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Full length article

Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades

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ABSTRACT

This study assesses the environmentally optimal wood utilisation patterns under varying wood cascading options, using the example of Switzerland. Cascading is the use of the same wood unit in multiple, successive product cycles. To consider aspects relevant at the system level (e.g. stocks/flows, demand/supply constraints) as well as at the product level (e.g. process inventories), we present a model that combines material flow analysis (MFA), life cycle assessment (LCA) and mathematical optimisation to identify environmentally optimal wood use scenarios concerning climate change and particulate matter formation. We separately include the temporal dynamics of biogenic carbon flows, i.e. carbon uptake, storage and subsequent release, which may have a considerable influence on the climate change performance of wood products.

Results indicate that multiple cascading (mC) of wood can decrease environmental impacts: total systemic impact reductions over the modelled 200-year time horizon compared to single cascading (i.e. all waste wood is directly incinerated), are between 35–59 Mt CO_2-eq. and 43–63 kt PM10-eq. Driving factors for the environmental impact of future wood use scenarios are: waste wood processing efficiency, wood storage effects (in case of biogenic carbon accounting), and available cascading options. Particularly, high quality wood cascade of wooden beams is a promising recycling path for reducing environmental impacts.

We conclude that by implementing wood cascading, future Swiss wood utilisation can be further improved in terms of environmental impact. The tool combination of dynamic MFA, LCA and optimisation proved to be suitable to identify environmentally optimal scenarios for a complex value chain.

1. Introduction

Wood serves as a raw material for a wide range of products and may also be used for energy purposes. It is therefore of particular interest to define national strategies for wood's efficient and ecological use (Werner et al., 2010; Mantau, 2014; FOEN et al., 2014). Due to its versatility, wood can substitute fossil energy carriers as well as conventional building materials such as concrete, steel and brick. As wood-based products are often found to have lower environmental impacts than functionally equivalent products from fossil or mineral sources, an increased use of wood might lead to substitution benefits (Werner et al., 2005; Gustavsson et al., 2006; Sathre and O'Connor, 2010). In addition, long-lived wood products act as a carbon stock during their service life and therefore contribute to the mitigation of climate change (Taverna et al., 2007; Werner et al., 2010; Cintas et al., 2015; Jasinevicius et al., 2016).

After Sirkin and ten Houten (1994), introduced the resource cascade concept, several recent studies have dealt with the potential benefits of cascading uses of wood, i.e. for multiple successive product cycles, first for material uses (typically with decreasing quality requirements) and finally for energy. Sathre and Gustavsson (2006) analysed energy and carbon balances of various wood cascade chains under different post-recovery options by considering direct cascade effects, substitution effects and land use effects. The authors concluded that wood cascading leads to carbon and energy balance benefits, predominantly through land use and substitution effects. Höglmeier et al. (2013) assessed cascading potentials of recovered wood from building deconstruction in Southern Germany and found considerable amounts of recovered wood in suitable condition. In a subsequent study, Höglmeier et al. (2015) then performed a systemic LCA-based optimisation of wood utilisation in the same region. Environmental benefits of cascading were determined for all the environmental impact categories considered, most notably for particulate matter formation and land occupation. However, particle board is the only recycling option of post-consumer wood included in the study. Also, temporal aspects regarding carbon emissions and storage are not considered.

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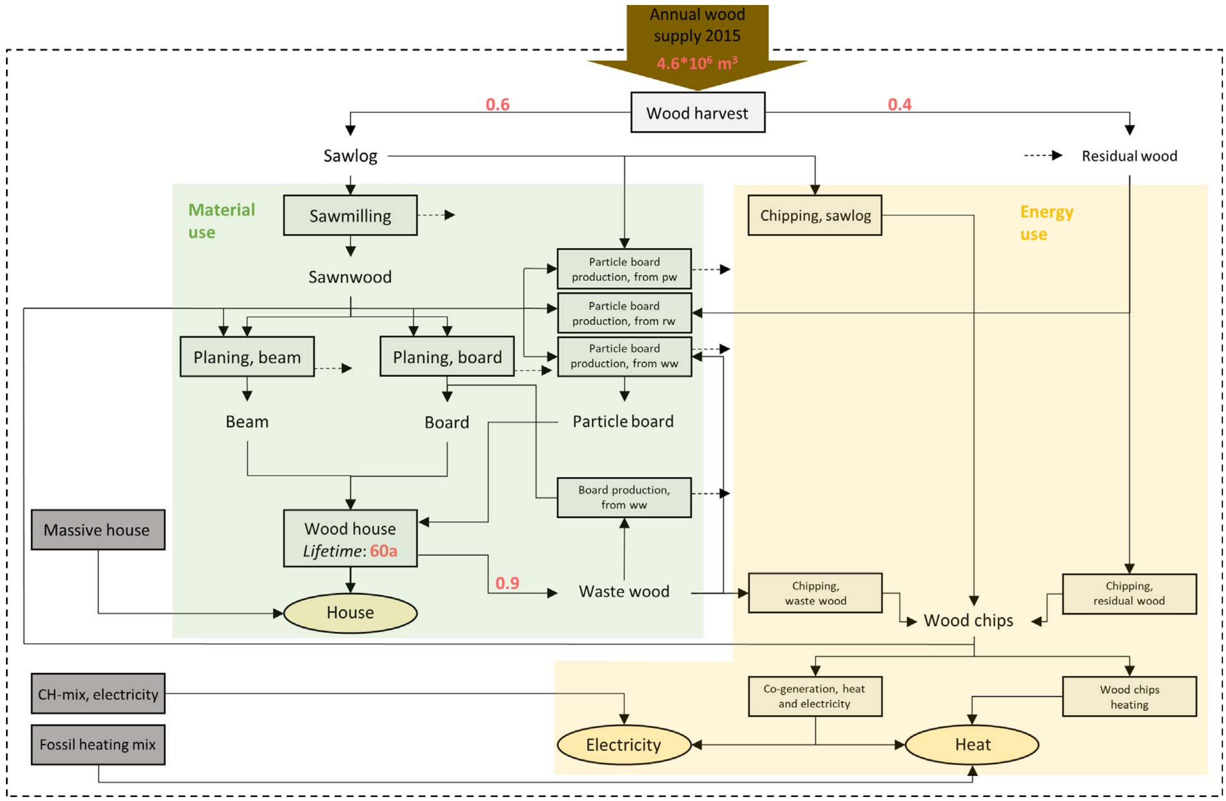

Fig. 1. Schematic overview of the wood flow model and associated assumptions (in red, Sections 2.1.1–2.1.3) as well as non-wooden substitution modules (rectangular grey boxes, Section 2.1.5). Yellow ellipses represent product demand (Section 2.1.4). Intermediate products are displayed as labelled arrows. Dotted arrows represent wood processing residues. Further (non-wood) material flows entailed by the corresponding LCA processes are provided in the *Supplementary data*.

