The potential role of wood acetylation in climate change mitigation

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Keywords: acetylated wood, carbon footprint, climate change mitigation, green building, greenhouse gas emissions

ABSTRACT

In a carbon footprint assessment, the greenhouse gas emissions during the life cycle of a material can be measured, and compared to alternative products in terms of kg CO_2 equivalent. If applied correctly, wood acetylation opens up a range of new innovative applications in which high performance yet carbon intensive non-renewable materials such as metals, plastics and concrete may be replaced by abundantly available non-durable wood species. To better understand the difference in greenhouse gas emissions of Accoya® wood (acetylated non-durable wood) and relevant alternative materials (steel, concrete, plastics, hardwood), this study first presents the emissions based on a cradle-to-gate scenario, thus including all emissions (sourcing, transport, processing, etc.) until the factory gate, for Accoya® wood based on the latest production figures for various suitable species. As the cradle-to-gate assessment excludes use-phase and end-of-life related aspects such as material use, durability, maintenance, recycling scenarios and carbon sequestration, the second part of this study takes the production results as input for an assessment of the full life cycle (cradle-to-grave) with a typical window frame as unit of comparison. The results show that if lifespan considerations are included, Accoya® wood has a considerably lower carbon footprint than non-renewable materials and unsustainably sourced hardwood, and is competitive in terms of carbon footprint with sustainably sourced hardwood. Because of the limited emissions during production and carbon credits related to temporary carbon storage and bio-energy production during End of Life, all sustainably sourced wood alternatives, including Accoya® wood, are even CO_2 negative over the full life cycle. The final part of this paper puts these outcomes in a global perspective and discusses the potential implications large scale acetylation could have in reducing greenhouse gas emissions worldwide.

INTRODUCTION

Climate change is increasingly being acknowledged as a threat to our environment and human society. There are various strategies for climate change mitigation either by reducing the causes of CO_2 emissions (*e.g.* higher energy efficiency, better insulation, using renewable energy, *etc*.) or by increasing the sinks (carbon sequestration), in which forests and forest products play a major role.

During growth, trees absorb CO_2 from the atmosphere, while producing oxygen in return, and store this in their tissue and soil, and after harvest in wood products

throughout their lifespan. As such, forests and wood products play an important role (both negative as positive) in the global carbon cycle through deforestation, forest conservation, afforestation (planting of trees on soils that have not supported forests in the recent past) and increasing application of wood in durable (construction) products.
Although afforestation in temperate regions is a positive development, for the world as a whole, carbon stocks in forest biomass still decreased worldwide by an estimated 0.5 Gigatons due to deforestation in (sub)tropical regions between 2005 and 2010 (see also Figure 1), where a region of over 8 million hectares was deforested (FAO 2010).

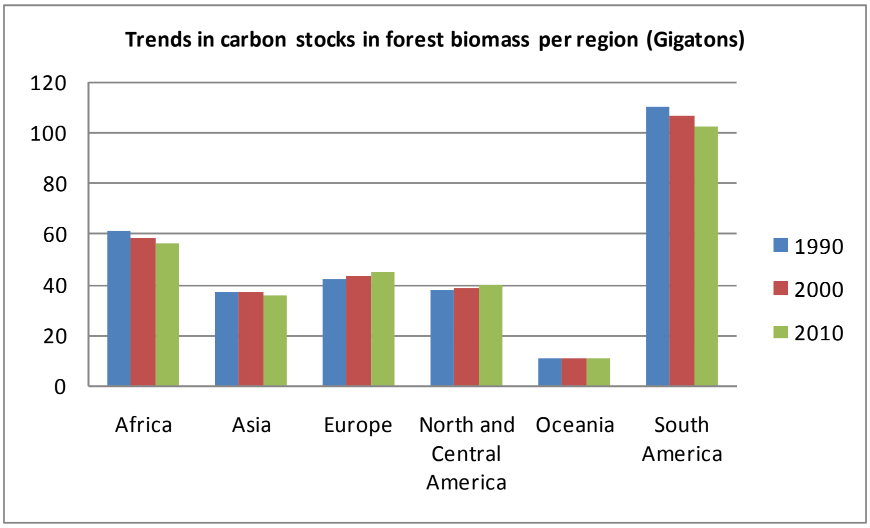


Figure 1: Trends in carbon storage in forests from 1990-2010 (FAO 2010)

