7 Sensitivity analysis results for each assembly (sLCA method), highest and lowest sensitivity analysis results individually labelled for each assembly (including module D)

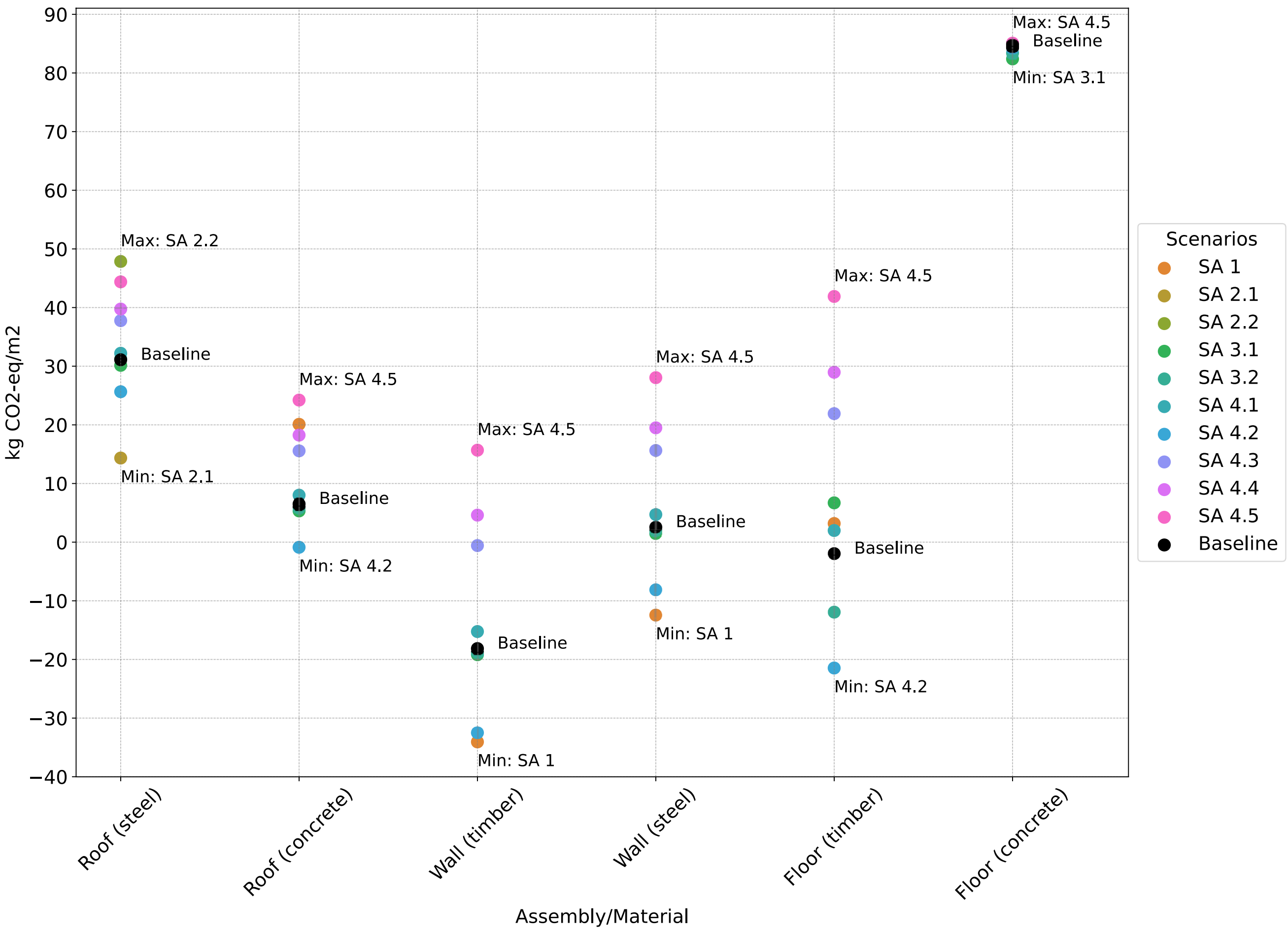


Fig. 8 Sensitivity analysis results for each assembly (sLCA method), highest and lowest sensitivity analysis results individually labelled for each assembly (excluding module D)