The method chosen by most studies to assess environmental impacts of wood processing and wood products is life cycle assessment (LCA) (Werner and Richter, 2007; Rüter and Diederichs, 2012; Sathre and González-García, 2014; Cambero et al., 2015). Klein et al. (2015) reviewed LCA studies of wood production and utilisation published in the past 20 years and concluded that, despite significant differences in the results, LCA is a well-established methodology to assess environmental impacts of the wood value chain.

However, assuming wood as carbon neutral may be problematic, as highlighted in the 5th IPCC report (Myhre, 2013). Brandão et al. (2012) reviewed six methods accounting for the potential climate impacts of carbon sequestration and temporary storage or release of biogenic carbon in LCA and carbon footprinting (CF) and identified that possible benefits depend on the time horizon and thus include value judgements. Cherubini et al. (2011) introduced a method to calculate the contribution of biogenic carbon emissions to global warming based on the timing of emissions, the sequestration of the forest, and the atmospheric CO_2 decay. The authors show that the temporal dynamics of carbon uptake in the forest, subsequent storage and eventual release through wood combustion strongly influence the global warming performance of wood products. Guest et al. (2013a) extended Cherubini's emission factors by including carbon storage benefits in case the harvested wood remains stored in products over a longer time period before its eventual combustion. Both studies proposed that these emission factors could be applied in LCA studies. Other studies assessing climate effects of increased bioenergy use underline that results strongly depend on biomass species, local forest management and local climate variables (Cherubini et al., 2012; Cintas et al., 2015). Yet, the potential climate effect of biogenic carbon is rarely accounted for in LCA-studies assessing the impacts of wood utilisation patterns (Werner and Richter, 2007; Höglmeier et al., 2015; Thonemann and Schumann, 2017).

Despite being a renewable resource, wood availability at any given time is limited. A systemic approach is thus needed to identify optimal wood allocation amongst competing uses. Therefore, this explorative study combines a dynamic material flow model containing flows and stocks of the most important wood use options for the case of Switzerland with an LCA-based optimisation problem formulation including process inventories and life cycle impact assessment (LCIA). We hereby account for aspects relevant at the system level such as stocks and flows, detailed process models and environmental impact assessment as well as constraints to identify environmentally optimal utilisation patterns. In addition, the temporal scope of the model enables for assessing the dynamics of biogenic CO_2 emissions, including storage effects of long-lived wood products, in the context of multiple successive product applications (cascade uses). This study discusses optimal wood utilisation patterns obtained under different constraints and provides insight into the most sensitive parameters for an environmentally optimised wood use in Switzerland.

2. Method and approach

To address the aforementioned research objectives, we combine three tools: dynamic material flow analysis (MFA), life cycle assessment (LCA), and mathematical optimisation. A high-level dynamic MFA model depicts archetypes of the most important wood use options in Switzerland and describes the material input and output flows of the related processes (here denoted *modules*). To calculate the environmental burdens associated with these MFA processes, we apply the modular LCA approach of Steubing et al. (2016), where several LCA processes can be combined into modules, reflecting the broader level of abstraction often found in MFA models. The product flows to and from each module, as well as its environmental impact, are stored in a spreadsheet-based module-product matrix. This matrix is then used within an optimisation model to identify environmentally optimal wood use options. This allows us to calculate the total environmental impact of the system over the modelled time horizon for different LCIA

Table 1
Wood cascade recovery factors for board and particle board regarding the collected, transported and processed waste wood fraction (based on Höglmeier et al., 2013, 2015; Swiss Confederation, 2016a).

	Waste wood suitable for (%)	
	Material use	Energy use
Board	25	75
Particle board, first step	80	20
Particle board, second step	70	30
Particle board, third step	0	100

categories and to determine the wood use patterns that minimise the overall impact under various conditions and constraints.

2.1. Dynamic material flow analysis (MFA)

2.1.1. Wood availability

The annual domestic wood supply of Switzerland is a key input parameter to the wood flow model (see Fig. 1). Availability is based on harvested wood amounts from 2015 (FOEN, 2015a), excluding amounts for pulp and paper production. It is assumed constant since the sustainably available wood use potential is assumed to remain more or less the same in future (Taverna et al., 2016). The distribution of wood into the "sawlog" and "residual wood" wood assortments is based on Hofer, 2011 and the supply chain is modelled using ecoinvent v3.2 datasets (ecoinvent, 2015). All major model assumptions as well as their relevance regarding results and findings are summarised in Appendix A.2 in the *Supplementary data*.

2.1.2. Material use options

Material use of wood is represented by the module *Wood house* (see Fig. 1). It is modelled as a stock where the wood remains stored until the house is demolished. Two wood house inventories – a composite wood construction and a wood-only wood house – based on Müller et al. (2012) and Heeren et al. (2015) are used in this study. They consist of wooden beams, boards, and particle boards apart from other (non-wooden) materials. To meet the housing demand over the modelled time horizon, a conventional massive house mix of concrete and brick buildings is added to the model and hence represents a substitution opportunity. The building inventories are listed in Appendix A.1, *Supplementary data*.

Beams and boards are produced from sawnwood by drying and planing, particle boards are produced from primary or residual wood. By allowing wooden and particle boards to be additionally produced from waste wood, wood cascading possibilities are implemented into the model (see Chapter 2.1.3). Degradation of woody biomass during storage is assumed to be negligible (Yue et al., 2013a).

2.1.3. Energy use options

Wood utilised for energy purposes is represented by the supply of two generic products heat and electricity. To meet the total heat and electricity demand, two substitution processes are added to the model: a fossil-fired heating mix and the Swiss electricity mix.

Options for heat generation include a conventional medium-scale wood chip furnace and a large-scale plant for the co-generation of heat and power (CHP). The combusted wood chips are produced from primary wood, residual wood or waste wood. Residual wood includes forest residues and wood processing residues e.g. from sawmilling, planing or particle board production.

Concerning the use of waste wood for energy, the Swiss legislation demands restrictions for the combustion of polluted waste wood, depending on the grade of pollution (Swiss Confederation, 2016a, b). Consequently, treated waste wood fractions are currently burned in cement plants and municipal solid waste incineration (MSWI) plants in Switzerland, which are both not optimised for wood combustion. However, we assume that in the course of the energy transition, higher efficiencies also for contaminated waste wood are to be expected. Thus, no distinction between burning primary wood, residual wood and waste wood is made with respect to furnace used.

