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Life-cycle assessment and carbon sequestration

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INTERNATIONAL NETWORK FOR BAMBOO & RATTAN

The Environmental Impact of Industrial Bamboo Products

Life-Cycle Assessment and Carbon Sequestration

P. van der Lugt, PhD J.G. Vogtländer, PhD

Second edition

International Network for Bamboo and Rattan
INBAR, the International Network for Bamboo and Rattan, is an intergovernmental organization bringing together some 41 countries for the promotion of the ecosystem benefits and values of bamboo and rattan.

Keywords: bamboo, life cycle assessment, product, carbon sequestration, climate change, INBAR

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International Network for Bamboo and Rattan (INBAR) is the multilateral development organisation of 41 Member States for the promotion of bamboo and rattan. INBAR supports its members to include bamboo and rattan in their sustainable development action plans and green economy strategies. It promotes innovative ways of using bamboo and rattan to improve rural livelihoods, protect the environment, address climate change and issues of international bamboo and rattan trade and standards. INBAR connects a global network of partners from government, private and NGO sectors to promote a global agenda for sustainable development using bamboo and rattan.

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This study was conducted in conjunction with the **Design for Sustainability (DfS) Program of the Faculty of Industrial Design Engineering of Delft University of Technology**. DfS focuses on research in the field of sustainable development. The mass consumption of goods and services should involve the continuous improvement of environmental, economic and social-cultural values. The central objective of the DfS research programme is the exploration, description, understanding and prediction of problems and opportunities for innovating and designing products and product service systems of superior quality.

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MOSO International was founded in the Netherlands in 1997 and since that time has established itself as the European market leader in the development of innovative and sustainable bamboo products in four product groups: flooring, outdoor (cladding and decking), panels, veneer and beams and unlimited solutions (customized solutions for industrial clients). Besides product excellence and innovation, sustainability is one of the key drivers of our business. We continuously strive to improve the already excellent environmental performance of MOSO's bamboo products and the company tries to communicate this in a transparent manner following internationally accepted methodologies. This INBAR Technical Report certainly contributes to that goal.

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Foreword

Dr. Hans Friederich
Director General, INBAR
October 2015

Changing consumption patterns are placing increasing pressure on the world's natural resources and fuelling financial, food and climate crises around the globe. A more sustainable approach to economic development is needed that accounts for all components of the production and consumption processes, from the raw materials used in production to the waste that is disposed after consumption.

This study considers whether the use of industrial products made from bamboo can help to offset the environmental effects of climate change, provided the bamboo is harvested from a natural forest or a plantation created to improve degraded lands.

The study used a Life-Cycle Assessment (LCA) approach to gauge the environmental impact, including the carbon footprint, of industrial products in Western Europe made from bamboo and to compare it with that of more commonly used materials such as tropical hardwood. The LCA also reveals how each step of the production process effects the overall environmental impact of the product. As a result of the assessment, MOSO International BV, the supplier of the bamboo materials used in this study, has been able to improve many of its production processes.

This report updates the environmental assessments made in the PhD thesis *Design Interventions for Stimulating Bamboo Commercialization* by Pablo van der Lugt (2008). The new data are based on the latest bamboo production figures and updates of relevant databases.

The authors have assumed that the raw bamboo cited in the study, which is sourced from China, originates from either natural bamboo stands or from plantations established through a national landscape improvement programme. This programme aims to transform slope agriculture and barren lands into healthy, productive bamboo forest.

We hope that this study might be useful to manufacturers and other stakeholders in bamboo and wood production chains that want to reduce the environmental impacts of their products. It also shows the positive role that bamboo can play in mitigating the effects of climate change and helping people to adapt to the impact of climate change on their surroundings. By highlighting the potential of bamboo to contribute to sustainable building practices, we also hope to increase its global market share.

Glossary

Biogenic CO2 is captured in biomass during the growth of a plant or tree and, consequently, in a biologically-based product.

Carbon footprint is a commonly used methodology in which the greenhouse gas emissions during the life cycle of a product can be measured in terms of their kg CO2 equivalent (CO2e).

Carbon negative is a negative outcome of the carbon footprint of a product, i.e. when carbon credits through carbon sequestration and energy production at the end of life phase are higher than the emissions caused by production and transport.

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide, in this case in bamboo biomass (forests and products).

Cradle-to-gate assessments describe the aggregated environmental impact of a product during production, i.e. from resource extraction, transport and final processing until it is ready for shipment to the customer at the factory gate.

Cradle-to-grave assessments include the aggregated environmental impact of a product during the use and end-of-life phases, thus throughout its full life cycle.

Eco-cost is an indicator in the Life-Cycle Assessment (see below) used to express the total environmental burden of a product over its life cycle on the basis of the prevention of that burden.

Life-Cycle Assessment (LCA) is a methodology used to assess the environmental impact associated with all stages of a product's life cycle from cradle-to-grave (see above). In contrast to a carbon footprint assessment, LCA is based on several environmental indicators which, besides the Global Warming Potential (carbon footprint), also include acidification, eutrophication, smog, dust, toxicity, depletion, land-use and waste.

Life-Cycle Inventory (LCI) is an element of the LCA, which involves the development of an inventory of the flows of a product system, including inputs of water, energy, and raw materials and releases to air, land, and water.

Executive summary

This report presents the results of a Life-Cycle Assessment (LCA) and carbon footprint analysis of a selection of industrial bamboo products that are manufactured by the company MOSO International. The analysis was done to determine the impact that their production and disposal have on the environment. Bamboo flooring, decking, panels and beams have been evaluated.

A comprehensive explanation is offered of how carbon sequestration can be calculated, following LCA methodology. This LCA is specific to the product evaluations described in this report and is not applicable to other manufacturers' products. The assessment described here is done for the production (cradle-to-gate) plus the waste (end-of-life) stages of the bamboo products, but does not include the user stage, when the product is in use by consumers after purchase.

Bamboo products are increasingly found in western markets, with recorded international trade of some $2 bn in 2012, the majority of which is imported to European and North American consumer countries. As bamboo products are increasingly perceived as "green" and environmentally friendly, it is important to have an effective way to evaluate and verify these claims – to reassure producers and consumers, and help producers find ways to make their production system even "greener". The LCA is a widely used and recognized method for achieving this.

This study shows that if production parameters are optimised, these industrial bamboo products can have a negative carbon footprint over their full life-cycle, from cradle to grave. This means that the credits gained through carbon sequestration, and from burning to produce electricity in a power plant at the end of each product's life, outweigh the emissions caused by the production and transport processes.

At end-of-life, it is assumed that 90% of the bamboo products are incinerated in an electrical power plant and 10% will end-up in landfill, a realistic scenario for Western Europe. The LCA was done following International standards ISO 14040 and 14044. In addition, the capture and storage (sequestration) of CO2 has been taken into account.

It is hoped that the analysis described here will inform and encourage other bamboo producers to do similar life-cycle analyses of their production systems, to better understand where they can focus investments to reduce the environmental impacts of their products. It also aims to inform policy-makers about the sustainability of bamboo products, to encourage them to specify the use of this resource in national and international policies and investment plans.

1. Introduction & Scope

Bamboo decking is increasingly popular in Europe

What is Life Cycle Analysis?

Life Cycle Analysis (also known as Life Cycle Assessment) is a means of systematically assessing the environmental aspects of a product's life, from raw material extraction to disposal and/or recycling ("cradle to grave"). It is an accounting instrument to support environmental decision-making and managing environmental risks. LCA is based on several environmental indicators which, besides the Global Warming Potential (carbon footprint), also include acidification, eutrophication, smog, dust, toxicity, depletion, land-use and waste. It can increase our understanding of how "environmentally friendly" a product is and, because it looks at every stage in a product's life, enable changes to be made at the right stages of a product's life-cycle to improve its environmental sustainability.

To standardise methods and procedures and ensure comparability and quality, the International Standards Organisation developed standards for LCA (ISO 14040:2006) that are now the basis for many of the LCAs conducted today.

An LCA comprises four components:

1. Goal and Scope definition - A description of the product under study, its function, aspects of the life cycle to be studied and the purpose of the study.
2. Generation of a Life Cycle Inventory – a detailed account of all the inputs and outputs involved in the defined environmental impact categories.
3. Inventory analysis - Components of the analysis are organised to enable evaluation of impacts in commonly-used categories as defined at the outset. These enable specific questions to be answered e.g. energy consumption, greenhouse gas emissions, resources depletion and so on.
4. Interpretation - the results are reported in the most informative way and the need and opportunities to reduce the impact on the environment are evaluated.

LCA's are increasingly used to evaluate the environmental impacts of building products including timber and other wood forest products, but have not yet been applied in the bamboo sector. Bamboo products are increasingly found in western markets, with recorded international trade of almost USD $2bn in 2012, the large majority of which is imported into affluent consumer countries and it is necessary that as bamboo products are increasingly perceived as "green" and environmentally friendly that means of evaluating this are employed. This can both reassure producers and consumers, and help producers to find ways of making the production system even "greener".

Specific benefits of carrying out LCAs on bamboo products

LCAs must be scientifically rigorous, and thus are technically challenging and time-consuming and may be expensive. But the benefits are many – they:

- Enable bamboo producers to prioritize investments to reduce the environmental impacts of the product.
- Reduce production costs by informing decisions that can increase the efficiency of resource use.
- Identify improvements to the product that make it better suited to the task it is designed for.
- Inform consumers of the environmentally-friendliness of the product, and thus help inform their purchasing and usage decisions. LCAs also form the basis of Environmental Product Declarations (e.g. http://www.environdec.com/) which are increasingly mandatory in sustainable building certification systems such as LEED and BREEAM.
- Inform and engage policy-makers, and the environment-related policies and legislation they produce, of the environmental status of the product.
- Help producers and retailers comply with relevant legislation, such as the display of environmental data on packaging.

Bamboo splits are selected for pressing into boards at a factory in China

Because of their rapid growth and widespread applications, giant bamboo species such as Moso bamboo (Phyllostachys pubescens), which is widely grown in China and forms the backbone of the country's bamboo sector, are increasingly seen as environmentally benign renewable material alternatives to wood products. Whilst aspects of wood and bamboo production are similar, bamboo production involves longer production chains than wood products, as well as longer transport distances to market. These factors are likely to influence the environmental profile of the products and need to be investigated and quantified within the LCA.

Bamboo has over 10, 000 uses, and more are added every year

This study is based on the product portfolio of MOSO International BV:

- Flooring & floor covering (solid strip, solid wide board, 2-ply flooring, industrial flooring, flattened bamboo)
- Thermally modified decking and cladding
- Panels & beams (solid panel, 1-ply panel, veneer, solid joist)

Engineered bamboo flooring products, e.g. bamboo top layer on a high or medium density fibreboard (MDF / HDF) carrier, were excluded from the scope of the study.

The LCA looked at the production chain of bamboo products manufactured by MOSO International BV following best practice and therefore is not typical for other industrial manufacturers of bamboo products.

The LCA is based on a cradle-to-warehouse-gate plus end-of-life analysis as shown in Figure 1. The use phase was kept out of the analysis, because the emissions in this step are negligible and are often based on user preferences (e.g. to apply oil to a floor or to leave it untreated).

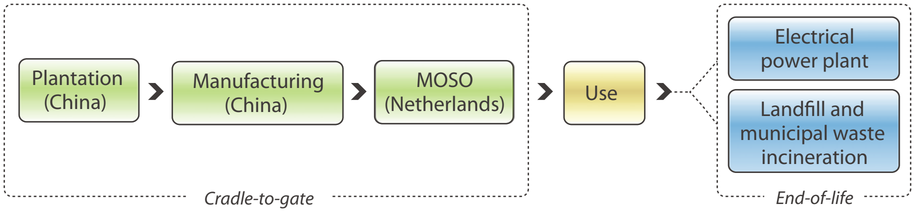


Figure 1: System boundary: cradle-to-gate plus end-of-life.