Combined with the conversion of forests to agricultural land or for development of infrastructure, one of the main causes of deforestation in tropical regions is (illegal) logging of tropical hardwood from rainforests, which is high in demand worldwide because of its superior performance over softwood in terms of durability, hardness and sometimes dimensional stability.
Although the amount of sustainable sourced and certified tropical hardwood on the market is increasing - due in part to new legal requirements like the European Timber Regulation and the expanded Lacey Act in the USA - demand is still considerably higher than supply and this trend is expected to continue with improving incomes in emerging economies. Sustainable and durable alternatives are needed to reduce pressure on endangered sources. Plantation grown hardwoods, while providing an important resource, do not have the durability and other important performance characteristics of increasingly scarce old growth forest harvests. Modified wood can play an important role in bridging this supply gap as it enables abundantly available, sustainably sourced non-durable wood species to be used in high performance applications through the significantly improved stability and durability. However, wood modification in itself may result in additional greenhouse gas emissions.
It is therefore important to understand to what extent the increased durability outweighs the increased emissions caused by the modification process, also in comparison with alternative non-renewable materials. In this study this comparison is executed for acetylated wood (Accoya®), one of the best known and performing methods of chemical wood modification. Accoya®'s performance (Figure 2) has been widely reported as exceeding that of even the most durable and stable old growth tropical hardwoods (see for example Bongers *et al.* 2013).

Figure 2: Accoya® wood used for cladding, decking and structural beams in boathouse in Horning, Norfolk, UK.

METHODOLOGY

Carbon Footprint Methodology

In a carbon footprint assessment, the greenhouse gas emissions (GHG) during the life cycle of a material can be measured, and compared to alternative products in terms of kg CO_2 equivalent (CO_2e). Although not as comprehensive as the Life Cycle Assessment (LCA) methodology, as defined in the ISO 14040/44 series (ISO 2006), which besides the Global Warming Potential (GWP), also includes environmental effects such as acidification, euthrophication, smog, dust, toxicity, depletion, land-use and waste, a carbon footprint assessment is an excellent – and most commonly used - tool to assess a material's environmental impact.

Cradle to Gate Data (Production Phase)

A carbon footprint assessment was executed for Accoya® wood (Trueman 2013) in line with the World Business Council for Sustainable Development and World Resources Institute's Greenhouse Gas Reporting Protocol best practice guidelines (WBCSD and WRI 2004), based on a cradle to gate scenario, thus until the factory gate. This includes sourcing, harvesting and processing of the input timber, as well as all energy and raw material consumption and waste production in the acetylation plant of Accsys Technologies in Arnhem, the Netherlands.

The main input resources to produce acetylated wood are timber and acetic anhydride, with acetic acid as main co-product. This acetic acid is sold into a wide range of industries and therefore replaces merchant acetic acid on the market. As such the allocated GHG emissions of acetic acid are deducted from the emissions relating to the acetylation process, which is in line with PAS 2050 requirements (BSI group 2011) as well as ISO 14044 (2006), section 4.3.4.2 ("system expansion").

Compared to an earlier cradle to gate carbon footprint assessment presented at ECWM 5 (van der Lugt *et al*. 2010), several adjustments were made in the Accoya® production process, taken into account in the assessment by Trueman (2013).

- Besides radiata pine, also Accoya® wood made from red alder, European alder and Scots pine were included. The first three species are already commercially available on the market, the latter is currently being used in pilot application installations on commercial buildings and is expected to become commercially available in the near future.

- Increased focus on purchase of acetic anhydride produced through methyl acetate carbonylation because of significant lower greenhouse gas emissions compared to the other main production method (cracking acetic acid to Ketene).
- Increased production efficiency in the acetylation plant relating to less consumables (energy, acetic anhydride, *etc*.) per cubic metre Accoya® produced.