2.1.4. Wood cascading

Höglmeier et al. (2013) found considerable amounts of recovered waste wood in suitable condition for material recycling, in particular a significant fraction of structural components suitable for re-use. Following the idea of reusing each wood unit in the application with the highest quality possible, large structural components i.e. beams can first be reused as boards of smaller dimensions, before then being chipped after their second service life, and being recycled into particle boards in a second cascade step. After a third cascade step, again recycled as particle board, the remaining waste wood is eventually utilised for energy purposes. These options represent technically feasible wood cascade utilisations in the context of Switzerland. Apart from waste wood volumes and quality requirements, such as particle size and grade of pollution, recycling losses must be taken into consideration. Höglmeier et al. (2015) assessed a technical yield of 95% including transportation and processing for the area of Bavaria, which is assumed to be transferrable to Switzerland. With an additional waste wood collection rate of 95%, an approximate loss of 10% is resulting. Table 1 lists waste wood fractions from building deconstruction suitable for cascading material reuse.

2.1.5. Product demand

The wood flow model is demand-driven, meaning wood flows are analysed under the condition that the satisfaction of a certain demand for products is enforced as a model constraint that needs to be met. For the case of Switzerland, we here focus on the demand for electricity, heat, and housing (see Table 2). It is assumed that the wooden and non-wooden alternatives for meeting this demand are fully interchangeable, which is a simplifying assumption as people may display preferences for one or the other option.

2.1.6. Alternative (non-wood) technologies

To reflect substitution effects through wood utilisation, conventional alternatives for each demanded product are included into the model (see Table 3). The choice of conventional alternatives is based on current Swiss conditions (Heeren et al. 2015, Suter et al., 2016).

2.1.7. Model dynamics

To account for storage effects occurring with multiple consecutive wood cascading steps, a temporal dimension is added to the MFA model. All model calculations are performed for a time horizon of 200 years, in time steps of 10 years from 2016 to 2216.

In accordance with Neubauer-Letsch et al. (2012) and Heeren et al. (2015), the service life of wooden elements in buildings is assumed to be 60 years (a sensitivity analysis for 40 and 80 years is presented as well). At the end-of-life, this wood becomes waste wood. Wooden construction elements from reprocessed waste wood are assumed to have an identical service life as elements produced from primary wood.

For a better illustration of temporal effects regarding the environmental performance of the system, no initial wood stock is assumed at

Table 2
Rounded annual product demands in Switzerland.

Annual demand		Source
Heat (MJ)	3.0×10^{11}	SFOE, 2014
Electricity (kWh)	5.0×10^{10}	SFOE, 2014
New buildings[a] (unit)	50,000	FSO, 2016

[a] Demand to maintain the building stock.

Table 3
Demanded products and conventional alternatives of the model (based on Heeren et al., 2015; Suter et al., 2016).

Demanded product	Conventional alternative
Housing Wood house composite and wood-only	Massive house mix (70% concrete house and 30% brick house)
Heat Heat from wood chips a) wood chips heating b) combined heat and power plant	Fossil heating mix (70% light fuel oil, 30% natural gas)
Electricity Electricity from CHP plant	Swiss electricity mix (roughly 60% hydropower, 40% nuclear)

the first time step. Note that towards the end of the modelled time span, border effects might occur: wood utilisation patterns might change due to possible immediate benefits. The relevance of these temporal effects on the results is further discussed in Section 4.2.

2.2. Modular life cycle assessment (LCA)

2.2.1. Functional unit and system boundaries

Based on Steubing et al. (2016) a modular LCA approach is used to calculate the environmental impact of each module of the wood flow model. It allows flexible calculations on a system level by simply adding up module-based impacts over all modules of the system. Depending on the scenario, different modules might be combined to meet the total annual demand of heat, electricity and housing. Meeting this demand (assumed constant; see Table) over the modelled time horizon of 200 years represents the functional unit of the LCA and is therefore the basis for the calculations of total environmental impacts of the system. Hereby, the housing demand represents the number of new houses to maintain the overall building stock.

2.2.2. Life cycle inventories

For all LCA calculations performed, version 3.2 of the ecoinvent database is used (ecoinvent, 2015). For the wood-fired CHP process, efficiencies from a large-scale co-generation plant in Aubrugg, Switzerland, are used (Hofer and Angleitner, 2013; Jenni, 2015). Detailed information about all modules with corresponding ecoinvent v3.2 processes are listed in Appendix A.3, *Supplementary data*.

2.2.3. Life cycle impact assessment (LCIA)

The LCIA of this study includes two environmental indicators that are considered to be very relevant in the context of wood systems: Climate change (CC; including the climate effect of both fossil and biogenic carbon emissions) and particulate matter formation (PMF). The biogenic global warming potential (GWP_{bio}), introduced by Cherubini et al., 2011 and extended by Guest et al. (2013a), allows one to weight carbon emissions through wood combustion depending on prior carbon storage in the anthroposphere. Due to cascade flows in the wood flow model, which involves the mixing of primary and post-consumer wood, we chose to use an approximation for the biogenic CO_2-emissions in this study: the biogenic carbon uptake in the forest – as *potentially emitted carbon content* at the end-of-life – is accounted for in the module *Wood harvest*. Storage benefits are calculated based on a linearised GWP_{bio} factor of -0.1 [tonne CO_2-eq.] per decade and tonne CO_2 stored (see Fig. 2). PMF is assessed based on the ReCiPe 1.08 assessment method under the hierarchist (H) perspective (Goedkoop et al., 2013). LCA-scores of all other ReCiPe midpoint categories are listed in the *Supplementary Data*.

2.3. Optimisation model

To determine the most environmentally-friendly wood utilisation patterns, the dynamic mass flow model is described as an optimisation problem, which is set up to be solved in General Algebraic Modelling

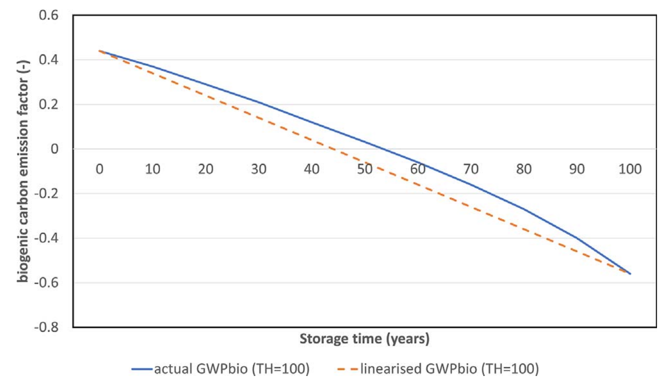

Fig. 2. Actual emission factors and linearised GWP_{bio} approximation used in this study based on Cherubini et al. (2011) and Guest et al. (2013a) for a rotation period of 100 years (see Appendix A.8, *Supplementary data*). Values apply for a 100-year time horizon.

System GAMS (GAMS Development Corporation, 2013), based on Section 3.2 of Steubing et al. (2016). The model objective is to minimise the systemic environmental impacts over the modelled time horizon from 2016 to 2216. The model is subject to several constraints including product demands (i.e. fulfilment of the functional unit) and cascading limitations such as the fulfilment of the cascade factors listed in Table 1. The optimisation statement and its constraints, including all relevant parameters, variables, and indices are listed in Appendix A.5, *Supplementary data*.