The report uses two single impact indicators, which have the advantage of expressing the combined environmental impact of all environmental categories in a product's life cycle in one number:

- The CO2 equivalent (carbon footprint), which can easily be understood and explained but omits other polluting emissions (like SOx, NOx, carcinogens, fine dust, etc.)
- The eco-costs system, which incorporates 3000 polluting substances (as well as materials depletion). [1]

An important advantage of bamboo is its high growing speed. The sustainability issues related to the resulting yield of land, typically excluded in LCAs, are dealt with in Annex I.

[1] For more information, see Wikipedia http://en.wikipedia.org/wiki/Eco-costs

2.Scientific background of the LCA and the CO2 cycle

The use of bamboo for outdoor applications is increasing in Europe and North America

Sequestration – the capture and storage of CO_2 in wood – is an important concept for sustainability. It is also a highly complex topic that is subject to much discussion among experts. This chapter attempts to clarify some of the issues around this complex topic, including delayed pulse and system expansion (For a complete scientific analysis, see Vogtländer at al. (2014).

Carbon sequestration at the product level

Biogenic CO_2 is captured in wood/bamboo during the growth of a tree or stem. Figure 2 shows the carbon pathway as it applies to a bamboo product. Here, there are no net carbon emissions, as carbon captured in the plant when it grows is recycled back into the atmosphere later. It is stored in the products the plant is used to produce and only released at the end-of the product's life when it degrades or is burned. If a product is burned in an electrical power plant, then the system generates electricity or heat - which can replace electricity from fossil fuels and so gives the product 'carbon credit', a contribution towards a negative carbon footprint.

This phenomenon is known as the substitution approach in consequential modelling.[2] For a complete scientific analysis, see Vogtländer at al. (2014).

Note: the text in this chapter is largely taken from Section 4 of Vogtländer et al. (2014)

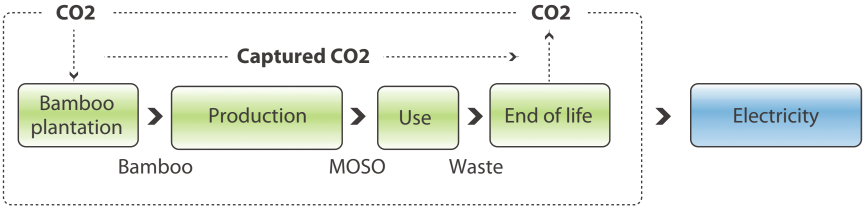


Figure 2: The CO2 cycle on a product level

Carbon sequestration can be included in an LCA if the bamboo is burned for electricity or heat. The positive effect of temporary carbon storage in durable products cannot be analysed on the basis of a single product, although an attempt to do so has been made in two important LCA systems – the ILCD Handbook (EC-JRC 2010) and the PAS 2050:2011 Specification (BSI 2011) – by providing a credit for the temporary storage of carbon in bio-based renewable products. However, this method results in an overestimation of the benefits of temporary fixation of biogenic CO2 and should therefore be avoided in LCA (Vogtländer et al. 2014).

The effects of carbon sequestration at the global system level

CO2 is stored in vegetation, in the ocean and in products (e.g. buildings and furniture). The details of global carbon mass balances are very complex; however, understanding the basics of the LCA allocation method used in this report requires starting from the highest possible aggregation level (the so-called Tier 1 and Tier 2 approach of the Intergovernmental Panel on Climate Change - IPCC). Using this approach, we look at vast forest areas (e.g. in Scandinavia, the Baltic countries, European Russia, Siberia, Canada, New Zealand), where there is a continuous rotation of the forests. The local carbon sequestration effects caused by harvesting are levelled out within such regions, since only a small proportion of the trees are harvested each year.

Figure 3 provides a simplified schematic overview of this level of the global carbon cycle.

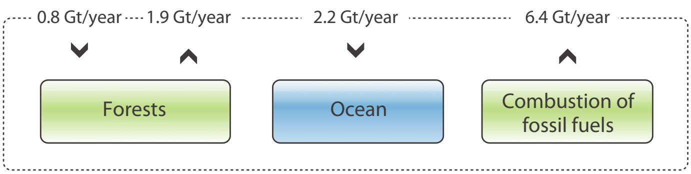


Figure 3: Global anthropogenic fluxes of CO2 (Gt/year) over the period 2000–2010

[2] See Section 14.5 of the ILCD Handbook (ECJRC 2010).

Anthropogenic CO_2 emissions on a global scale can be characterized by three main flows:

- Carbon emissions per year caused by burning fossil fuels: 6,4 Gt/year (Solomon et al. 2007)
- Carbon emissions per year caused by deforestation in tropical and sub-tropical areas (Africa, Central America, South America, South and Southeast Asia): 1,93 Gt/year (FAO 2010)
- Carbon sequestration per year by regrowth of forests on the Northern Hemisphere (Europe, North America, China): 0,85 Gt/year (FAO 2010).

It can be concluded that the global carbon cycle can be significantly improved in the short term by making the following changes:

- Burning fewer fossil fuels
- Stopping deforestation
- Intensifying the use of forests in the Northern Hemisphere through better management and wood production on plantations
- Afforestation (planting trees on soils that have not supported forests in the recent past)

As we have seen above, increasing the use of wood in buildings would appear to be an additional approach. However, it is unrealistic to think that merely using more wood in design and construction will lead to carbon sequestration and thus counteract global warming. Among other things, such a result depends on the origin of the wood and the growth of wood markets. Yet it is clear that if there is no change in the area of forests and no change in the volume of wood used in buildings, there will be no change in the amount of sequestered carbon globally and hence no effect on carbon emissions. There will be additional carbon sequestration only when more carbon is stored in forests (either by area expansion or by increased productivity in existing forests through improved management), and when the total volume of wood in buildings has increased. In boreal and temperate regions such as in Europe and North America, for example, the forest area has been increasing steadily for several decades due to afforestation and reforestation (see Figure 4), which has resulted in increased carbon storage over the past few decades (see Figure 5).

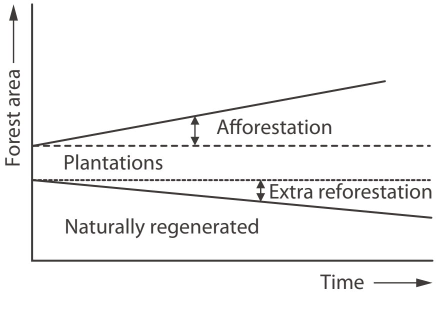


Figure 4: Higher demand for boreal and temperate softwood from Europe and North America leads to more carbon sequestration because of afforestation and reforestation.

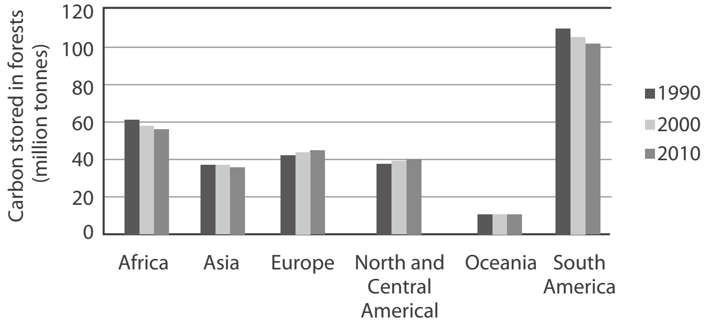


Figure 5. Trends in carbon storage in forests from 1990–2010 (Source: FAO 2010)

Figure 5 also shows that carbon storage in tropical areas is decreasing due to the conversion of forests to agricultural or cattle land, the development of infrastructure and illegal logging of tropical hardwood. Reduced impact logging is a better way to fulfil the market demand for tropical hardwood in a more sustainable way (e.g. van Dam and Savenije 2011, Hodgdon et al. 2015, Putz et al. 2012). Nevertheless, it still reduces the carbon sequestration capacity and the biodiversity of natural forests (Figure 6).

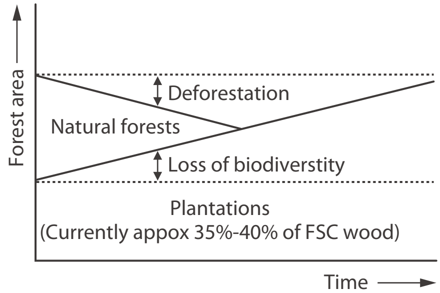


Figure 6: Higher demand for tropical hardwood leads to deforestation and less carbon sequestration

Carbon sequestration by wood in houses and offices is slowly rising globally due to population growth. This additional carbon sequestration, however, is low in comparison with the volume of standing trees in the forests: less than 30% of the carbon above the ground ends up in housing (see Section 5, Step 1 and Step 4 in Vogtländer et al [2014]) and for bamboo this difference is even greater. See also Chapter 5 of this report.

Another key issue is that carbon sequestration does not increase per house that is built, but per extra house that is built beyond the number of houses required to replace discarded dwellings. This point is often overlooked by LCA practitioners when studying carbon sequestration at the product level during the LCI (Life-Cycle Inventory, i.e., analysis of all input and output flows in the product system) phase of the assessment. These conclusions have implications for bamboo as well. Creating additional demand for bamboo would have an effect on carbon sequestration that is similar to that of European and North American wood, leading to better forest management and an increase in bamboo forest area (Lou Yiping et al. 2010).

Figure 7. Bamboo is increasingly used by Western architects as building material, for example in the Barajas International Airport in Madrid designed by Richard Rogers.

The Richard Roger's designed Barajas airport in Madrid has a laminated bamboo roof

3. Cradle-to-gate calculations on bamboo products

Bamboo is used in high-end cars as interior decoration

The production system for bamboo from cradle-to-warehouse-gate is depicted in Figure 8.

The calculations are based on the production system used by the company MOSO International BV for products consumed in the Netherlands:

- Type of bamboo: *Phyllostachys Pubescens* (density 700 kg / m3, length up to 15 m, diameter on the ground 10-12 cm, wall thickness 9mm), also called 'Moso bamboo;'
- Plantation and first processing: the Anji region, Zhejiang province, China;
- Final processing: Hangzhou, Zhejiang province, and Jianyang, Nanping county, Fujian province, both in China;
- The product is shipped via Shanghai and Rotterdam to the warehouse of MOSO International BV in the Netherlands (Zwaag).

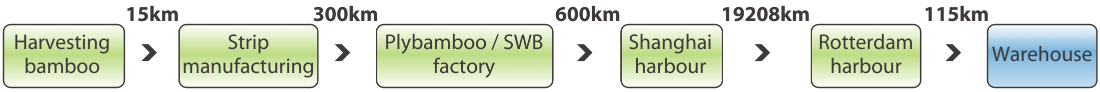


Figure 8. The production system for bamboo products used by MOSO International BV (cradle-to-warehouse-gate).

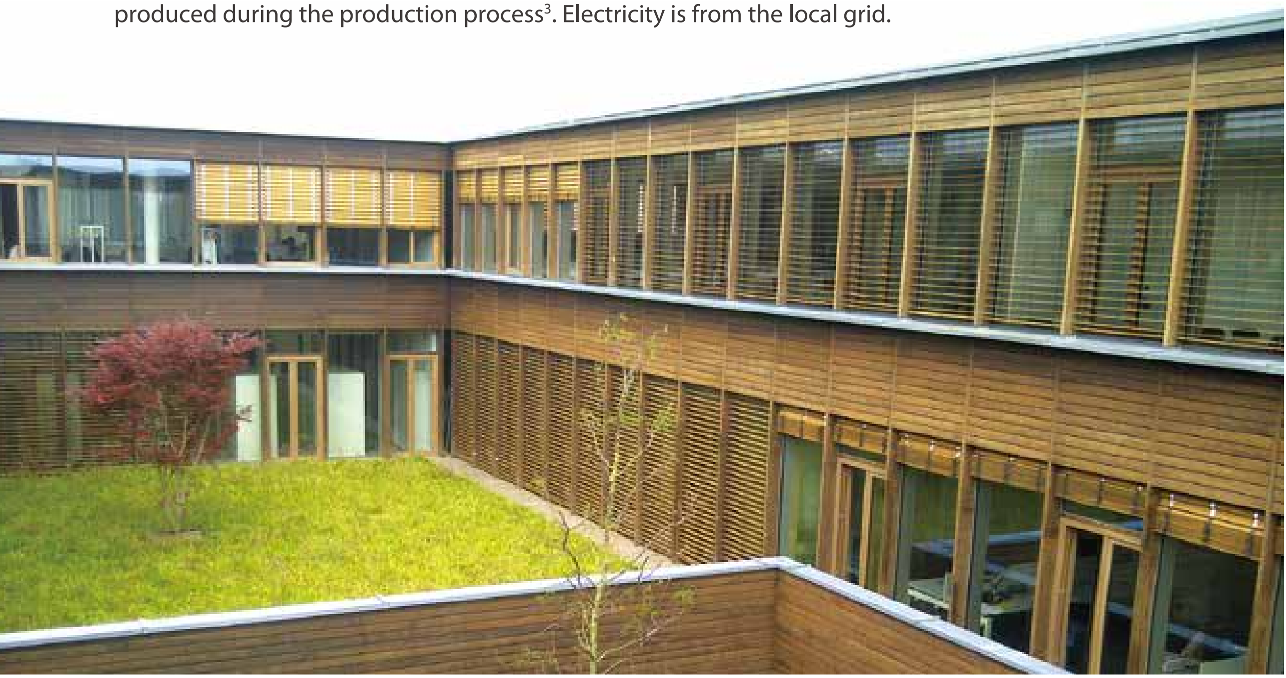
The calculations for the LCAs have been made with the computer programme Simapro version 8.04, applying LCI databases of Ecoinvent v3.1 (allocation, recycled content, 2014) and Idemat 2015 (a database of the Delft University of Technology, partly based on Ecoinvent data).