5.2 Modelling of future activities (modules B, C and D)

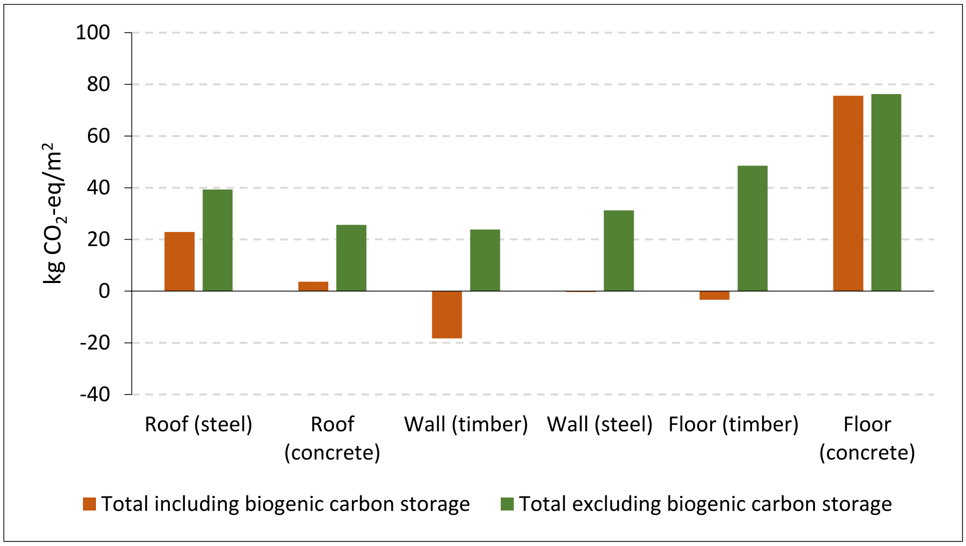
EN15804:A2 specifies that EofL practices for products containing biogenic carbon “are modelled as closely to reality as possible based on current practices” (CEN 2019, Sect. 6.3.5.5, Note 4), displaced heat and power from EofL modelled in module D is “calculated using current average substitution processes” (CEN 2019, Sect. 6.3.5.5, Note 4; Sect. 6.3.9), and recycling practices are modelled as based on “current average technology or practice” (CEN 2019, Sect. 6.4.3.3). However, manufacturing and EofL activities are likely to have significantly lower emissions in future, and particularly in 50 or 90 years’ time at the EofL of buildings currently being constructed.

Figure 5 shows that the majority of the fossil climate change result is related to activities occurring in year 0, except for the steel roof where replacement occurs at year 30. The majority of the biogenic climate change result is due to the forest cultivation in years 1–28, and there are smaller contributions in year 50 onwards due to landfill emissions. The module D contributions occur at year 50 due to recycling activities (except for the steel roof where it also occurs at year 30). The refurbishment and EofL activities occurring 30 or more years into the future are likely to have quite different climate change impacts from current practices given the focus on moving towards low carbon technologies. Given the likely misrepresentation of these future activities as regards their climate change impacts (Sect. 2.2), they should be reported separately in the results with clear communication about the uncertainties. For example, the climate change results could be presented in “current decade (< 10 years)” and “future decades (10 + years)” categories, and the latter category result presented as a range between modelling based on current technologies and anticipated low or net zero carbon technologies.

5.3 Modelling of forestry and timber use

In this study we used an attributional approach to model use of timber in typical residential building elements at the individual dwelling level, assuming that timber is sourced

Fig. 9 sLCA climate change results for assemblies, including and excluding biogenic carbon storage in landfill (including biogenic carbon dioxide and methane emissions from the landfill up to year 190, and module D)



from radiata pine plantations that are in a “steady state” (Sect. 2.1). Modelling of future changes in national forestry and building stocks, and their influence on the calculated climate change impact of timber used in individual buildings, was outside the scope of this research. Researchers undertaking these types of studies (e.g. Smyth et al. 2014; Soimakallia et al., 2016; Werner et al. 2010; Yamashita et al.; 2024) have found that additional parameters such as the future human population, import/export of timber and engineered wood products, forestry management practices, and characteristics of the building stock can have an important role in determining the final results.

In Aotearoa New Zealand the area of radiata pine established annually in Aotearoa New Zealand has fluctuated markedly since large-scale commercial plantations began in the 1920s (MPI 2024), related to the relative economics of alternative land uses, principally livestock grazing. Therefore, an important extension to this study, in the context of national policymaking, would be to investigate the influence of alternative assumptions about future national and international forestry and building stocks, and associated management practices, on the results.