2.4. Scenario description

The optimisation model is run considering four basic scenarios: The reference single-cascade (sC) scenario allows a one-time material use of wood with subsequent energy use. To assess effects of waste wood recycling, the multiple cascade (mC) scenario allows the recycling of post-consumer wood according to the cascade factors listed in Table 1. Additionally, a no-cascading (nC) scenario prohibits wood to be used materially, meaning that also high quality primary wood is chipped and combusted. Finally, the no-wood (nW) scenario represents the case where the whole demand is met by conventional alternatives.

2.5. Sensitivity analysis

A number of model parameters are varied to determine their sensitivity as well as to account for critical assumptions (see Table 4). Since it influences the temporal dynamics of the wood in the system, the service life of wood in buildings is the first parameter to be analysed. In this case, the annual amount of buildings required to maintain the building stock (functional unit) differs (75,000 in case of a 40-year lifetime, 37,500 in case of an 80-year lifetime). In all cases the assumption was made that wood and massive buildings have an identical lifetime. In addition, the waste wood recovery efficiency as well as the fraction of waste wood reusable as wooden boards are varied to analyse cascading efficiency.

Table 4
Overview of sensitivity analyses conducted.

Scenario	Parameter varied	Default value	Variation	Examined effects
Lifetime40 Lifetime80	Wood lifetime in building	60 years	40 years 80 years	Total environmental impact/ changes in optimal wood use pattern
Yield60 Yield95	Waste wood yield	90%	60% 95%	
Beam0.15 Beam0.5	Fraction of waste wood usable for beam reuse	25%	15% 50%	Total environmental impact/ amount of beam cascaded

Table 5
Total systemic impact for the four basic scenarios regarding wood house types "composite" and "wood-only" by optimising for CC (fraction of fossil greenhouse gas (GHG) in brackets) and PMF, respectively. Absolute (δ) and relative (Δ) differences are in relation to the single cascading (sC) scenario. Results for all ReCiPe 1.08 midpoint categories are listed in Table S7 in the *Supplementary Data*.

	Climate change					PMF				
		sC	mC	nC	nW		sC	mC	nC	nW
Wood house, composite	[10^9 t CO_2-eq] (fossil GHG)	6.03 (96.53%)	5.97 (96.95%)	6.33 (94.45%)	6.41 (99.34%)	[10^9 kg PM10-eq]	4.86	4.80	5.09	5.05
	δ [10^8 t CO_2-eq]	–	−0.59	3.05	3.77	δ [10^8 kg PM10-eq]	–	−0.63	2.29	1.89
	Δ [%]	–	−0.98	5.05	6.25	Δ [%]	–	−1.29	4.72	3.89
Wood house, wood-only	[10^9 t CO_2-eq] (fossil GHG)	6.14 (96.30%)	6.11 (96.65%)	6.33 (94.45%)	6.41 (99.34%)	[10^9 kg PM10-eq]	4.96	4.91	5.09	5.05
	δ [10^8 t CO_2-eq]	–	−0.35	1.90	2.62	δ [10^8 kg PM10-eq]	–	−0.43	1.37	0.96
	Δ [%]	–	−0.57	3.09	4.27	Δ [%]	–	−0.86	2.76	1.94

A further sensitivity analysis regarding environmental impacts of the conventional alternatives is performed, as their choice is based on subjectivity and as they may be subject to change in future. The LCIA scores of each dataset for CC is systematically varied between factor 0.25 and 10 of the original score to analyse whether optimal wood use patterns are influenced.

3. Results

3.1. Basic scenarios

Compared to the sC scenario, multiple cascading leads to a smaller total environmental impact of the system when optimising for both CC and PMF (see Table 5), which results of increased wood amounts in the system by recycling post-consumer wood. Comparing the sC and nC scenarios underlines that using wood in a single cascade is beneficial even if the post-consumer wood is not materially recycled. Finally, omitting any material use of wood altogether results in the highest total CC impacts. From a PMF perspective, on the other hand, exclusively using wood for energy leads to the highest total impact, which is due to particulate matter (PM) emissions associated with wood combustion. Using the wood-only wood house type as a housing option results in considerably higher total impacts regarding wood cascading for both LCIA methods. This finding is discussed further in Section 4.1.

In contrast to considerable absolute impact reductions (δ) through multiple cascading, relative differences between the scenarios (Δ) are rather small in comparison. This is due to the demand-driven nature of the model framework: in all scenarios, a significant fraction of the demand cannot be met by wood, and is hence supplied by other products. In the following sections, we examine the optimal wood allocation and time resolved annual impacts regarding CC in more detail. For corresponding CC fossil-only (excluding biogenic carbon effects) and PMF-optimised results see Appendix A.6 and A.7 in the *Supplementary data*.

3.1.1. Optimal strategies for cascading

Looking at the mC and sC scenarios, the optimal fractions of housing, heat and electricity demand covered by wood products differ by when optimising for CC (see Fig. 3). We summarise the key findings:

(1) **Primary wood is used exclusively for material purposes in the optimal case**: For both scenarios, more than 50% of the housing demand is covered by wood in the optimal case. This is equal to a full material use of domestically-available primary wood.
(2) **Particle board is preferably produced from residual or post-consumer wood:** As long as it is not possible to produce respective amounts from post-consumer wood, particle boards are produced from residual wood.
(3) **Post-consumer wood is reused materially in the optimal case:** The wood building stock is increasing in the case of multiple cascading, which is due to additional waste wood available for board and particle board production.
(4) **Incinerated wood is preferably used for heat-only energy recovery:** In both scenarios, residual wood is energetically used for heat production rather than CHP in the optimal case, which is a consequence of the low-carbon Swiss electricity mix. This result changes when marginal electricity is credited (see Section 3.2).

3.1.2. Time-resolved impacts

Displaying the total CC impacts from Table 5 resolved over time allows for illustrating three main effects concerning wood cascading (see Fig. 4). Note that the dynamic profile of the impacts is a result of our approximation choice for the release of biogenic carbon (accounting for the emission at the time of wood harvest and not at the point of combustion and subsequently assigning credits based on duration of storage) and do not reflect the actual temporal progression of the impacts. However, the overall balance of emissions and the (indirect) benefit of storage is warranted by our approach, leading to correct time-accumulated impact scores.