In general, there are three main production techniques used for the development of industrial bamboo products:

- Lamination of strips (700 kg / m^3)
- Compression of rough strips / fibres (1100-1200kg / m^3)
- Flattened bamboo (850 kg / m^3)

The eco-costs of various derived products can be calculated based on these production techniques. For example, a 1-ply plybamboo panel and a 5-ply plybamboo panel are produced in a similar way and a finished product will only have slightly lower (1-ply, less resin content, less pressing) or slightly higher (five-ply, more resin, more pressing) eco-costs.

The necessary heat for manufacture is generated by combusting the sawdust and bamboo waste produced during the production process[3]. Electricity is from the local grid.



Bamboo cladding and walling at AGC's head office in Belgium, designed by SAMYN + partners.

[3] Note: a cogeneration plant for electricity and heat is an opportunity for the future that could reduce the carbon footprint even further.

The three production technologies are further explained below and the LCI is provided for each technology.

A more comprehensive description of the production processes and tables for the other varieties can be found in van der Lugt (2008) and van der Lugt et al. (2009a, 2009b). The total scores (carbon footprint as well as eco-costs) of the various processes for producing the industrial bamboo products are provided in Chapter 6.

Lamination of strips (plybamboo)

Laminating fine, straight strips to produce panels, beams and flooring boards is the most common technology for industrial bamboo products. The style is called plain pressed (flat strips) or side pressed (strips on side) depending on how the strips are positioned on the product. The strips can be bleached (resulting in a natural colour), carbonized (resulting in a caramel colour) or double carbonized (resulting in a chocolate colour). This type of bamboo product is referred to as plybamboo.

Figure 9. Plybamboo boards are available in various colours, sizes and styles. In the plain pressed style; the nodes are clearly visible (see the two pictures top right). In the side pressed version, they are less visible (two pictures bottom right).

The standard length of the bamboo strips is 2,66 metres throughout the Chinese bamboo industry. Usually about 8 metres (3 x 2,66 m) of a harvested bamboo stem will be used in the development of bamboo products. The bottom two thirds of the 2,66 metres are mostly used for manufacturing industrial bamboo materials, such as laminated bamboo boards, while the upper third is used in smaller bamboo products, such as blinds and chopsticks. The bottom segments of the stem are first processed into rough strips (approximately 2 630 x 23 x 8 mm). This is done near the plantations. The strips are then transported to the manufacturing site (See Figure 8). In the case of MOSO International BV, the distance to the manufacturing site for laminated bamboo board was 300 km.

Description of process step	Amount	Unit	CO2e / FU	CO2e / kg	Percentage
1. Cultivation and harvesting from plantation					
Gasoline consumption	0,224	liter / FU	0,651	0,0156	1,5%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3[4], transport of 23.1 FUs)	30	km / truck	0,699	0,0168	1,6%
3. Strip making	1,38	kWh/ FU	0,797	0,0191	1,9%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	2,314	0,0555	5,5%
5. Rough planing	8,62	kWh/ FU	4,977	0,1193	11,7%
6. Strip selection					
7. Carbonization	4,73	kWh/FU	2,731	0,0655	6,4%
8. Drying carbonized strips	9,66	kWh/FU	5,577	0,1337	13,1%
9. Fine planing	5,8	kWh/FU	3,349	0,0803	7,9%
10. Glue application (1-layer boards)					
Added amount of Melamine formaldehyde (dry condition)	0,483	kg / FU	1,657	0,0397	3,9%
11. Pressing strips to 1- layer board	1,89	kWh/FU	1,091	0,0262	2,6%
12. Sanding 1- layer board	1,62	kWh/FU	0,935	0,0224	2,2%
13. Glue application (3-layer board)					
Added amount Emulsion Poly Isocyanate (dry condition)	0,908	kg / FU	1,476	0,0354	3,5%
14. Pressing three layers to one board	1,65	kWh/FU	0,953	0,0228	2,2%
15. Sawing	0,29	kWh/FU	0,167	0,0040	0,4%
16. Sanding 3-layer board	0,86	kWh/FU	0,497	0,0119	1,2%
17. Dust absorption (during all steps)	8,67	kWh/FU	5,005	0,1200	11,8%
18. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	2,314	0,0555	5,5%
19. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19208 km)	801	ton.km / FU	6,456	0,1548	15,2%
20. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	4,80	ton.km / FU	0,806	0,0193	1,9%
TOTAL carbonized			42,45	1,018	100,0%

*Table 1: Input data and results in **CO2 equivalent** (carbon footprint, cradle-to-gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed at the outsides, and one layer of 10 mm side pressed in the core). The functional unit (FU) used as the base element for this assessment is one board of 2440 x 1220 x 20 mm (2,98 m2), with a weight of 41,7 kilograms (based on a density of 700 kg/m3).*

[4] EURO 3 refers to the European Emission Standard for vehicles as of 2000. Trucks meeting this standard are often used in this case for local transport, sometimes trucks meeting more advanced emissions standards
(e.g. EURO 4 – 2005, EURO 5 – 2008 or EURO 6 -2014) are used as well.

Description of process step	Amount	Unit	Ecocosts/FU	Ecocosts/kg	Percentage
1. Cultivation and harvesting from plantation					
Gasoline consumption	0,224	liter / FU	0,215	0,0052	1,8%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3, transport of 23.1 FUs)	30	km / truck	0,094	0,0023	0,8%
3. Strip making	1,38	kWh/ FU	0,185	0,0044	1,6%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	0,488	0,0117	4,1%
5. Rough planing	8,62	kWh/ FU	1,153	0,0276	9,7%
6. Strip selection					
7. Carbonization	4,73	kWh/FU	0,633	0,0152	5,3%
8. Drying carbonized strips	9,66	kWh/FU	1,292	0,0310	10,9%
9. Fine planing	5,8	kWh/FU	0,776	0,0186	6,5%
10. Glue application (1-layer boards)					
Added amount of Melamine formaldehyde (dry condition)	0,483	kg / FU	0,541	0,013	4,5 %
11. Pressing strips to 1- layer board	1,89	kWh/FU	0,253	0,0061	2,1%
12. Sanding 1- layer board	1,62	kWh/FU	0,217	0,0052	1,8%
13. Glue application (3-layer board)					
Added amount of Emulsion Poly Isocyanate (dry condition)	0,908	kg / FU	0,616	0,0148	5,2%
14. Pressing three layers to one board	1,65	kWh/FU	0,221	0,0053	1,9%
15. Sawing	0,29	kWh/FU	0,039	0,0009	0,3%
16. Sanding 3-layer board	0,86	kWh/FU	0,115	0,0028	1,0%
17. Dust absorption (during all steps)	8,67	kWh/FU	1,159	0,0278	9,7%
18. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	0,488	0,0117	4,1%
19. Transport from harbour to harbour					
Eco-costs (20,ft container in a transoceanic freight ship, 19,208 km)	801	ton.km / FU	3,268	0,0784	27,5%
20. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	4,80	ton.km / FU	0,153	0,0037	1,3%
TOTAL carbonized			11,90	0,285	100,0%

Table 2. Input data and results in ***eco-costs*** *(€, cradle to gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed on the outside, and one layer of 10 mm side pressed in the core). The FU used as the base element for this assessment is one board of 2,440 x 1,220 x 20 mm (2,98 m2), with a weight of 41,7 kilograms (based on a density of 700 kg / m3).*

Compression of rough bamboo fibres

A new production technology places rough bamboo strips in resin after which, under strong compression, they are pressed in moulds to form high-density beams and panels. The result is an extremely hard material (Brinell Hardness ≥ 9,5 kg / mm2 following EN 1534) that looks almost identical to tropical hardwood. Because of the hardness, the material is ideally used for top layers of flooring and panels for tabletops as well as for outdoor decking. A benefit of this production technology is that bamboo strips of lower quality can be used as inputs. The product is available in natural or caramel colours and is known as 'High Density' or 'strand woven bamboo.' A recent innovation thermally modifies the input strips for outdoor use, and increases the durability to the highest class possible (Class 1, according to EN 350). Due to the higher resin content (6,2% instead of 3,5%) and compression, this product has an even higher density than the regular strand woven bamboo boards (1,200 kg / m3 instead of 1,080 kg / m3). However, because of thermal modification (an electricity-intensive process) and the increased resin content, the environmental impact of this product is higher than that of regular strand woven bamboo.

Figure 10. Strand woven bamboo beams are made by compressing rough bamboo fibres in moulds under very high pressure.

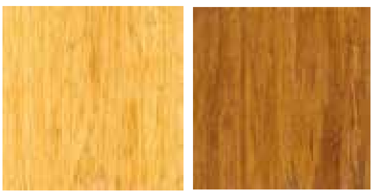


Figure 11. In the High Density and strand woven bamboo styles, the bamboo nodes are hardly visible.