5.4 Building reference service life

Figure 10a shows the climate change results for a 90-year RSL alongside the 50-year RSL. Although the ranking order for any pair of assemblies does not change, the magnitude of the results changes markedly for all the assemblies except the concrete floor; this is due to the additional refurbishment activities for the longer RSL. The concrete floor does not change because it is not replaced during either RSL scenario.

Figure 10b shows the results when the 50 and 90-year RSL results are normalised to one year of the RSL. Again, the ranking between any pair of assemblies does not change. However, the magnitude of some results changes markedly due to the additional refurbishment activities. For example, for the concrete floor, the 90-year RSL result is almost half the climate change impact for the 50-year RSL; this is because the floor is not replaced during either the 50 or 90-year RSL.

The importance of the chosen RSL for a construction product or building has previously been discussed in the literature (Potr Obrecht et al. 2019; Grant and Ries 2013). For building and construction sector carbon footprint tools, robust guidelines must be provided to ensure a level playing field for choice of appropriate RSLs, given the differences in results associated with varying this parameter.

5.5 Accounting for landfill emissions

The sLCA results show that between 21 and 25% of the biogenic carbon credit for timber is offset by GHG emissions in landfill across the assemblies. This proportion changes considerably when different assumptions are made about landfill emissions (Sect. 4.3.3). The timber wall and floor assemblies contain the largest quantities of timber, and the sensitivity analyses shows that different assumptions about methane generation from landfilled timber give results ranging from − 32 to + 5 kg CO_2eq/m^2 for the timber wall (compared to − 18 kg CO_2eq/m^2 for the baseline), and − 23 to + 28 kg CO_2eq/m^2 for the timber floor (compared to − 3 kg CO_2eq/m^2 for the baseline). Across all the sensitivity analysis scenarios, the choice of DOCf, methane recovery efficiency and/or type of landfill, produce the highest, and lowest or second lowest, climate change results for each assembly apart from the concrete floor (where the sensitivity analysis results are all very similar).

The choice of most appropriate parameters for modelling biogenic carbon degradation in landfill is not always obvious (Sect. 2.4). It is therefore important that default parameter values for calculating landfill emissions associated with timber and engineered wood products are made available to ensure consistency in carbon footprint tools.

5.6 Use of a dynamic LCA approach

Dynamic LCA introduces new information about timing of GHG emissions and removals into climate change impact assessment results. This is useful in the context of the current climate change crisis which implies a need to prioritise near-term initiatives to reduce GHG concentrations in the atmosphere. At the same time, though, dLCA may introduce additional subjectivity into environmental analysis if there is inadequate information available about the timing of future activities (e.g. repair/replacement/refurbishment of buildings, landfill emissions, concrete carbonation). For forestry, dLCA also adds complexity as the timing of biogenic carbon sequestration associated with the timber and engineered wood products used in buildings must be modelled compared to a baseline. The strengths and weaknesses of dLCA in the context of climate change assessment of buildings are discussed in Sects. 5.6.1 to 5.6.4.