3.2. Sensitivity analysis (mC scenario)

An increased lifetime of (wood) buildings leads to a smaller annual demand for housing in order to maintain the stock size, and vice versa. Therefore, total impacts are considerably smaller for an 80-year lifetime

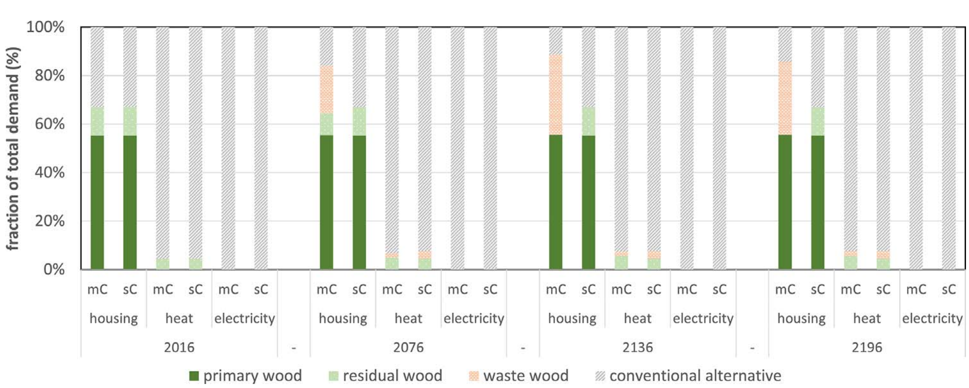

Fig. 3. Optimal wood allocation regarding the demanded products housing (composite wood house), heat and electricity for four time steps with and without the possibility of multiple cascading by optimising for CC. The origin of the wood fraction is additionally differentiated by colour. The time steps chosen represent moments of stock-emptying, where additional waste wood amounts are available (see also Fig. 4).

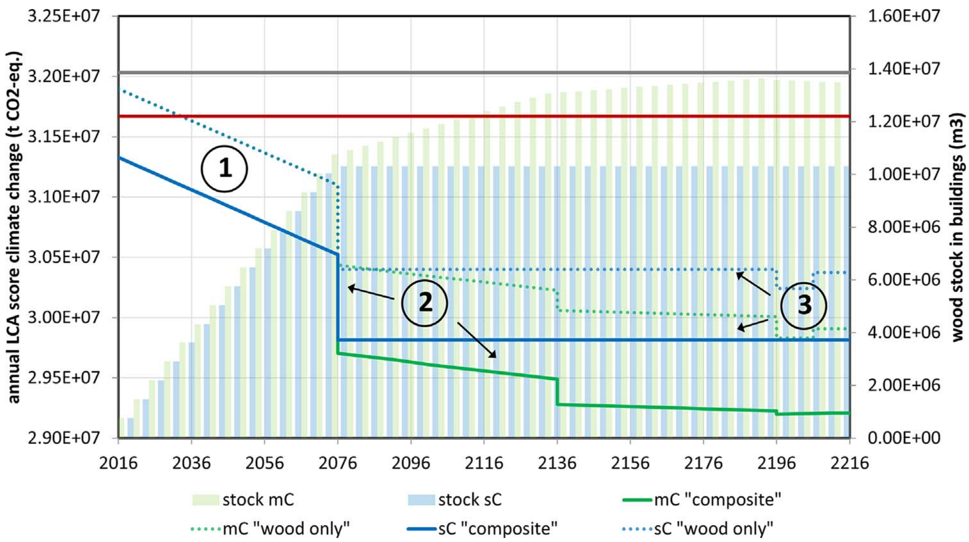

Fig. 4. Time resolved annual climate impacts regarding the four basic scenarios (primary y-axis) and wood building stock for the mC and sC scenarios (secondary y-axis) by optimising for CC. Environmental impacts of scenarios with cascading are displayed for the composite (solid line) and wood-only (dotted line) wood house types. (1) The wood stock in buildings is continuously increasing over the first 60 years (and over subsequent storage periods). The delay of CO_2 emissions leads to simultaneously increasing storage benefits. (2) The impact reductions after respective storage periods result from additional waste wood availability: cascading leads to larger wood amounts in the system and thus, a larger fraction of the housing demand can be met by wood houses. Concerning the sC scenario, the impact reduction arises from additional energy produced (and therefore conventional energy substituted) from waste wood. Towards the end of the time period, a new equilibrium of the wood stock is reached, and thus impacts remain constant. (3) The wood-only wood house consists of much higher wood amounts than the composite version, hence, less conventional buildings can be substituted by the same harvested wood amount. Since climate impacts per unit of wood house are similar for both wood building types, possible total material use benefits are larger for the composite wood building.

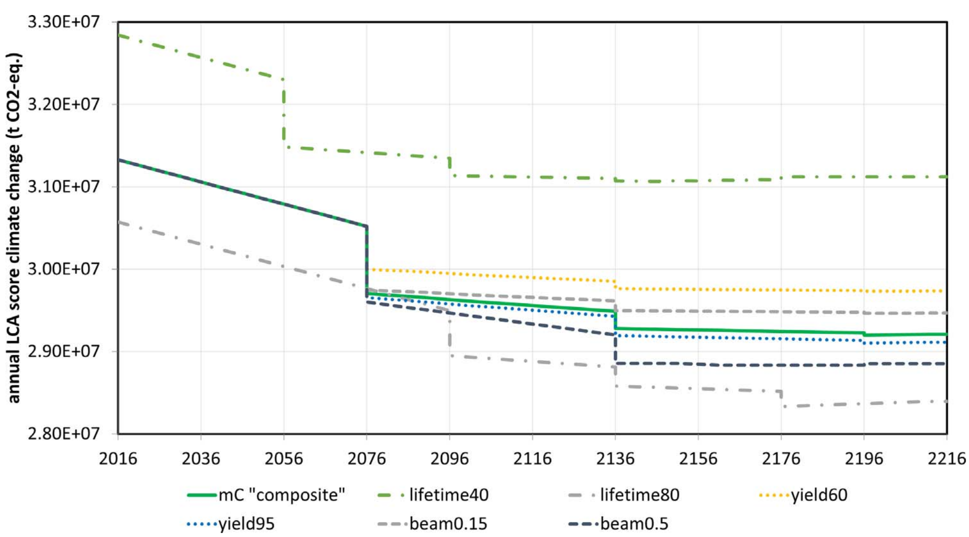

Fig. 5. Time resolved annual climate impacts regarding the multiple cascading (mC) scenario and respective sensitivity analyses, by optimising for CC. All sensitivity analyses are in the mC scenario and for the composite wood house type.

and conversely larger for a 40-year lifetime (see Fig. 5). Storage benefits additionally play a role: as wood cannot cover the full demand for houses, an 80-year lifetime results in potentially larger wood amounts stored in the system and, thus, higher storage benefits in the long run.

Environmental benefits directly scale with the waste wood processing efficiency: the higher the efficiency, the lower the resulting environmental impact. However, as direct substitution benefits are highest in the material use sector, multiple cascading is beneficial even under relatively low recovery efficiencies.

Finally, the waste wood fraction suitable for high-quality board reuse is another influential parameter. Since boards produced from waste wood add substantial wood amounts available for construction, a 50% increase in the beam yield from post-consumer wood enables a larger wood stock increase. This scenario – albeit currently not entirely realistic - clearly demonstrates the importance of high quality wood cascading.