Description of process step	Amount	Unit	CO2e / FU	CO2e / kg	Percentage
1. Cultivation and harvesting of bamboo on sustainable managed plantations					
Gasoline consumption	0,0832	liter / FU	0,242	0,0096	1,0%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3, transport of 23.1 FUs)	30	km / truck	0,262	0,0104	1,1%
3. Strip making	0,8	kWh/ FU	0,462	0,0183	2,0%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	1,376	0,0545	5,9%
5. Rough planing	5,28	kWh/ FU	3,048	0,1206	13,2%
6. Splitting strips in half	0,8	kWh/FU	0,462	0,0183	2,0%
7. Carbonization	2,8	kWh/FU	1,617	0,0640	7,0%
8. Drying carbonized strips	5,624	kWh/FU	3,247	0,1285	14,0%
9. Crushing strips	1,36	kWh/FU	0,785	0,0311	3,4%
10. Glue application					
Added amount of phenol formaldehyde (dry condition)	1,68	kg / FU	2,672	0,1057	11,5%
11. Pressing strips to beam	2,32	kWh/FU	1,339	0,0530	5,8%
12. Activating glue in oven	2,8	kWh/FU	1,617	0,0640	7,0%
13. Sawing beams	0,352	kWh/FU	0,203	0,0080	0,9%
14. Sanding beams	0,188	kWh/FU	0,109	0,0043	0,5%
15. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	1,376	0,0545	5,9%
16. Transport from harbour to harbour					
Eco-costs (19,208 km, 20 ft container in a transoceanic freight ship)	476,8	ton.km / FU	3,843	0,1521	16,6%
17. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	2,88	ton.km / FU	0,484	0,0191	2,1%
TOTAL carbonized			23,144	0,916	100,0%

*Table 3. Input data and results in **CO2 equivalent** (carbon footprint, cradle to gate) of a carbonized strand woven bamboo beam. The FU used as the base element for this assessment is one solid beam, gross size 1,900 X 110 X 140 mm, net size 1,800 x 100 x 130 mm with a weight of 25,3 kilograms (based on a density of 1,080 kg / m3).*

Description of process step	Amount	Unit	Ecocosts/FU	Ecocosts/kg	Percentage
1. Cultivation and harvesting of bamboo on sustainable managed plantations					
Gasoline consumption	0,0832	liter / FU	0,08	0,0032	1,2%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO3, transport of 61,5 FUs)	30	km / truck	0,035	0,0014	0,5%
3. Strip making	0,8	kWh/ FU	0,107	0,0042	1,6%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	0,290	0,0115	4,3%
5. Rough planing	5,28	kWh/ FU	0,706	0,0279	10,4%
6. Splitting strips in half	0,8	kWh/FU	0,107	0,0042	1,6%
7. Carbonization	2,8	kWh/FU	0,374	0,0148	5,5%
8. Drying carbonized strips	5,624	kWh/FU	0,752	0,0298	11,1%
9. Crushing strips	1,36	kWh/FU	0,182	0,0072	2,7%
10. Glue application					
Added amount of Phenol formaldehyde (wet condition)	1,68	kg / FU	1,074	0,0425	15,8%
11. Pressing strips to beam	2,32	kWh/FU	0,310	0,0123	4,6%
12. Activating glue in oven	2,8	kWh/FU	0,374	0,0148	5,5%
13. Sawing beams	0,352	kWh/FU	0,047	0,0019	0,7%
14. Sanding beams	0,188	kWh/FU	0,025	0,0010	0,4%
15. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	0,290	0,0115	4,3%
16. Transport from harbour to harbour					
Eco-costs (19,208km, 20 ft container in a transoceanic freight ship)	476,8	ton.km / FU	1,945	0,077	28,6%
17. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	2,88	ton.km / FU	0,092	0,0036	1,4%
TOTAL carbonized			6,793	0,269	100,0%

*Table 4. Input data and results in **eco-costs** (€, cradle to gate) of a carbonized strand woven bamboo beam. The FU used as the base element for this assessment is one solid beam, gross size 1,900 X 110 X 140 mm, net size 1,800 x 100 x 130 mm with a weight of 25,3 kilograms (based on a density of 1,080 kg / m3).*

Flattened bamboo

Another recent technology involves cutting the original bamboo stem longitudinally in half and flattening it using a special steam treatment process, after which it can be used to produce flooring board. As with the strand woven bamboo technology, a larger portion of the bamboo stem can be used as input materials (usually the whole 8m stem). The best flattened segments (2,66m in length) are used as top layer in flooring boards because of their hardness (Brinell Hardness ≥ 9,5 kg/mm2; EN 1534), whereas lower quality boards (with small visual defects, smaller width) are used as middle or bottom layers of a 3-ply flooring board. This production process is more efficient (a larger part of the input stem can be used; there is less waste) and less glue is required than for plybamboo and strand woven bamboo

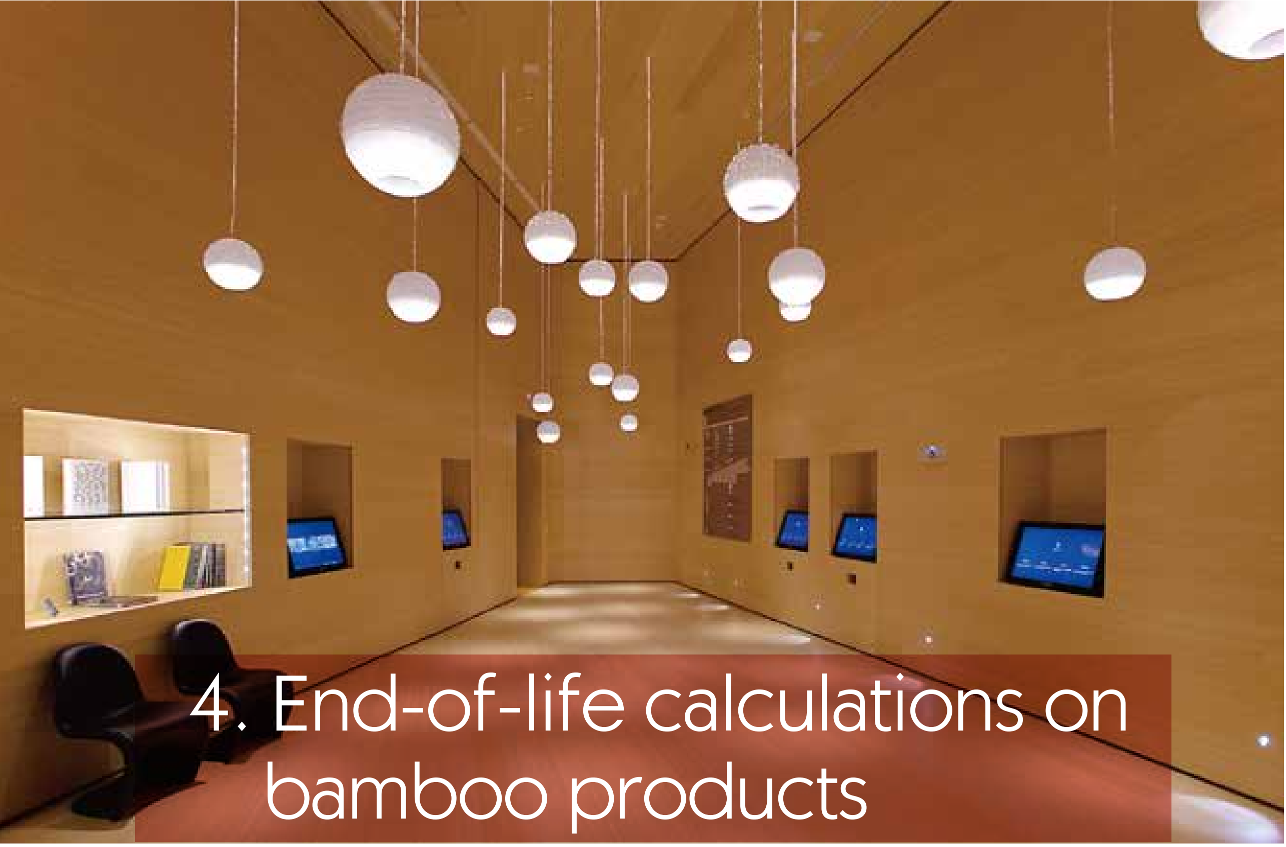
Description of process step	Amount	Unit	CO2e / FU	CO2e / kg	Percentage
1. Cultivation and harvesting from sustainably managed plantation					
Gasoline consumption	0,006	liter / FU	0,016	0,0090	1,5%
2. Transport from plantation to factory					
Eco-costs of a 5 tons truck (EURO3, transport of 780 FUs)	120	km / truck	0,087	0,0478	7,7%
3. Cutting stem segments longitudinally in half	0,0066	kWh/ FU	0,004	0,0021	0,3%
4. Removing internal parts of the stem	0,079	kWh/ FU	0,045	0,0250	4,0%
5. Removing outside parts of the stem	0,026	kWh/ FU	0,015	0,0083	1,3%
6. Shortening	0,006	kWh/FU	0,004	0,0020	0,3%
7. Softening – vapour treatment	0,013	kWh/FU	0,007	0,0040	0,6%
8. Flattening boards	0,063	kWh/FU	0,036	0,0200	3,2%
9. Finalizing shape - press	0,079	kWh/FU	0,045	0,0250	4,0%
10. Surface planing (2 sides)	0,070	kWh/ FU	0,041	0,0223	3,6%
11. Drying flat boards	0,459	kWh/FU	0,265	0,1457	23,5%
12. Cutting to final width	0,0258	kWh/FU	0,015	0,0082	1,3%
13a. Glue application					
Added amount Emulsion Poly Isocyanate (dry condition)	0,023	kg / FU	0,037	0,0206	3,3%
13b. Pressing three layers to one board	0,117	kWh/FU	0,067	0,0370	6,0%
14. Balancing (climate chamber)	0,027	kWh/FU	0,015	0,0085	1,4%
15. Cutting to final length	0,0158	kWh/FU	0,009	0,0050	0,8%
16. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	0,546	ton.km / FU	0,101	0,0555	8,9%
17. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19,208 km)	35	ton.km / FU	0,282	0,1548	25,0%
18. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	0,21	ton.km / FU	0,035	0,0193	3,1%
TOTAL			1,13	0,620	100,0%

*Table 5. Input data and results in **CO2 equivalent** (carbon footprint, cradle to gate) of a flattened bamboo board. The FU used as the base element for this assessment is one 3-ply flooring board, 1210x125x18 mm with a weight of 1,819 kilograms.*

Figure 12. Flattened bamboo features the original bark of the bamboo stem as top layer.

Description of process step	Amount	Unit	Ecocosts/FU	Ecocosts/kg	Percentage
1. Cultivation and harvesting from sustainably managed plantation					
Gasoline consumption	0,006	liter / FU	0,005	0,0030	1,4%
2. Transport from plantation to factory					
Eco-costs of a 5 tons truck (EURO3, transport of 780 FUs)	120	km / truck	0,054	0,0300	14,4%
3. Cutting stem segments longitudinally in half	0,0066	kWh/ FU	0,001	0,0005	0,2%
4. Removing internal parts of the stem	0,079	kWh/ FU	0,011	0,0058	2,8%
5. Removing outside parts of the stem	0,026	kWh/ FU	0,004	0,0019	0,9%
6. Shortening	0,006	kWh/FU	0,001	0,0005	0,2%
7. Softening – vapour treatment	0,013	kWh/FU	0,002	0,0009	0,4%
8. Flattening boards	0,063	kWh/FU	0,008	0,0046	2,2%
9. Finalizing shape - press	0,079	kWh/FU	0,011	0,0058	2,8%
10. Surface planing (2 sides)	0,070	kWh/ FU	0,009	0,0052	2,5%
11. Drying flat boards	0,459	kWh/FU	0,061	0,0337	16,2%
12. Cutting to final width	0,0258	kWh/FU	0,003	0,0019	0,9%
13a. Glue application					
Added amount Emulsion Poly Isocyanate (dry condition)	0,023	kg / FU	0,016	0,0086	4,1%
13b. Pressing three layers to one board	0,117	kWh/FU	0,016	0,0086	4,1%
14. Balancing (climate chamber)	0,027	kWh/FU	0,004	0,0020	0,9%
15. Cutting to final length	0,0158	kWh/FU	0,002	0,0012	0,6%
16. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	0,546	ton.km / FU	0,021	0,0117	5,6%
17. Transport from harbour to harbour					
Eco-costs (20 ft container in a transoceanic freight ship, 19,208 km)	35	ton.km / FU	0,143	0,0784	37,7%
18. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	0,21	ton.km / FU	0,007	0,0037	1,8%
TOTAL			0,38	0,208	100,0%

Table 6. Input data and results in ***eco-costs*** *(€, cradle to gate) of a flattened bamboo board. The FU used as the base element for this assessment is one 3-ply flooring board, 1,210x125x18 mm with a weight of 1,819 kilograms.*



4. End-of-life calculations on bamboo products

Bamboo is used from floor to ceiling at the Guggenheim museum in Bilbao

As explained in Chapter 2, a credit can be earned for avoided fossil fuels if the bamboo (or any other bioproduct such as wood) is burned for electricity or heat.