Figure 3 presents the results in cubic metres Accoya® made from several different sources as compared with other commonly used material alternatives such as PVC and aluminium, based on the "market mix" figures, *i.e*. the mix of recycled and virgin materials on the market. Note that "sustainably sourced wood" in this paper relates to a relatively consistent biomass at the forestry level, in which the carbon stored in the standing volume remains stable. In this paper "unsustainably sourced wood" relates to common clear cutting practices.

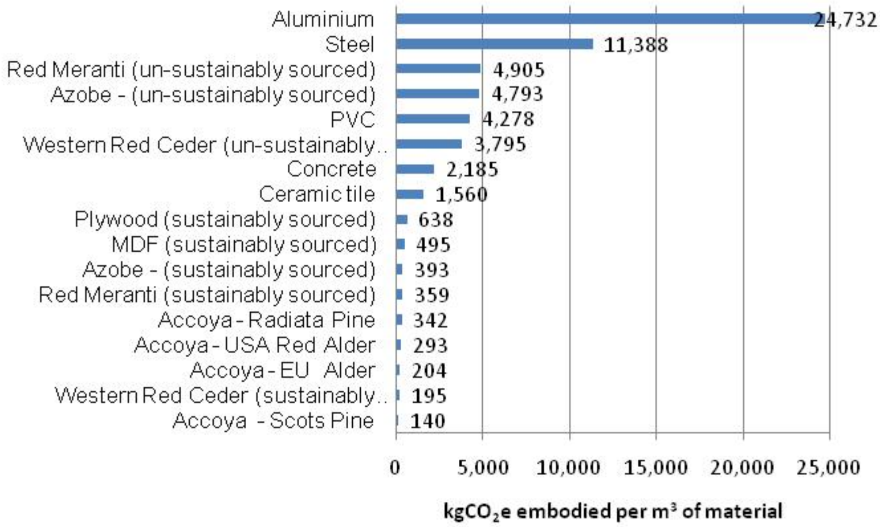


Figure 3: the greenhouse gas emissions of several building materials per cubic metre based on a cradle to gate scenario (Trueman 2013, Hammond and Jones 2011, Ecoinvent 2013)

Cradle to Grave Data (Including Use Phase)

It is important to understand that the carbon footprint per cubic metre provides limited information for a realistic comparison with other materials since additional use-phase related aspects of the various material alternatives are not yet included.

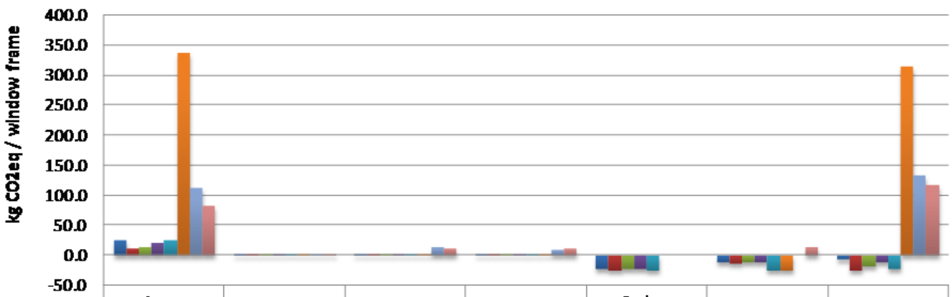
For the materials illustrated above, in-use emissions are likely to be centred around i) material properties such as density or strength, which dictate the volume of material required, ii) durability of the material which influences lifespan, iii) maintenance requirements including procedures and frequency, iv) carbon sequestration properties of renewable materials and v) Reuse, disposal and recycling routes available.

Therefore, to avoid comparing 'apples with oranges', for a complete "cradle to grave" assessment the carbon footprint results per cubic metre need to be 'translated' to application examples, in this case a common window frame, to include the in-use and end of life phase related aspects mentioned above. In order for the comparison to be fair, all alternatives in this application have to meet the same functional requirements.