By varying the LCIA scores of the conventional alternatives, changes regarding optimal wood use patterns arise for factors above 1.5 and below 0.75, respectively (see Fig. 6). These variations are, however, plausible for electricity generation. As indicated in Fig. 6, the application of marginal technologies (natural gas for electricity) would lead to the conclusion that CHP were applied instead of heat-only technologies. Furthermore, reducing the LCIA score of the fossil heating mix also eventually results in an optimal solution using CHP. In contrast, an increase leads to a reduced material wood use, as substituting the conventional heating mix becomes more beneficial.

Increasing the LCIA score of the conventional massive house has no influence on the optimal wood utilisation pattern. A significantly lower LCIA score, on the other hand, favours the energetic use of wood. However, storage benefits and larger wood amounts in case of wood cascading entail that material use is favourable even if the LCIA score of the massive house is reduced considerably.

Based on these findings, results of optimal wood utilisation patterns by minimising CC are relatively robust regarding modelling uncertainties of alternative technologies. Reduced LCIA factors can also be interpreted as technology transitions towards other renewables. This sensitivity analysis thus suggests that the main findings are also valid beyond the key assumption of fossil marginal technologies.

For CC-optimised sensitivity analysis results without consideration of biogenic CO_2 emissions and storage effects see Appendix A.7 in the *Supplementary data*.

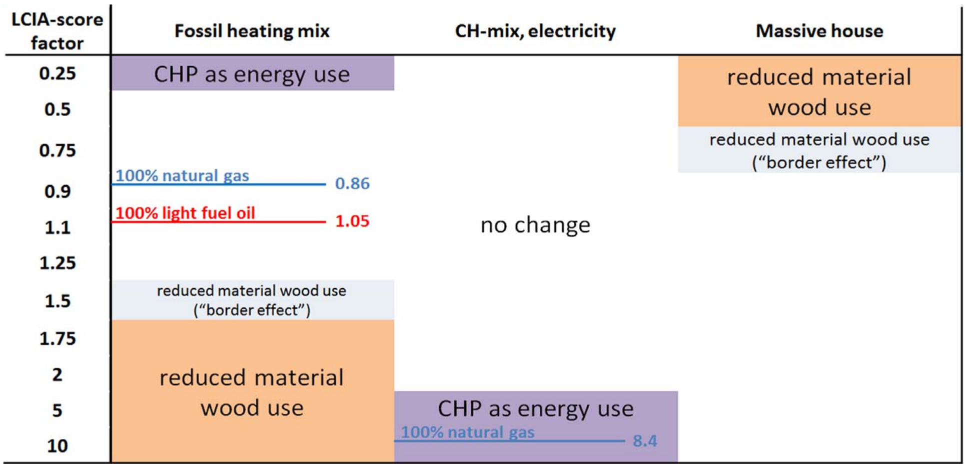

Fig. 6. Changes regarding the optimal wood utilisation pattern by varying the CC LCIA score of conventional alternatives ("fossil heating mix", "CH-mix, electricity" and "massive house") by multiplying the original LCIA score with factors from 0.25 to 10 (i.e. no change = multiple cascading of wood). Factors of a selection of fossil marginal technologies are highlighted (line and associated value). Changes only affecting the last two time steps are indicated by "border effect".

4. Discussion

The first section of the discussion aims to embed specific findings of this study in a larger context. For this, we refer to current wood utilisation practices in Switzerland and compare to the scientific literature. We then discuss novelties, strengths and weaknesses of the chosen modelling approach, and also focus on the results of the assessment of biogenic carbon stocks and flows. Finally, we discuss overall data quality and further investigate trade-offs obtained in the sensitivity analyses.

4.1. Case study results

Between 2010 and 2014, an average of 1,793,000 m^3 of waste wood was generated in Switzerland annually, of which 51% was exported (FOEN, 2015a). Of the quantity used domestically, 42% was incinerated in MSWI plants, 45% in waste wood furnaces and 13% in cement plants (Suter et al., 2016). There is currently no waste wood recycling for material use, e.g. for particle board production, in the country, although it is permitted for untreated and low-contaminated waste wood (FOEN, 2015a; Swiss Confederation, 2016c). Our results demonstrate that both from a climate perspective and in terms of particulate matter formation, additional systemic impact reductions are possible by multiple cascading of wood compared to a single material application and subsequent use for energy. This result relies on the assumption that there are no preference restrictions in the housing demand of consumers and, thus, that additional wood is kept in use through cascading (and not only substituting primary wood). Hence, efforts should be undertaken to promote the demand for wood products and encourage material recycling of waste wood into national wood management strategies. The latest Swiss federal wood resource policy acknowledges the potential of wood cascading by stating that "sustainably available wood should be used efficiently in the sense of an optimised cascade use" and further that "material use of wood assortments that can be used both materially and energetically is generally preferable under consideration of 'cascade criteria' (added value, ecology and multiple use)" (FOEN et al., 2014). In addition, by decreasing waste wood exports, carbon emissions in Switzerland could be further reduced, albeit disregarding the potential environmental benefits from substitution occurring abroad. Taverna et al. (2010) suggested that a decrease of the export to 15%, for instance, would generate over 400'000 tonnes of additional waste wood available for domestic use per year.

For the present study, we assumed that the market potential for wood products in Switzerland is only restricted by the overall demand and that there are no limitative consumer preferences. Currently, this is not entirely given: 25% of the domestically available wood was materially used in the year 2015 (FOEN, 2015a) and the share of wood in new buildings amounts to around 5% for the past decade (FOEN 2015b), whereas the share of domestic wood in the wood building sector amounts to roughly 35% (FOEN, 2016). In addition, the sustainable utilisation potential of Swiss forests is currently not fully exploited (Hofer, 2011; Thees et al., 2013; Taverna et al., 2016). Under these circumstances, an increase of waste wood recycling could intensify the under-exploitation of Swiss forests by primary wood substitution or result in more primary forest wood being used energetically, unless the demand for wood buildings and products increases substantially (Bergeron, 2014). The share of wood in construction is increasing since 2006, however, and the latest update of the fire protection regulation of buildings (VKF, 2017) is expected to further promote wood construction, particularly for multi-storey buildings (FOEN, 2016). In addition, the largest sawmill in Switzerland has recently invested over 10 million Swiss francs to quadruple its production capacity (FOEN, 2016).