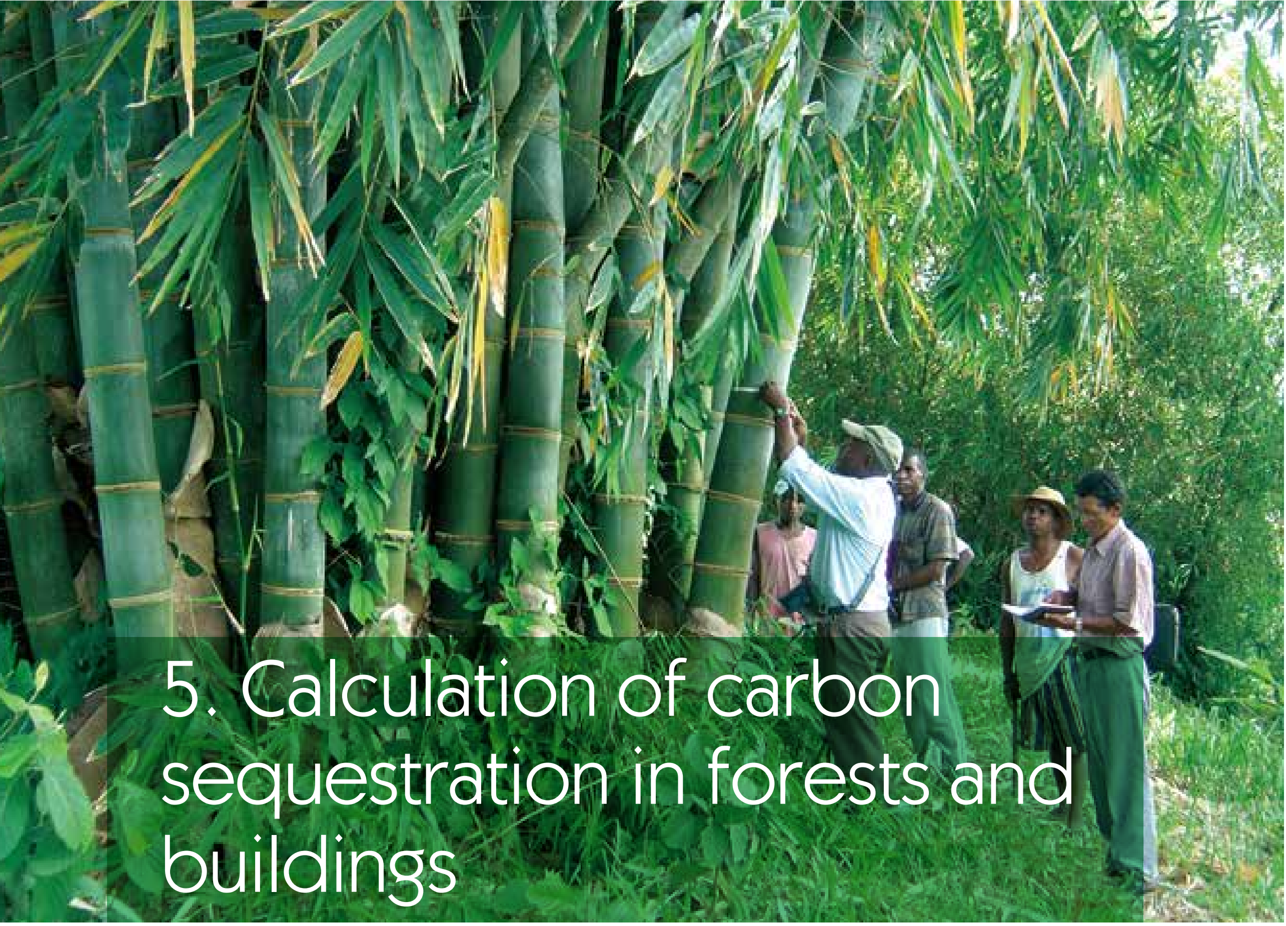
In many Western European countries, the large majority of wood and bamboo products waste end up in electrical power plants. Although the efficiency of a modern coal-fired electrical power plant is higher, i.e. 45% (IEA 2007), the current practice is to combust the biomass in smaller electrical power plants specializing with an approximately 30% lower efficiency than the large coal plants. It is estimated that just 10% of the material perishes in landfills, as specified in the NEN 8006 on LCA. The end-of-life credit for electricity production from bamboo waste is (data from the Idemat database: *Idemat2015 Hardwood 12% MC*, bamboo, cork, combustion in small electric power plant):

- Carbon footprint: 0,779 kg CO2 per kg of bamboo waste;
- Eco-costs: 0,145 € per kg of bamboo waste.

In this report we assume that 90% of bamboo products will eventually be combusted for the production of electricity and/or heat, leading to a credit of:

- Carbon footprint: 0,779 x 0,9 = 0,70 kg CO2 per kg of bamboo product (MC 12%);
- Eco-costs: 0,145 x 0,9 = 0,131 euro eco-costs per kg of bamboo product (MC 12%).

Although the above scores are according to the formal LCA (according to ISO 14040 and 14044) and the European LCA manual (EC-JRC 2010), the effects of the carbon sequestration at the global level must be taken into account before the final result can be calculated. This is treated in the next two chapters.



5. Calculation of carbon sequestration in forests and buildings

The calculation of carbon sequestration resulting from land-use change and additional use of bamboo products in the building industry involves five steps (the calculation updates the data in Vogtländer et al. [2014])]:

1. Calculating the ratio of carbon stored in forests to carbon stored in end products (plybamboo, strand woven bamboo, flattened bamboo). This step complies with the baseline LCA
2. Calculating a land-use change correction factor to reflect the fact that another type of biomass existed in the area before it was changed to forests / plantations). This step complies with the IPCC standards.
3. Calculating the additional stored carbon in forests and plantations (see Figure 4 in Chapter 2) due to the growth of bamboo production and its allocation to the end products. This step is more realistic than assigning credits for temporary carbon storage as described in PAS 2050 and the ILCD handbook. For more details, see Vogtländer et al. (2014).
4. Calculating the additional stored carbon in the building industry.
5. Calculating the total result of carbon sequestration requires the multiplication of the results of Steps 1, 2, 3 plus the result of Step 4.

Detailed calculations are provided below for the Chinese bamboo production system. The calculations relate to carbon sequestration in industrial bamboo products from cradle to grave. The geographical system boundary is China, as defined by FAO (2010).

Step 1. Calculating the carbon ratio

An end product generally derives from a larger amount of biomass than is contained in its final weight.

- One kg of bamboo equates to about 0,42 kg of bamboo in the end product (see also annex I). The amounts vary for different bamboo products:

- 0,42 kg d.m. of bamboo, is used in 0,425 kg d.m. flattened bamboo (the resin content is on average approx 1,3 % of the weight of flattened bamboo), 0,431 kg d.m. plybamboo (the resin content is on average approx 2,5 % of the weight of plybamboo),0,435 kg d.m. Strand Woven Bamboo - SWB (the resin content is 3,5 % of the weight of SWB) and for thermally modified "outdoor" SWB 0,446 kg d.m. (the resin content is on average approx 6,2% of the weight of outdoor SWB).

- One kg d.m. of flattened bamboo originates from 1/0,425=2,35 kg dry matter above-ground biomass on the bamboo plantation. One kg d.m. of plybamboo originates from 1/0,431=2,32 kg d.m. above- ground biomass. One kg d.m. indoor strand woven bamboo originates from 1/0.435=2,30 kg d.m. above-ground biomass and one kg outdoor strand woven bamboo originates from 1/0,446=2,24 kg above ground biomass.

The carbon content of bamboo is 0,5 kg C per 1 kg(Aalde et al. 2006, Verchot et al. 2006). With a molar weight ratio of 3,67 for CO2 versus C, this leads to the following carbon storage on the plantation related to above ground biomass: one kg d.m. flattened bamboo is equivalent to storage of 2,35×0,5x3,67= 4,31 kg CO2; one kg d.m. plybamboo is equivalent to storage of 2,32×0,5x3,67=4,25 kg CO2; one kg d.m. indoor SWB is equivalent to storage of 2,30×0,50x3,67=4,22 kg CO2; and one kg d.m. of outdoor SWB equals storage of 2,24 x0.5x3,67 = 4,11 kg CO2.

These numbers only concern the above ground biomass involved in the final bamboo product. However, the most important aspect of carbon storage is underground because of the extensive root system and carbon captured in the soil layer, with a stem – ecosystem ratio of 3.1[5]. This number is somewhat conservative compared with various recent studies found in Lou Yiping et al. (2010), see footnote.

The additional CO2 stored underground that is related to bamboo products on the market should also be taken into account, with the result that:

- One kg d.m. flattened bamboo is related to 4,31x3,1=13,37 kg CO2 storage in the bamboo ecosystem;
- One kg d.m. plybamboo is related to 4,25x3,1=13,21 kg CO2 storage in the bamboo ecosystem;
- One kg d.m. indoor strand woven bamboo is related to 4,22x3,1=13,09 kg CO2 storage in the bamboo ecosystem for the outdoor strand woven bamboo version, this is 4,11x3,1 = 12,75 kg CO2 storage in the bamboo ecosystem.

[5] Besides in the trunks, branches and shrubs, there is CO2 stored below ground in the soil and roots of a plantation. Zhou and Jiang (2004) found that, for a medium intensity-managed Moso bamboo plantation in Lin'an, Zhejiang province, the distribution of biomass above ground versus below ground is 32,2% and 68,8% respectively. Furthermore, Lou Yiping et al (2010) reported the following "Moso bamboo forest ecosystem carbon storage capacity was reported to be between 102 t C/ha and 289 t C/ha, of which 19-33% was stored within the bamboo culms and vegetative layer and 67-81% stored within the soil layer (rhizomes, roots and soil carbon)."

Step 2. Calculating the land-use change correction factor.

The second step in the calculation relates to the fact that before afforestation, the land had also stored biomass. In this case, the Tier 2 Gain-Loss Method (Verchot et al. 2006) of the IPCC is used to compare the steady state before and after the land use change.

As shown in Step 3, there has been a large growth of the Moso bamboo-growing area over the past few decades as a result of better forest management and the natural expansion of existing Moso bamboo forests either on farmland or on shrubland, with low biomass and biodiversity changes as a result. This fast growing species has the capacity to expand in area by 1-3% every year (a figure that can be even higher if the process is facilitated by the right agricultural practices). These secondary natural bamboo forests provide a large portion of the bamboo used in industry. [6]

Another reason for the expanded bamboo area is the reforestation of barren wasteland or poor farming grounds (see example in Figure 12) to create bamboo plantations (among others) through the Grain for Green programme of the Chinese government.

For the purposes of this report, it is assumed that the new plantations are established on grassland and do not come at the expense of natural forests. This is a plausible assumption since a large portion of the Moso bamboo resources comes from the industrialized provinces around Shanghai (Zhejiang, Fujian, Anhui, Jiangxi). Furthermore, this assumption is in line with the current policy for afforestation and natural forest protection of the Chinese State Forestry Administration (CSF 2013).

Figure 12. Typical barren grassland being prepared for rehabilitation with bamboo.

[6] Note that despite the fast growth, in fewer than 5% of the plantations / managed bamboo forests used for industrial bamboo, production pesticide and / or fertilizer is used as prescribed in the Chinese standard for high yield Moso plantations (GB/T 20391-2006). In a well-managed bamboo plantation / forest the fallen branches and leaves should provide sufficient nutrition for new shoots (this choice is also often made for economic reasons).

The calculation

- Total above-ground and below-ground non-woody biomass is 7,5 tonnes d.m./ ha (it ranges from 6,5 to 8,5) with a carbon content of 47% (Verchot et al. 2006).
- The biomass on bamboo plantations is 35,8 x 3,1 = 111 tonnes[7] d.m./ ha for biomass above and below the ground (Van der Lugt 2009a&b, Zhou and Jiang 2004) with a carbon content of 50%.
- The land-use change correction factor for afforestation is therefore:
  [(111 x 0,50) – (7,5 x 0,47)] / (111 x 0,50) = **0,936**

Much of the additional Chinese bamboo production in the past has resulted from better management of existing bamboo forests (Lou Yiping et al. 2010). In this case, the land-use change correction factor is **1** for additional bamboo production.

Note that in the case of converted shrubland (according to Aalde et al. [2006], the above ground biomass is 60 tons d.m. for tropical shrubland in continental Asia with root-shoot ratio of 0,4) to bamboo plantation the land-use change correction factor is [(111 x 0,50) – (84 x 0,46)] / (111 x 0,50) = **0,30**

Step 3. Calculating the additional stored carbon in forests and its allocation.