The functional unit chosen for the window frame was adopted from Richter *et al.* (1996) and is expressed as "one window frame with the outer dimensions of 1650 mm x 1300 mm with a total surface of 4,38 m^2 (interior and exterior)". Relevant alternatives for this application were tropical hardwood (red meranti), both sustainably and unsustainably sourced, aluminium and PVC. Lifespans for the window frame alternatives were assumed to be mainly determined by the durability of the frame (Accoya® 50 years, meranti 35 years, aluminium 50 years, PVC 35 years), and are based on a typical Dutch window frame design, well executed and maintained. For a detailed explanation of the assumptions as well as the related calculations please refer to Vogtländer (2013). The assessment includes End of Life considerations and the effect of carbon sequestration over a 100 year timeframe as suggested in the leading standards in carbon footprint and LCA (ILCD, PAS 2050: 2011 and the EN development norm EN16449). These methods account for the carbon sequestered in the wood to be included as a negative CO_2 value with respect to the emissions, which is deducted from the total fossil CO_2 emissions. A higher negative CO_2e value is allocated if the life span of the wood in-use is longer. In the End-of-Life phase it is assumed that 100% of the material is incinerated for energy production, applying the Lower Heating Value of the waste material. For the Western European situation this is a plausible and easily comparable assumption. This energy output from biomass substitutes heat from oil, leading to a "carbon credit" for the avoided use of oil. The Life Cycle Inventory (LCI) data, required for the calculations are from the commonly referenced Ecoinvent v2.2 database (2013) of the Swiss Centre for Life Cycle Inventories, and the Idemat 2012 database (2013) of the Delft University of Technology. The Idemat LCIs are based on Ecoinvent LCIs and some data of the Cambridge Engineering Selector (2013).

RESULTS

The results of the cradle to grave window frame carbon footprint comparison are presented in the graphs below, first per process step (Figure 4) then for the total emissions (Figure 5).



	Input materials	Transport	Profiling	Coating	Carbon sequestration	End of Life	TOTAL
Accoya® Radiata pine	23.4	0.86	1.25	2.25	-22.97	-12.30	-7.5
Accoya® Scots pine	9.6	0.95	1.25	2.25	-25.39	-13.60	-25.0
Accoya® EU Alder	14.0	0.90	1.25	2.25	-24.20	-12.95	-18.8
Accoya® USA Alder	20.1	0.87	1.25	2.25	-23.20	-12.42	-11.2
Red meranti (sustainable)	24.6	1.20	1.25	2.25	-25.97	-26.31	-23.0
Red meranti (unsustainable)	336.0	1.20	1.25	2.25		-26.31	314.4
Aluminium	110.8	0.50	12.9	8.31			132.5
PVC / steel	81.9	1.17	10.04	10.05		12.84	116.0

Figure 4: Greenhouse gas emissions (kg CO2eq) per process step for a window frame

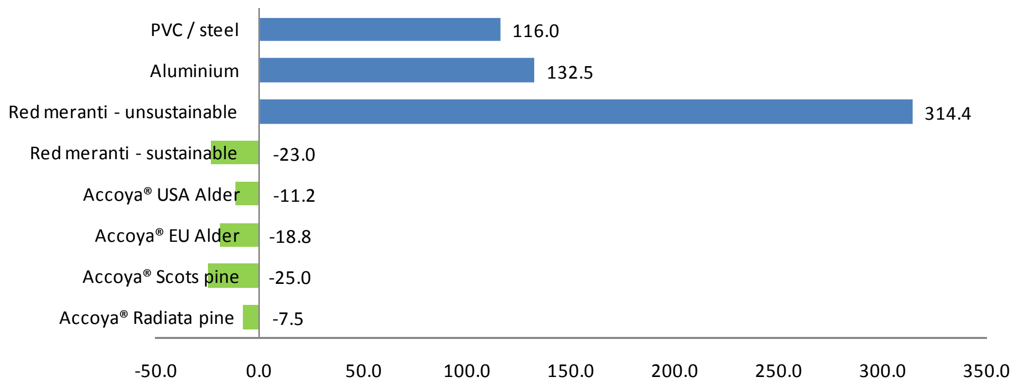


Figure 5: Greenhouse gas emissions (cradle to grave) in kg CO2eq per window frame