With the aim of this study being identification of the environmental effects of various wood utilisation patterns, the results clearly demonstrate the ecological potential of both increased material use of domestic forest wood and efficient recycling of post-consumer wood. Höglmeier et al. (2015) came to similar results in a systemic assessment of Bavaria (Germany), with greenhouse gas (GHG) and PM emission reductions in cases of wood cascading. It is, however, not possible to directly compare the results because LCA data sources, model framework, material recycling options and substitution product choices differ in certain aspects. In addition, our study also accounts for biogenic CO_2 emission patterns, which influence benefits regarding GHG emissions. Suter et al. (2016) examined the environmental performance of current wood utilisation in Switzerland and found that direct substitution benefits regarding GHG emissions are highest for energy generation. However, material use followed by an energetic end-of-life utilisation is preferable, provided that losses are kept sufficiently low. Yet our results show that direct substitution benefits (meaning without effects of cascading and wood storage) are higher in case of a composite-house material wood use and only slightly lower in case of the wood-only house material use scenario. These different results underline the strong dependency on substitution choices and inventories.

Concerning the cascading use of wood, we identified three aspects that strongly influence the overall environmental performance of the system: (1) material recycling options and associated substitution benefits, (2) waste wood processing efficiencies, and (3) lifetimes of wood in material applications. Recycling of wooden construction elements such as beams was found to have a particularly large effect on total environmental impacts as large wood volumes are additionally available in the system. On the other hand, composite wood constructions allow a more efficient use of wood, since more conventional buildings can be substituted by the same wood amount. It is therefore of special interest to promote wood construction types that enable efficient use of preferably untreated domestic wood (FOEN and SFOE, 2009).

The higher the waste wood processing efficiency, the higher are also the potential benefits. In case of multiple cascading, losses accumulate with each additional service cycle of the wood and are inevitably lost for energy generation at the end-of-life (Höglmeier et al., 2015). From a resource efficiency perspective, it is therefore of great importance to keep respective losses at a minimum.

An increased lifetime of wood in material applications, finally, leads to a decreased annual demand for new housing. Having said that, longer storage times in combination with sufficient demand lead to larger potential wood volumes in the building stock in the long run. Consequently, storage benefits are larger and the systemic climate impacts lower. In other words, GHG emissions through wood combustion are postponed further into the future (Werner et al., 2005; Eriksson et al. 2012). On the other hand, the further waste wood incineration is postponed into the future, the less that is known about future heat and electricity mixes and hence the potential substitution benefits. Most likely, cleaner energy technologies will be available and more widespread in the future, thus reducing or even effacing the potential substitution benefits thereof (Werner et al., 2010; Gärtner et al., 2013; Suter et al., 2016). Nonetheless, results underline the climate mitigation potential of long-lived wood products, which are predominantly found in the construction sector (Neubauer-Letsch et al., 2012).

Like wood construction, wood energy plays an increasingly important role in Switzerland (SFOE, 2016). Results indicate the lowest environmental impacts for energy generation at the end of the cascade: wood is combusted when its quality is not sufficient for or does not allow for further material application. Hereby, legal restrictions for the combustion of contaminated waste wood must be considered (Swiss Confederation, 2016a, b). Consequently, problematic waste wood is currently burned in MSWI or cement plants with efficient off-gas filtration. CO_2 savings at the end of the cascade could be increased by incinerating a larger waste wood fraction in adequate waste wood furnaces (Taverna et al., 2010). This is in line with Bergeron (2016) highlighting the importance of efficient waste wood sorting to ensure that all non-hazardous waste wood is incinerated in waste wood furnaces.

In the case of Switzerland, unlike for example Germany (Höglmeier et al., 2015), heat-only recovery was observed to be the most beneficial option, which is due to relatively low climate impacts associated with the average Swiss electricity mix (high shares of nuclear power and hydropower). In this context, the Swiss Energy Strategy 2050 (SFOE, 2012) which contains strategies for a step-by-step withdrawal from nuclear energy must be considered. Consequently, the 36%-share of nuclear energy must be gradually substituted and energy from wood is foreseen as part of the substitution (SFOE, 2012; Prognos, 2012; Nussbaumer, 2013).

Regarding PM formation, wood combustion is a known issue, for example with respect to respiratory health impacts. Small-scale, outdated or incorrectly operated furnaces are particularly problematic in Switzerland (FOEN, 2015c). Optimising for minimal PM formation, CHP is the preferred option over heat-only energy recovery. Hence, wood is ideally combusted in efficient large-scale combustion plants (boiler or co-generation, depending on national strategies) with adequate off-gas filtration systems.

4.2. Modelling approach

This study assessed major influencing factors of environmentally optimal wood use in Switzerland and determined optimal wood use patterns in the future. Special focus was put on wood cascading and biogenic carbon effects. The applied tool combination of dynamic MFA, modular LCA and mathematical optimisation allowed for an explorative assessment of the Swiss wood utilisation system. The combination of LCA and optimisation techniques was applied before (Azapagic and Clift, 1998; Guillén-Gosálbez et al., 2008; Tan et al., 2008; Saner et al., 2014; Vadenbo et al., 2014a, b; Höglmeier et al., 2015; Steubing et al., 2016) and proved to be a suitable approach for systemic identification and assessment of environmental improvement potentials.

Through a number of simplifying assumptions (see also Table S2 in the *Supplementary Data*), we circumvented an overly complex model scope, while allowing us to focus on exploring the main drivers for the optimal wood utilisation patterns. While each of these assumptions has little influence on the overall results, the absolute values of our calculations should be taken with caution. The temporal scope of the model of 200 years implies that aspects like future consumption mixes are uncertain and should not be misunderstood as a realistic prediction of the future.

Firstly, all wood was assumed to be softwood in the model. Material properties and thus possible applications of hard- and softwood are quite different (Krackler and Niemz, 2011). Softwood is mainly used in the construction sector, while hardwood is predominantly used for direct energy generation. However, since all wood processing steps covered in the model are principally conceivable using both hard- and softwood as an input, environmental impacts were assumed to be similar. What is more, the sawlog and residual wood fractions resulting from wood harvest are based on current harvesting considering both softwood and hardwood characteristics. Also, as the hardwood share in native forests is generally increasing, the Swiss wood action plan aims at reinforcing outlet markets for hardwood in the material use sector (FOEN et al., 2014).

Secondly, in this model the material use of wood is limited to the construction sector. The corresponding demanded service *housing* is representative for a range of different material use applications, yet it involves limitations: Both wood house inventories consist of fixed shares of the wooden products beam, board and particle board, which restrict the usage flexibility of these products. Cascaded amounts of particle board, for instance, are bounded on this account, as particle board amounts needed for one unit of wood house are much smaller compared to required beam and board amounts. In other words, the cascade potential of particle board is not fully exploited within the given model framework. Other material use applications such as furniture and packaging could be added to the model to also include other uses (e.g. based on Neubauer-Letsch et al., 2012).

Thirdly, energy use of wood is limited to wood chips. The environmental performance of alternative modern wood heating systems, such as wood pellets, is similar to wood chips (ecoinvent, 2015). Thus, a further differentiation would not provide any benefits for the analysis of the major effects in this work.