According to van der Lugt and Lobovikov (2008), the annual growth of the market for industrial bamboo products in EU and China ranges between 17% and 25%. However, the establishment of new plantations does not always follow increase in market demand directly but is delayed. This phenomenon was highlighted in the 7th Chinese National Forestry Inventory (State Forestry Administration of P.R. China 2010) where it was shown that the area of bamboo resources in China in 2004-2008 grew from 4,84 million ha to 5,38 million ha in 2008, thus experiencing a growth of 11,18% in 5 years with an average annual growth of 2,24%. The growth of tree forest area in China is at a similar level (11,74%) with a growth of 174,91 million ha to 195,45 million ha during the same period (2004-2008).

More recent figures (2013) from China's State Forestry Administration indicate that the growth of bamboo forests and plantations in China has accelerated in recent years, with a growth from 5,38 million ha in 2008 to 6,73 million ha in 2011; this corresponds to an annual growth of 8,36%. These calculations are based on an average bamboo coverage growth from 2004 – 2011, which corresponds to an annual growth of 5,54[8].

Given the high GDP growth of the Chinese economy over this period (approximately 7.5%), a **5%** increase in bamboo production seems to be a safe estimation for calculating the additional stored carbon in bamboo plantations. The related annual growth in carbon storage on plantations is allocated to the total production of bamboo products: for every kg of bamboo, **0,05 kg** relates to the new plantations needed to cope with market growth, which adds to the global carbon sequestration accordingly.

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[7] Note that Lou Yiping et al (2010) have reported considerably higher outputs (101.6-288.5 tC/ha), see also Footnote 5.

[8] It must be mentioned here that this growth does not always require extra agricultural land. Much of the bamboo production in the past has come from better forest management (Lou Yiping et al. 2010). in fact, one of the short term goals (2011-2015) of the national bamboo development plan is to improve the quality (and therefore yield) of existing 1,9 mio forests (INBAR 2014). Moreover, due to the extensive root system, bamboo is planted in areas where farming is not feasible, e.g., on slopes for erosion prevention and for rehabilitating degraded land and re-establishing functioning and productive ecosystems by improving soil quality and restoring the water table (Kuehl and Lou Yping 2011).

Bamboo flooring complements the light and airy feeling of this office (photography: Fred Sonnega).

Step 4. Calculating the additional stored carbon in buildings.

The additional carbon sequestration in buildings relates to the bamboo products minus processing losses, which we estimate at 10%. Taking into account the resin content in the end product (1,3% for flattened bamboo, 2,5% for plybamboo, 3,5% for indoor SWB and 6,2% for outdoor SWB), this results in:

- 0,987 x 0,9 x 0,5 x 3,67 = 1,63kg biogenic CO2 storage in the buildings per one kg d.m. of flattened bamboo. Given the market growth described in Step 3, this results in the additional carbon sequestration of 1,63 x 0,05 = 0,082 kg CO2 per kg d.m. of flattened bamboo.
- 0,975 x 0,9 x 0,5 x 3,67 = 1,61 kg biogenic CO2 storage in the buildings per one kg d.m. of plybamboo. Given the market growth described in Step 3, this results in the additional carbon sequestration of 1,61 x 0,05 = 0,081 kg CO2 per kg d.m. of plybamboo.
- 0,965 x 0,9 x 0,5 x 3,67 = 1,59 kg biogenic CO2 storage in the buildings per one kg d.m. of indoor strand woven bamboo. Given the market growth described in Step 3, this results in the additional carbon sequestration of 1,59 x 0,05 = 0,080 kg CO2 per kg d.m. of indoor strand woven bamboo.
- 0,938 x 0,9 x 0,5 x 3,67 = 1,55 kg biogenic CO2 storage in the buildings per one kg d.m. of outdoor SWB. Given the market growth described in Step 3, this results in the additional carbon sequestration of 1,55 x 0,05 = 0,077 kg CO2 per kg d.m. of outdoor strand woven bamboo.

Step 5. Calculating the total result.

The overall effect on carbon sequestration due to land-use change is calculated by multiplying \the results of Steps 1, 2, 3 and adding the results of Step 4:

- Carbon sequestration = 13,37 x 0,936 x 0,05 + 0,082 = 0,707 kg CO_2 per kg d.m. of flattened bamboo (0,637 kg CO_2 at 10% MC); in eco-costs this equates to €0,095 per kg d.m. of flattened bamboo (€0,086 at 10%MC).
- Carbon sequestration = 13,21 x 0,936 x 0,05 + 0,081 = 0,699 kg CO_2 per kg d.m. of plybamboo (0,629 kg CO_2 at 10% MC); in eco-costs this equates to €0,094 per kg d.m. of plybamboo (€0,085 at 10%MC).
- Carbon sequestration = 13,09 x 0,936 x 0,05 + 0,080 = 0,692 kg CO_2 per kg d.m. of indoor strand woven bamboo (0,623 kg CO_2 at 10% MC); in eco-costs this equates to €0,093 per kg d.m. of indoor strand woven bamboo (€0,084 at 10%MC).
- Carbon sequestration = 12,75 x 0,936 x 0,05 + 0,077 = 0,674 kg CO_2 per kg d.m. of outdoor strand woven bamboo (0,607 kg CO_2 at 10% MC); in eco-costs this equates to €0,091 per kg d.m. of outdoor strand woven bamboo (€0,082 at 10%MC).

These amounts can be allocated as credit in the LCA calculation.

The carbon sequestration credits for bamboo due to land change are higher than they are for wood. European softwood acquires a credit for carbon sequestration as a result of land change of 0,17kg CO_2 per kg softwood 10% MC. For detailed calculations, see Vogtländer et al. (2014).

There are several reasons why this is the case:

- The reforestation rate in China is higher for bamboo than it is in Europe for softwood. This is the result of a faster market growth for bamboo products as and the higher reforestation potential of bamboo on degraded lands.
- The root – shoot ratio of bamboo is generally higher than it is for wood. As a result of its extensive root system, bamboo stores more CO_2 under ground as in the surrounding soil.
- Unlike trees, which are usually clear cut, the regular and selective harvesting of bamboo culms doesn't kill the plant or damage the ecosystem and below-ground carbon is not emitted as the bamboo forest continues to live on after harvest (Kuehl et al. 2011).

Due to the high speed of growth, the establishment time required for new bamboo plantations is a lot shorter than for wood forests while bamboo plantations can also be planted in locations where it is impossible to plant trees (e.g. on degraded slopes), making it a good crop for reforestation (see also Chapter 7).

6. Results: Tables on combined cradle-to-grave calculations, including carbon sequestration

Close-up of a finished bamboo board

The calculations expressed on the tables in Chapter 3 cover the different styles, colours and layer types of bamboo products. The tables below show the combined results of the calculations of the LCA (Chapters 3 and 4) and the carbon sequestration (Chapter 5) for the product portfolio of MOSO International BV.

Outdoor					Carbon Footprint (CO2e) per kg final product				Eco-costs (€) per kg final product			
	Thickness (mm)	**Type**	**Style**	**Color**	**PRODUCTION cradle to gate** CO2e / kg	**End-of-life** CO2e / kg	**CO2 storage** CO2e / kg	**CO2 total** CO2e / kg	**PRODUCTION cradle to gate** Euro / kg	**End-of-life** Euro/kg	**eco-costs CO2 storage** Euro/kg	**eco-costs Total** Euro/kg
Decking & cladding (MOSO Bamboo X-treme)	20		DT	C	1,193	-0,704	-0,607	-0,1176	0,356	-0,132	-0,082	0,142

Note: SP = Side Pressed, PP = Plain Pressed, DT= Density / Compressed, N = Natural (bleached), C = Caramel (Carbonized), E0 = produced with glues with no added formaldehyde (formaldehyde emission: Class E0, < 0,025 mg/m3).

Flooring	Thickness (mm)	Type	Style	Color	Carbon Footprint (CO2e) per kg final product				Eco-costs (€) per kg final product			
					PRODUCTION cradle to gate CO2e / kg	End-of-life CO2e / kg	CO2 storage CO2e / kg	CO2 total CO2e / kg	PRODUCTION cradle to gate Euro / kg	End-of-life Euro / kg	eco-costs CO2 storage Euro / kg	eco-costs Total Euro / kg
Solid strip (MOSO Purebamboo)	15		SP	N	0,925	-0,704	-0,629	-0,4084	0,257	-0,132	-0,085	0,040
	15	E0	SP	N	0,911	-0,704	-0,629	-0,4217	0,253	-0,132	-0,085	0,036
	15		PP	N	0,951	-0,704	-0,629	-0,3822	0,268	-0,132	-0,085	0,051
	15	E0	PP	N	0,945	-0,704	-0,629	-0,3884	0,266	-0,132	-0,085	0,049
	15		SP	C	0,964	-0,704	-0,629	-0,3690	0,265	-0,132	-0,085	0,048
	15	E0	SP	C	0,951	-0,704	-0,629	-0,3824	0,262	-0,132	-0,085	0,045
	15		PP	C	0,990	-0,704	-0,629	-0,3429	0,276	-0,132	-0,085	0,059
	15	E0	PP	C	0,984	-0,704	-0,629	-0,3491	0,275	-0,132	-0,085	0,058
	15		DT	C	1,048	-0,704	-0,623	-0,2795	0,301	-0,132	-0,084	0,085
	15		DT	N	1,008	-0,704	-0,623	-0,3194	0,292	-0,132	-0,084	0,076
Solid wide board (3 ply) (MOSO Bamboo Elite)	15		SP	N	1,015	-0,704	-0,629	-0,3176	0,286	-0,132	-0,085	0,069
	15	E0	SP	N	0,957	-0,704	-0,629	-0,3764	0,271	-0,132	-0,085	0,054
	15		PP	N	1,006	-0,704	-0,629	-0,3266	0,283	-0,132	-0,085	0,066
	15	E0	PP	N	0,952	-0,704	-0,629	-0,3807	0,269	-0,132	-0,085	0,053
	15		SP	C	1,055	-0,704	-0,629	-0,2783	0,294	-0,132	-0,085	0,077
	15	E0	SP	C	0,996	-0,704	-0,629	-0,3371	0,280	-0,132	-0,085	0,063
	15		PP	C	1,046	-0,704	-0,629	-0,2873	0.291	-0,132	-0,085	0,074
	15	E0	PP	C	0,992	-0,704	-0,629	-0,3414	0.278	-0,132	-0,085	0,061
	13		DT	N	1,004	-0,704	-0,623	-0,3227	0.288	-0,132	-0,084	0,071
	13		DT	C	1,042	-0,704	-0,623	-0,2846	0.296	-0,132	-0,084	0,080
2-Ply flooring (MOSO Bamboo Supreme)	10		SP	N	0,876	-0,704	-0,629	-0,4573	0,248	-0,132	-0,085	0,031
	10	E0	SP	N	0,870	-0,704	-0,629	-0,4626	0,247	-0,132	-0,085	0,030
	10		PP	N	0,871	-0,704	-0,629	-0,4620	0,246	-0,132	-0,085	0,029
	10	E0	PP	N	0,868	-0,704	-0,629	-0,4653	0,246	-0,132	-0,085	0,029
	10		SP	C	0,915	-0,704	-0,629	-0,4183	0,256	-0,132	-0,085	0,039
	10	E0	SP	C	0,909	-0,704	-0,629	-0,4237	0,248	-0,132	-0,085	0,031
	10		PP	C	0,910	-0,704	-0,629	-0,4232	0,255	-0,132	-0,085	0,038
	10	E0	PP	C	0,907	-0,704	-0,629	-0,4265	0,247	-0,132	-0,085	0,030
	10		DT	N	0,939	-0,704	-0,623	-0,3883	0,270	-0,132	-0,084	0,054
	10		DT	C	0,978	-0,704	-0,623	-0,3491	0,279	-0,132	-0,084	0,062
On-edge / Industrial floor (MOSO Bamboo Industriale)	10, 15		SP	N	0,816	-0,704	-0,629	-0,5168	0,229	-0,132	-0,085	0,012
	10, 15		SP	C	0,856	-0,704	-0,629	-0,4775	0,238	-0,132	-0,085	0,021
	10		DT	N	0,971	-0,704	-0,623	-0,3556	0,283	-0,132	-0,084	0,067
	10		DT	C	1,010	-0,704	-0,623	-0,3170	0,291	-0,132	-0,084	0,075
Flattened bamboo (3 ply) (MOSO Bamboo Forest)	18		EO		0,620	-0,704	-0,637	-0,7208	0,208	-0,132	-0,086	-0,010