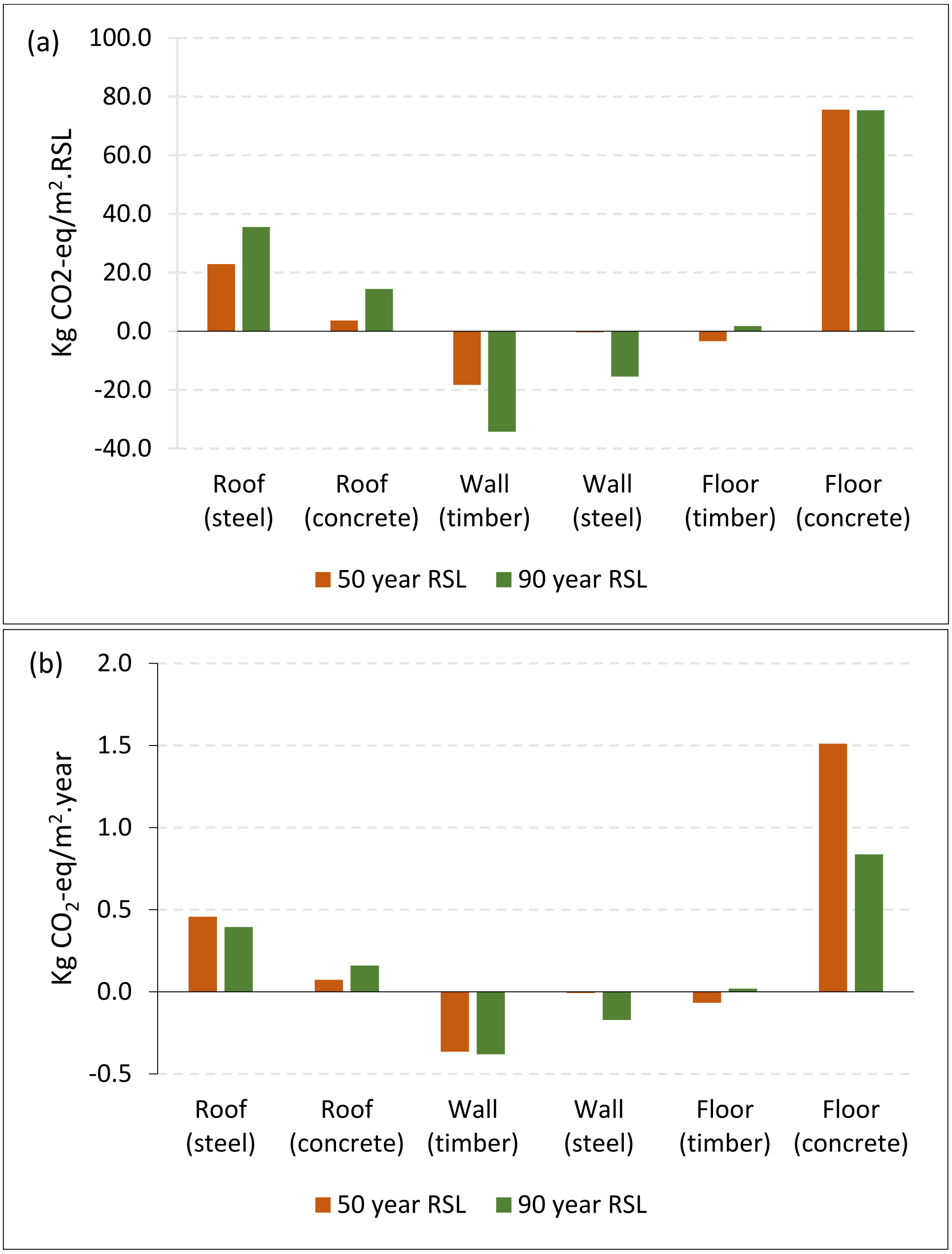


Fig. 10 Climate change impact of assemblies for 50 and 90-year building reference service life (RSL) measured in (**a**) kg CO_2eq/m^2.RSL and (**b**) kg CO_2eq/m^2.year (including module D)

5.6.1 Understanding of timing of GHG emissions and removals

Using the sLCA approach and GWP100 characterisation factors, the climate change impact of a GHG emission over the 100 years following an emission, is accounted in the life cycle module in which the emission occurs. Thus, in Fig. 4 it is not possible to see when these emissions occur unless one knows the timing of activities in each of the named modules. For example, by looking at the diagram it is not obvious that steel manufacturing emissions occur in years 0 and 30, and that steel recycling credits (accounted in module D) occur in years 30 and 50. The representation of timeframes is improved in Fig. 5 where emissions are disaggregated into distinct time periods.

In contrast to the sLCA approach, a dLCA approach models how emissions of GHGs (and sequestration of atmospheric carbon dioxide) contribute to changes in RF along timelines. Therefore, it has the potential to be more informative for policymaking, for example, as it enables an understanding of how GHG emissions or removals occurring at a specified point in time contribute to RF in any particular year (e.g. 2030, 2050) or over a specified time period (e.g. 2024 to 2050). Additionally, it provides insight into both the shorter- and longer-term contributions to RF as a result of strategies, policies or options implemented in the shorter term. On the other hand, if the timing of future activities is not known, additional uncertainty is introduced into the results – although this could be managed through scenarios modelled using alternative timescales for future activities.

5.6.2 Achievement of net zero carbon

An sLCA approach can provide insights about whether a construction achieves net zero carbon i.e. the climate change impact from GHG emissions is cancelled out by biogenic carbon storage and potential benefits from recycling or reuse of materials (assuming inclusion of module D in the calculations). An example is the sLCA results for the steel wall assembly in Fig. 4 in which the dot shows that the net result is very close to zero. However, this static approach provides no indication about when the construction in the assembly achieves net zero carbon.