Fourthly, wood availability and overall product demands are assumed given and constant over the modelling period from 2016 to 2216. Prognos (2012) calculated scenarios of the Swiss energy demand up to 2050. Depending on the scenario, the electricity demand remains relatively constant whereas the heat demand decreases considerably. Since multiple cascading leads to the lowest environmental impact, a reduced heat demand over time is not expected to change the key findings. Yet, future research could indeed couple the model with scenarios for the Swiss energy system (SFOE, 2012; Prognos, 2012), building inventory and refurbishment patterns (Ostermeyer et al., 2017) and wood supply (Thees et al., 2013, 2017; Taverna et al., 2016).

Fifthly, it is assumed that the initial building stock does not contain any wood. In other words, we focus on the part of the building stock that changes from now on. Consequently, the wood stock is continuously built up and a new stock equilibrium is only reached towards to end of the modelled time horizon. This assumption allows for an illustration of storage effects in case of a wood stock increase, but disregards the potential for recovery from the existing wood stock.

Several studies highlighted the importance of biogenic carbon accounting when assessing climate impacts of bioenergy systems (Cherubini et al. 2011; Myhre, 2013). The linear approximation applied in this work allows for an efficient inclusion into the model. The credited *storage benefits* facilitate the illustration of environmental effects through wood storage, albeit slightly overestimating storage benefits for medium storage times (see Fig. 2). Also, while we are able to reflect storage duration and total release magnitude, impacts are not accounted for at the time they actually occur, meaning temporal impact patterns in Figs. 4 and 5 are merely the consequence of our model choice. Therefore, concepts such as discounting cannot be applied to the results. The scientific community further states the importance of the time horizon involved in the assessment of biogenic carbon emissions (Cherubini et al. 2011; Guest et al., 2013b; Cintas et al., 2015). Extending the time horizon for the GWP factors would lower the importance of biogenic CO_2 emissions in comparison to fossil CO_2 emissions. Therefore, the results would lie in between the CC scores shown here and those presented in Appendix A.6 in the *Supplementary Data*, excluding the effects of biogenic emissions.

Finally, we focused on optimising environmental impacts while disregarding other relevant aspects such as economic feasibility or social factors. Economic aspects may influence optimal solutions in life cycle optimisation processes i.e. the environmentally optimal solution may be economically infeasible (You and Wang, 2011; You et al., 2011). A multi objective approach thus allows for analysing trade-offs between economic, environmental and/or social optima as well as the inclusion of related aspects such as non-cooperative stakeholders (Yue et al., 2013b; Gao and You, 2017). While this paper focuses on environmental aspects concerning wood cascade use, the model structure applied in this study combined with the flexible spreadsheet-based matrix also allows for an inclusion of other factors (economic, social, technical), by adding optimisation constraints or by including additional objectives (e.g. cost minimisation). The development of such additional constraints could be a next step in improving the model and generating more realistic suggestions.

4.3. Data quality and uncertainty

Generally, availability and quality of LCA data relevant to the geographical scope of this study found in ecoinvent v3.2 is very good, not least due to recent updates of the wood value chain (Werner, 2015). All data used represent suitable processes under Swiss or European conditions. Concerning energy generation from wood, ecoinvent v3.2 processes denoted as currently representing state-of-the-art were used.

Substitution choices of conventional alternatives and consumption mixes are never without subjectivity and thus major uncertainties that can influence the results, as the meta-analysis of various studies determining substitution benefits of wood products showed (Sathre and O'Connor, 2010). In a similar vein, the choice of the wooden buildings also represents a subjective assumption.

Uncertainties in this regard are, to some extent, considered by the sensitivity analysis of LCIA scores of conventional alternatives. The analysis showed for climate change that optimal wood utilisation patterns are relatively robust regarding uncertainties in the choice of conventional alternatives. However, natural gas is likely to play a more dominant role in the future electricity mix due to the overall increasing electricity demand, while the overall heat demand is decreasing (SFOE, 2014). Taking natural gas-fired power plants as the marginal technology for electricity would mean that CHP is the optimal energy-recovery option also from a climate perspective (the same trade-off holds true for fossil GWP only, see A.6.3, *Supplementary data*). Additional statistical analyses such as Monte Carlo analysis would further prove the robustness, as within the sensitivity analysis conducted, only one LCIA factor is adapted at a time.

The sensitivity analysis of core model parameters is another measure to account for major uncertainties within the model. Lifetimes of wood in different product applications showed the strongest impact. Whereas the technical life length of wooden construction elements may be longer than 60 years (Ramage, 2017), average lifetimes of furniture are between 15 and 20 years (Neubauer-Letsch et al., 2012; Kim and Song, 2014). A further differentiation of the material use sector would enable more accurate estimations of the total wood storage potential in this regard. Due to high annual waste wood amounts and to strict legislation and efficient collection systems, high waste wood recovery shares can be expected (FOEN, 2006), and thus we assume that losses assessed by Höglmeier et al. (2015) for the state of Bavaria are transferrable to Switzerland. Finally, a detailed assessment regarding wood amounts and compositions in the Swiss building stock would allow for more targeted estimations of the potential of high-quality recycling of wooden beams.

5. Conclusions and outlook

Based on our findings, we conclude with the following recommendations for optimal wood use in Switzerland:

(1) Under the assumption of complete interchangeability of wooden and non-wooden alternatives, results indicate the lowest environmental impacts for the case of multiple cascading both in terms of climate change and particulate matter formation. Waste wood is thus preferably reused repeatedly in the highest quality possible: first as wooden construction elements followed by further recycling steps as particle board. At the end of the cascade, the remaining waste wood should still be incinerated.
(2) Regarding GHG emissions, heat-only recovery leads to larger substitution benefits due to Switzerland's low-carbon electricity mix (CHP would be optimal under average European conditions or when assuming marginal Swiss electricity supply from natural gas). Regarding PM emissions, CHP is the preferred energy recovery option. PM emissions from wood combustion still pose a critical area for improvement, especially regarding small-scale furnaces.
(3) Concerning wood cascading, both waste wood processing efficiencies and available cascade options are decisive for the total environmental impacts. Benefits through cascading can be increased considerably by an efficient waste wood management including material recycling.
(4) When considering biogenic carbon flows, longer lifetimes of wood products are the decisive factor to increase their climate change mitigation potential.

The tool combination of dynamic MFA, LCA and optimisation was found to be helpful for identifying optimal wood utilisation patterns in Switzerland. It integrates the strengths of all methods, i.e. it enables a simultaneous consideration of system and product level data and constraints, environmental assessment and the identification of optimal scenarios. A major advantage is its flexibility: both the wood flow model and the constraints of the optimisation model can be easily adapted and extended, or a similar model developed for a different sector or value chain. For example, by coupling the model with respective data, future scenarios also including dynamic consumption mixes, wood supply patterns, and building stock development could be accounted for, which would allow for developing more detailed future wood utilisation scenarios for Switzerland. In addition, the potential and limitations for cascading wood recovered from building deconstruction should be assessed for Switzerland.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2017.12.026

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