Panels & Beams					Carbon Footprint (CO2e) per kg final product				Eco-costs (€) per kg final product			
	Thickness(mm)	Type	Style	Color	PRODUCTION cradle to gate CO2e / kg	End-of-life CO2e / kg	CO2 storage CO2e / kg	CO2 total CO2e / kg	PRODUCTION cradle to gate Euro/kg	End-of-life Euro/kg	eco-costs CO2 storage Euro/kg	eco-costs Total Euro/kg
1 ply panel	3, 5		SP	N	0,925	-0,704	-0,629	-0,4084	0,257	-0,132	-0,085	0,040
	3, 5	E0	SP	N	0,911	-0,704	-0,629	-0,4217	0,253	-0,132	-0,085	0,036
	3, 5		PP	N	0,915	-0,704	-0,629	-0,4180	0,253	-0,132	-0,085	0,036
	3, 5	E0	PP	N	0,907	-0,704	-0,629	-0,4263	0,251	-0,132	-0,085	0,034
	3, 5		SP	C	0,964	-0,704	-0,629	-0,3690	0,265	-0,132	-0,085	0,048
	3, 5	E0	SP	C	0,951	-0,704	-0,629	-0,3824	0,262	-0,132	-0,085	0,045
	3, 5		PP	C	0,954	-0,704	-0,629	-0,3786	0,262	-0,132	-0,085	0,045
	3, 5	E0	PP	C	0,946	-0,704	-0,629	-0,3869	0,260	-0,132	-0,085	0,043
	4		DT	N	1,008	-0,704	-0,623	-0,3194	0,292	-0,132	-0,084	0,076
	4		DT	C	1,048	-0,704	-0,623	-0,2795	0,301	-0,132	-0,084	0,085
multi-layer panel	16, 20, 30, 40		SP	N	0,995	-0,704	-0,629	-0,3383	0,282	-0,132	-0,085	0,065
	16, 20, 30, 40	E0	SP	N	0,965	-0,704	-0,629	-0,3676	0,275	-0,132	-0,085	0,058
	16, 20, 30, 40		PP	N	0,979	-0,704	-0,629	-0,3543	0,277	-0,132	-0,085	0,060
	16, 20, 30, 40	E0	PP	N	0,958	-0,704	-0,629	-0,3752	0,272	-0,132	-0,085	0,055
	16, 20, 30, 40		SP	C	1,034	-0,704	-0,629	-0,2990	0,291	-0,132	-0,085	0,074
	16, 20, 30, 40	E0	SP	C	1,005	-0,704	-0,629	-0,3283	0,284	-0,132	-0,085	0,067
	16, 20, 30, 40		PP	C	1,018	-0,704	-0,629	-0,3150	0,285	-0,132	-0,085	0,069
	16, 20, 30, 40	E0	PP	C	0,997	-0,704	-0,629	-0,3359	0,280	-0,132	-0,085	0,063
	20, 38		DT	N	0,976	-0,704	-0,623	-0,3513	0,289	-0,132	-0,084	0,073
	20, 38		DT	C	1,015	-0,704	-0,623	-0,3123	0,297	-0,132	-0,084	0,081
Veneer	0.6		SP	N	1,110	-0,704	-0,629	-0,2231	0,300	-0,132	-0,085	0,083
	0.6	E0	SP	N	1,106	-0,704	-0,629	-0,2271	0,292	-0,132	-0,085	0,075
	0.6		PP	N	1,330	-0,704	-0,629	-0,0032	0,352	-0,132	-0,085	0,135
	0.6	E0	PP	N	1,325	-0,704	-0,629	-0,0079	0,335	-0,132	-0,085	0,118
	0.6		SP	C	1,153	-0,704	-0,629	-0,1799	0,310	-0,132	-0,085	0,093
	0.6	E0	SP	C	1,149	-0,704	-0,629	-0,1839	0,301	-0,132	-0,085	0,084
	0.6		PP	C	1,381	-0,704	-0,629	0,0478	0,300	-0,132	-0,085	0,083
	0.6	E0	PP	C	1,376	-0,704	-0,629	0,0431	0,346	-0,132	-0,085	0,129
Solid joist	55, 60, 72, 100		SP	N	1,020	-0,704	-0,629	-0,3130	0,266	-0,132	-0,085	0,049
	55, 60, 72, 100	E0	SP	N	0,991	-0,704	-0,629	-0,3423	0,266	-0,132	-0,085	0,049
	55, 60, 72, 100		SP	C	1,059	-0,704	-0,629	-0,2737	0,2742	-0,132	-0,085	0,057
	55, 60, 72, 100	E0	SP	C	1,030	-0,704	-0,629	-0,3031	0,2742	-0,132	-0,085	0,057
	60, 72, 100		DT	N	0,878	-0,704	-0,623	-0,4485	0,261	-0,132	-0,084	0,045
	60, 72, 100		DT	C	0,916	-0,704	-0,623	-0,4111	0,269	-0,132	-0,084	0,053

7. Conclusion and discussion

Bamboo walls, doors and window frames

This study used Life-Cycle Assessment and carbon footprint calculations to analyse the environmental impact of industrial bamboo products. Following a best-case scenario based on the production figures of MOSO International BV, in which the effect of carbon sequestration was included. From the results, based on use in Europe, it can be concluded that almost all industrial bamboo products are CO2 negative. The credits for bioenergy production during the end-of-life and carbon sequestration due to land change outweigh the emissions during production and shipping. See Figure 13.

The only industrial bamboo product that is not CO2 negative is plain pressed carbonized veneer. In general, veneer has a relatively high environmental impact because of the thinness of the veneer sheets, which results in more resin consumption per sheet (especially in case of multi layered veneer) and high fragility (especially in its plain pressed form), resulting in a lower processing efficiency and more waste. Side pressed versions of the veneer are CO2 negative, however, and, with some efficiency improvements, (e.g., recycling waste) this might also be the case for plain pressed caramel veneer.

Figure 13 gives a good indication of how bamboo production technologies compare in terms of environmental impact.

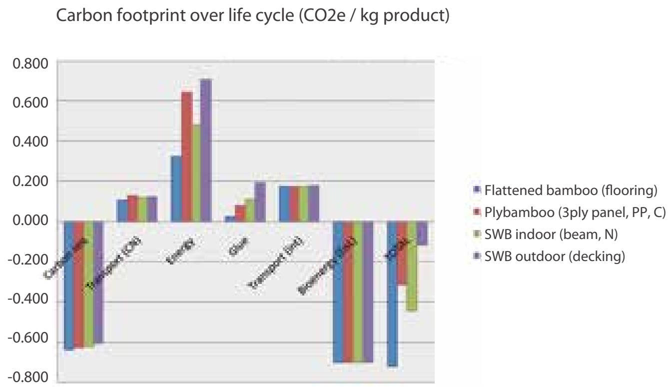

Figure 13. Carbon footprint over life cycle (kg CO2e / kg product) for industrial bamboo products manufactured using different production technologies.

It is clear from the graph that although all of the technologies are CO2 negative over their life cycle, because of variations in carbon sequestration and bioenergy production during end-of-life, there are significant differences between them:

- Because of the relatively short production process involved, high efficiency and low resin content, flattened bamboo boards are clearly the best choice from an environmental point of view.
- As a result of relatively high-energy consumption due to thermal modification and higher resin content, the outdoor strand woven bamboo performs less well than the indoor type. However the outdoor SWB is the only bamboo product which has the durability performance to be used in outdoor applications where it can substitute tropical hardwood (see also comparison in tables 7 & 8).
- Indoor strand woven bamboo material appears to perform better than plybamboo in terms of carbon footprint, which seems strange because of the higher resin content. This is due to its shorter production process, resulting in lower energy consumption per kg material.

The outcomes with regard to eco-costs are similar, with slight differences for sea transport as for impact of resins. See Figure 14.

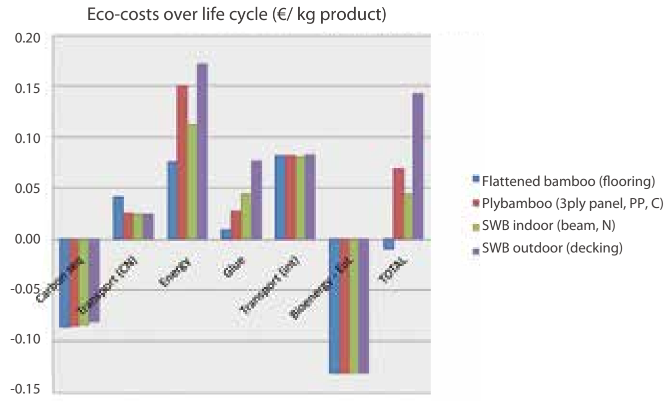

Figure 14. Eco-costs over life cycle (kg CO2e / kg product) for various industrial bamboo products manufactured using different production technologies

The study leads us to the following conclusions:

- **Energy consumption** in processing industrial bamboo products makes the largest contribution to environmental impact, being responsible for 36–53% of eco-costs and 52-63% of the carbon footprint of the total eco-burden. Since bamboo processing facilities generally use bamboo waste for heat, the remaining energy required is provided by electricity from the local grid. This electricity could be replaced by electricity from a combined power generator (bamboo waste is abundantly available) at the production facility or through the on-site production of solar energy.

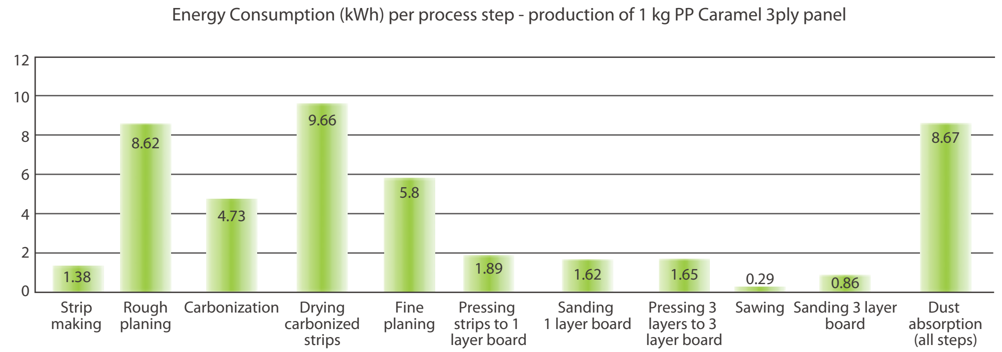

Figure 15. Carbon footprint for electricity consumption over life cycle (kg CO2e / kg product), in this case for a 3-ply carbonized solid bamboo panel

- **International sea transport** has the next largest influence on the environmental impact, being responsible for 15-25% of the carbon footprint and 28-37% of the eco-costs of industrial bamboo products. In the case of local consumption, this additional eco-burden can be directly subtracted from the total. For products destined for the European market, this is of course not a possibility, but closer sourcing (e.g., from Ethiopia with its large bamboo resources) could be an option for improving environmental impact (the electricity mix of Ethiopia is largely focussed on hydropower).
- Some improvements could also be made in **local transport** –contributing approximately 10% of the eco-burden - by opting for larger trucks in the first stages of the production chain (28 tons instead of 5 tons) and/or by using more efficient trucks (EURO 5 instead of EURO 3).
- The **use of resin** in industrial bamboo products is not the most significant factor in determining their environmental impact, which ranges from 3% (for flattened bamboo) to 16% (for outdoor strand woven bamboo) in terms of the carbon footprint and 4% (for flattened bamboo) to 21% (for outdoor strand woven bamboo) in terms of eco-costs. Increasing the amount of formaldehyde-free resins, such as EPI (Emulsion Poly Isocyanate) could reduce the environmental impact still further (carbon footprint 1,63 kg CO2e / kg, eco-costs €0,68 / kg) and switching to a fully biobased resin (EPI is a synthetic resin) would have the additional benefit that the industrial bamboo product would have a 100% biobased content.