From the graphs several conclusions can be made:
First of all, because of the limited emissions during production in case of sustainable sourcing, credits that can be earned through carbon sequestration (especially in case of a long lifespan) and incineration for energy production in the End of Life phase, all wood products, including Accoya®, *are CO_2 negative over the full life cycle*. The best performing alternative is Accoya® made from locally sourced species (in this case Scots pine). The graphs also show that the non-renewable materials PVC, steel and aluminium perform considerably worse than sustainably sourced wood, especially because of the high embodied energy (emissions during production). Although through recycling (based on current market mix figures) aluminium, PVC and steel earn some credits back, this does not outweigh the high emissions during production.
However, in the case of tropical hardwood from rain forests (deforestation) the picture totally shifts and wood is the worst performing alternative (see unsustainably sourced Meranti). This shows the importance of conservation of tropical rainforests as they act as important carbon sinks. Furthermore, the eco-burden of transport and maintenance (coatings) of the window frames appears to be negligible in the total context.

Note that another recent environmental impact (LCA) study on window frames in the UK executed on behalf of the Wood Window Alliance (Menzies, 2013) provides similar independent results as the study presented in this paper.

DISCUSSION

It should be noted that several environmental issues cannot be caught by a carbon footprint. Although the scope of a LCA is a lot broader than the carbon footprint, and as mentioned earlier, also includes several other eco-indicators, in both instruments the issue of social sustainability is not included. Land-use change is incorporated in LCA indicators like Recipe and Eco-costs, and is strongly related to the harvesting of tropical hardwood. For example, globally FSC certified tropical hardwood is partly sourced from plantations and semi-natural forests, but the lions share (64%) is still coming from natural forests (harvested with Reduced Impact Harvesting), having a negative impact on biodiversity and carbon sequestration.
Yield of land is another specific aspect of sustainability, not included in a carbon footprint, which is related to the fact that land is becoming scarce, especially when current materials (metals, fossil fuels) will be replaced by renewable materials like wood and crops for biomass. The high growing speed of species suitable to produce

Accoya®, such as radiata pine, is an environmental competitive advantage over regular wood species, and in particular for the slow growing tropical hardwood species it tries to substitute.

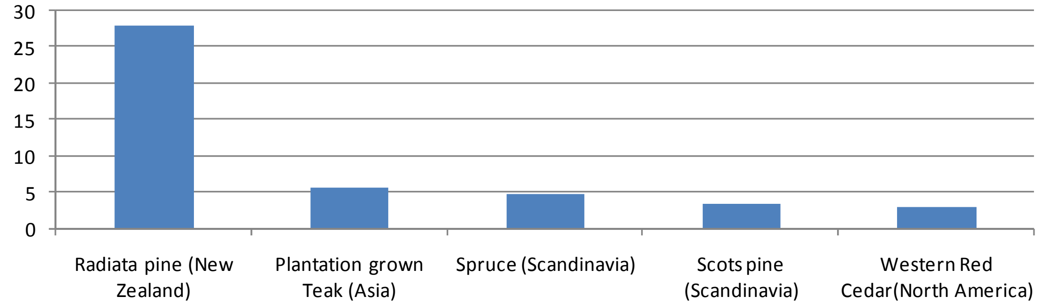


Figure 6: Annual yield for various wood species in cubic meters produced per hectare per year (FAO 2006, MAF 2008, USDA 2013)

This does put the results of the carbon footprint in another perspective by looking at a global level. One of the important conclusions of the cradle to grave carbon footprint comparison is that when sourced from tropical rainforests, wood is the worst performing alternative. This shows the importance of conservation of (tropical) forests as they act as important carbon sinks, and further highlights the potential important role of non-toxic wood modification technologies such as acetylation; These technologies enable abundantly available softwood to substitute tropical hardwood, and even carbon intensive manmade materials such as plastics, metals and concrete further reducing greenhouse gas emissions Furthermore, they provide a powerful drive for reforestation as softwood species can now serve as input for high performance wood.

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