Using a dLCA method, however, net zero carbon can be interpreted as being achieved when the cumulative RF line is at or below zero. This means that there is no remaining net RF impact caused by construction, use and end-of-life of the assembly. As an example, Fig. 6d shows the results for the steel wall assembly using a dLCA method; the steel wall assembly achieves net zero carbon about 170 years after construction. In contrast, Fig. 6d shows that the timber wall achieves net zero carbon approximately 25 years after construction, i.e. almost 150 years before the steel wall assembly. Thus, dLCA shows how quickly assemblies can achieve net zero carbon and thus addresses the shortcomings of having to select a specified time period for assessing the durability of carbon storage (Brunner et al. 2024). Of course, in this analysis the assumptions about the timing of future activities are also critical to the usefulness of the analysis.

5.6.3 Accounting for forestry

Regarding timber, biogenic carbon storage in forest cultivation was modelled using a stand-level replacement approach (see Sect. 2.1) for the sLCA. Using sLCA, the timing of forest cultivation is irrelevant because the results are calculated independently of the time period when biogenic carbon emissions and storage take place (unless, of course, there is a change in forestry practices over time).

For the dLCA, biogenic carbon storage in forest cultivation was modelled in year 0 to year 28 using the same stand-level replacement approach. Alternatively, the biogenic carbon storage could have been modelled in the 28 years up to harvest and use in year 0 i.e. from year −28 to year 0 (stand-level historic approach). As an example, the instantaneous and cumulative RFs calculated using dLCA for these two approaches are shown in Fig. 11 for the timber floor. Considering the cumulative RF results, using the year 0 to year 28 timing, the timber floor contributes to RF at various points up to year 118 (solid line in Fig. 11b). Using the year −28 to year 0 timing (dotted line in Fig. 11b), the timber floor is zero carbon and remains below zero carbon for all the modelled years. Thus, the (subjective) choice of timing for modelling forestry leads to quite different dLCA results, an insight that is missing from the sLCA results.

5.6.4 Choice of functional unit

As discussed in Sect. 5.4, the climate change results are affected by the chosen RSL. Figure 10b shows that the concrete floor result is almost halved when using a 90 rather than 50-year RSL, and reporting results in “kg CO_2eq/m^2.year”. However, the dLCA result for the concrete floor (Fig. 6f) show the opposite result: the cumulative RF is larger at year 90 than year 50, indicating the cumulative RF of the assembly will continue to increase over time, irrespective of the RSL. This illustrates the additional perspective provided by use of dLCA: long-lived GHGs (carbon dioxide in this case) that are not offset by any removals (e.g. carbon sequestration by forests for timber products) continue to contribute to RF for many years into the future.

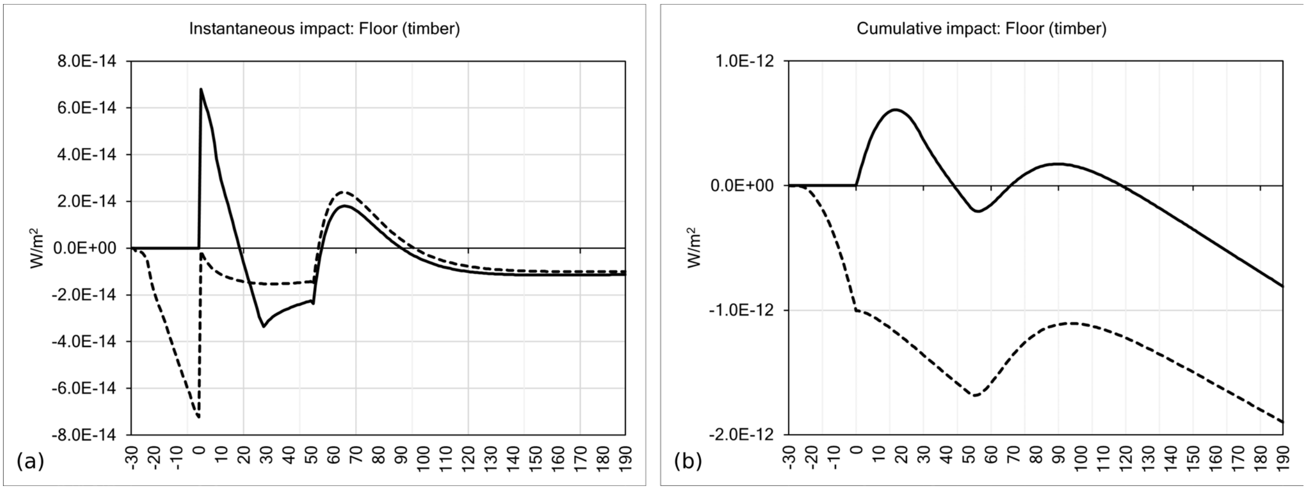


Fig. 11 dLCA results for timber floor showing (**a**) instantaneous radiative forcing, and (**b**) cumulative radiative forcing, when biogenic carbon storage is modelled from year 0 (solid line) or year −28 (dotted line) (including module D)

6 Conclusions

As governments around the world increasingly enact climate change policy that includes time-dependent targets, carbon footprint standards, guidelines and calculation tools should also more explicitly account for the timing of GHG emissions and removals. Some characteristics of the Aotearoa New Zealand case study reported here are less common or absent in some other countries (e.g. short forestry rotation, landfilling of end-of-life timber). However, many dwellings around the world utilise similar assemblies and the same main building materials (concrete, steel and timber). Therefore, as well as being relevant to Aotearoa New Zealand climate change policy, the insights from this research should also be addressed in international standards, guidelines and calculation tools supporting climate change assessment to ensure relevance to the diverse building and construction sectors operating in different countries.

The case study has shown that, for residential building elements, realistic modelling requires particular attention to time-dependent aspects that include the following:

- Landfilling of materials containing biogenic carbon: ongoing biogenic carbon storage and degradation in landfill (Sects. 5.1 and 5.4).
- Industrial processes that may occur many decades in the future (e.g. Use energy generation, EofL activities such as landfilling, and future manufacturing processes): future GHG emissions associated with these activities may be quite different from current GHG emissions (Sect. 5.2)
- Functional unit: choice of RSL, and use of total RSL or single year as functional unit (Sect. 5.4).

Modelling choices about these aspects significantly alter the climate change results across at least some of the studied assemblies in this case study. Therefore, for biogenic carbon stored in timber and engineered wood products that are landfilled at EofL, we conclude this should be modelled as ongoing storage minus landfill emissions; the existing research indicates that this is the reality for these products on timescales that are relevant for climate change policymaking (Sect. 2.4). An alternative approach that represents ongoing carbon storage in recycled timber/engineered wood products is also needed (Sect. 5.1). For future industrial processes, climate change results should be presented as a range to indicate the potential changes in GHG emissions and removals associated with future manufacturing practices (Sect. 5.2). This also applies for future forestry activities in the context of changing demand for timber and engineered wood products (Sect. 5.3).

Carbon footprint tools for the building and construction sector should be prescriptive about these aspects in order to create a level playing field for stakeholders. In addition, country-specific default values should be provided for building and construction product RSLs, and for parameters used to calculate (a) biogenic carbon sequestration in forestry, (b) EofL fate for different materials/products, and (c) landfill emissions.

The case study also raises the issue of how to report climate change results so that the timing of GHG emissions and removals can be aligned with climate change targets. The partially disaggregated sLCA results in Fig. 5 provide some information about the timing of emissions and removals. Another option is to report the climate change results in “current decade (< 10 years)” and “future decades (10 + years)” categories (Sect. 5.2); the latter category result could be reported as a range between modelling based on current technologies and "net zero" technologies. Dynamic LCA results provide additional insights about the time required for buildings and construction products to reach net zero carbon status, and further consideration should be given to their use in carbon footprint tools and to support policymaking. This is particularly relevant for countries and industries committed to achieving climate targets by specific years (e.g. net zero carbon by 2050).

The current standards either do not provide prescriptive guidance on the aspects discussed in this research or, in the case of EN15804:A2, require modelling that ignores consideration of the critical time-dependency of some activities (e.g. landfilled biogenic carbon storage, future manufacturing and EofL technologies). We recommend that these aspects should be reconsidered, and that building carbon footprint tools implement these recommendations. This will support the building and construction sector to prioritise initiatives that can deliver a net zero carbon sector in a timely fashion, and to align with the climate change targets of an increasing number of countries around the world.

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Declarations

Conflict of interest The authors declare no competing interests.

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