The bamboo stem is potentially the most eco-friendly building material available, as it can be used in construction in its natural form without further processing. However, as has been shown in, for example, van der Lugt (2008), the eco-burden of sea transport is calculated with a volume-based eco-indicator when the weight / volume ratio is low, as is the case for the bamboo stems, resulting in a carbon footprint for production of 1,369 kg CO2e / kg stem. When the bamboo stem is used locally, the cradle-to-gate carbon footprint is only 0,20 kg CO2e/ kg stem.

However, due to the irregularities of the material and its distinctive appearance, the market adoption in Western markets of the bamboo stem will be marginal.

The question arises as to how industrial bamboo materials compare to the materials it tries to substitute, e.g. tropical hardwood and non-renewable carbon intensive materials such as plastics (e.g. PVC) and metals (e.g. aluminium, steel). Table 7 and Figure 16 present the environmental impact of several commonly used materials as compared to bamboo.

Carbon footprint (CO2e per kg product)	**Density** (kg/m3)	**Production** cradle to gate	**End of Life** small elect. power plant (32% efficiency)	**Carbon seq** based on land use change	**Total** / kg	**Total** / m3
Flattened bamboo (d.m. 90%)	850	0,620	-0,704	-0,6370	-0,721	-613
Plybamboo (Caramel) (d.m. 90%)	700	1,018	-0,704	-0,6290	-0,315	-220
SWB indoor (Natural) (d.m. 90%)	1080	0,878	-0,704	-0,6230	-0,449	-484
SWB outdoor (d.m. 90%)	1200	1,193	-0,704	-0,6070	-0,118	-141
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90%)	460	0,260	-0,817	-0,1700	-0,727	-334
Idemat2014 Meranti plantation	640	0,710	-0,704	0,000	0,006	4
Idemat2015 Meranti natural forest	640	3.950	-0.704	included in prod	3,246	2077
Idemat2014 PVC (Polyvinylchloride, market mix)	1380	2,104			2,104	2904
Idemat2014 Steel (21% sec = market mix average)	7850	1,838			1,838	14429
Idemat2014 Aluminium trade mix (66% prim 33% sec)	2800	11,580			11,580	32423
Idemat2014 Concrete (reinforced, 40 kg steel per 1000 kg)	2400	0,231			0,231	554

Table 7. Carbon footprint over life cycle (kg CO2e / kg or m3 building material) for various common building materials (based on data developed for this report, Idemat's 2014 and 2015 databases and Vogtländer et al. 2014)

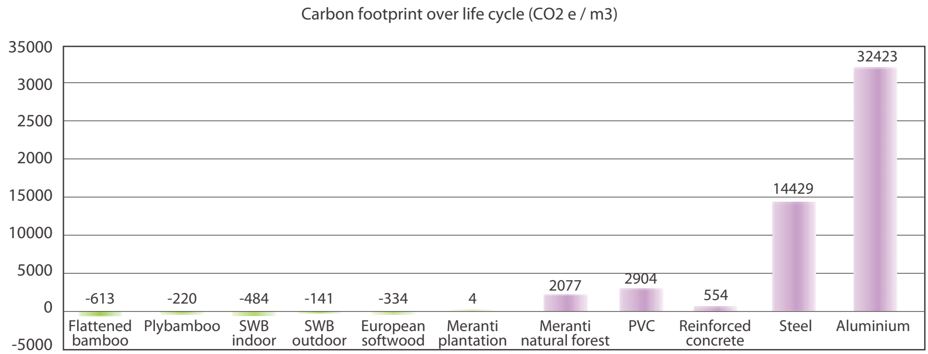

Figure 16. Carbon footprint over life cycle (kg CO2e / m3 building material) for various common building materials (based on data developed for this report, Idemat's 2014 and 2015 databases and Vogtländer et al. 2014).

In the best case scenario, the carbon sequestration credit of some tropical hardwoods, such as Meranti, is zero; this is also true for plantation wood (currently 35 – 40% of the FSC wood on the market). However, if Meranti is sourced from a natural forest, without planting new trees or crops, the carbon stored in the biomass is lost, hence establishing a far higher carbon footprint. The greatest disadvantage of harvesting hardwood from rain forests, is not the carbon sequestration debit, but the negative effect on biodiversity. See the three scenarios for Meranti (plantation, FSC, natural forest) in the table and graph below.

LCA | Eco-costs (€ per kg product)	Density (kg/m3)	**Production** cradle to gate	**End of Life** small elect. power plant (32% efficiency)	**Carbon seq** based on land use change	**Total** / kg	**Total** / m3
Flattened bamboo (d.m. 90%)	850	0,208	-0,132	-0,086	-0,01	-9
Plybamboo (Caramel) (d.m. 90%)	700	0,285	-0,132	-0,085	0,07	48
SWB indoor (Natural) (d.m. 90%)	1080	0,261	-0,132	-0,084	0,04	48
SWB outdoor (d.m. 90%)	1200	0,356	-0,132	-0,082	0,14	171
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90%)	460	0,035	-0.154	-0,023	-0,14	-65
Idemat2014 Meranti plantation	640	0,211	-0,132	0,000	0,08	50
Idemat2014 Meranti FSC	640	2,090	-0,132	0,000	1,96	1253
Idemat2015 Meranti natural forest	640	10,1	-0,132	included in prod	9,97	6380
Idemat2014 PVC (Polyvinylchloride, market mix)	1380	0,735			0,73	1014
Idemat2014 Steel (21% sec = market mix average)	7850	0,679			0,68	5329
Idemat2014 Aluminium trade mix (66% prim 33% sec)	2800	4,353			4,35	12190
Idemat2014 Concrete (reinforced, 40 kg steel per 1000 kg)	2400	0,059			0,06	142

Table 8. Eco-costs over life cycle (€ / kg or m3 building material) for various common building materials (data sourced for this report, Idemat's 2014 and 2015 databases and Vogtländer et al. 2014)

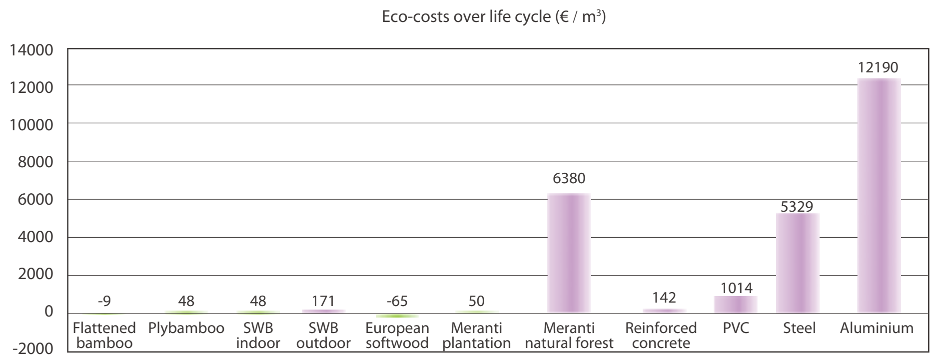

Figure 17. Eco-costs over life cycle (€/ m3 building material) for various common building materials (data sourced for this report, Idemat's 2014 and 2015 databases and Vogtländer et al. 2014).

Although the numbers are per m3 material, and not for a specific application - in which also maintenance and material use based on required mechanical and functional properties are included (functional unit) - these figures do give a good indication how the various materials compare from environmental point of view and can be used as basis for more specific calculations for several applications (functional units).

With respect to environmental impact, the graphs show that the various industrial bamboo materials compete well (especially in terms of their carbon footprint) with sustainably-sourced European softwood and score slightly better than tropical hardwood from sustainably-managed plantations. However, when taking into account the fact that much tropical hardwood,[9] including FSC certified hardwood, still comes from natural forests, the differences favour industrial bamboo materials due to the loss of biodiversity (included in the eco-costs) as well as the carbon sequestration debit.

A major environmental benefit of bamboo lies on the resource side. Since bamboo is a giant grass species, it is less susceptible to clear-cutting / deforestation and very suitable for reforestation for several reasons:

- The mother plant consists of many stems connected through a vast root system underground, with new stalks coming up each year.
- Bamboo is harvested like an agricultural crop. The annual harvest of the four to five year-old culms provides steady income to farmers and stimulates the bamboo plant to reproduce its stems more quickly. This is an important difference from wood production where rotation cycles of trees of over 30 years make forests vulnerable to illegal logging or clear-cutting for a short-term gain. Since giant bamboo can be harvested annually, clear-cutting of giant bamboo forests would mean a waste of capital for the farmer and thus it occurs rarely, if at all.
- Due to its extensive root system, bamboo can be planted in areas where farming is not feasible, e.g., by rehabilitating degraded land - including eroded slopes - and re-establishing functioning and productive ecosystems by improving soil quality and restoring the water table (Kuehl and Lou Yiping 2011). As the growing speed of bamboo is very fast, it also requires a significantly shorter establishment time than do wood plantations;
- Another important advantage of bamboo is that its fast growth results in a high annual yield (m3 of semi-finished material). This advantage is particularly important due to the fact that land might become scarce in the future. (See Annex I). The benefit of this high annual yield for carbon sequestration is covered in the following chapter, "The potential of bamboo for climate change mitigation".

In conclusion, it seems clear that industrial bamboo products, due to their hardness, dimensional stability and aesthetic appearance, could substitute for FSC certified hardwoods, both in terms of carbon footprint and eco-costs. From a *global perspective* (see Figure 3 in Chapter 2), taking into account the resource-side benefits of bamboo (high yield, annual harvesting, reforestation on degraded land, short establishment time, etc.), it becomes clear that bamboo could be a promising contributor to a more sustainable economy by: [10]

- Reducing emissions (and biodiversity loss) caused by deforestation in tropical and sub-tropical areas as a viable low emission alternative to tropical hardwood;
- Reducing emissions from burning fossil fuels by generating electricity at the end-of-life of a growing number of bamboo products, based on expected market growth;
- Carbon sequestration through reforestation of degraded grassland and slopes with bamboo forests.

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[9] Globally, FSC certified tropical hardwood is partly sourced from plantations and semi-natural forests, but the lions share (64%) still comes from natural forests (harvested with reduced impact harvesting).

[10] This is a necessity because, due to the growth of the global population and the increase of consumption per capita, the world's ecological footprint is 1,5 times the amount of required resources the Earth can produce. See Annex I for more information.

The potential of bamboo for climate change mitigation

Bamboo is an untapped strategic resource that countries in the world's tropical and sub-tropical regions can use to better manage climate change, provide beneficial ecosystem services and new income sources for rural populations. Bamboo can add value to climate change mitigation and adaptation in support of a number of UN Sustainable Development goals:

- SDG7: Ensure access to affordable, sustainable, and reliable modern energy services for all. Of special interest are SDG 7.2, which aims to double the share of renewable energy by 2030.
- SDG13: Promote actions at all levels to address climate change.
- SDG15: Protect and restore terrestrial ecosystems and halt all biodiversity loss. Of special interest are SDG 15.2, which calls for restoration of 15% of all degraded ecosystems by 2030, SDG 15.5, which aims to increase forest cover and SDG 15.11, which calls for the integration of natural resources into planning and development processes.

It is clear from our research that bamboo can reduce the negative effects that changing climate patterns have on millions of rural communities around the world. However, two obstacles remain: the current lack of appreciation of bamboo's significant benefits by national policy-makers and the classification of this grass species under forestry regulations, curtailing wider use for harvest and trade.

Note: Parts of the text in this chapter have been taken from Bamboo: A strategic resource for countries to reduce the impacts of climate change (INBAR 2014) and INBAR Technical Report 32 (Lou Yiping et al. 2010).

Bamboo in compliance and voluntary carbon markets

For bamboo to be accepted as a key resource in national and international policies, it is of crucial importance that it is recognized in the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCC was created to help mitigate climate change following targets set in the Kyoto Protocol.

The UNFCCC has established the following mandatory mechanisms to reduce GHG emissions: emissions trading, joint implementation and the Clean Development Mechanism (CDM). The CDM might be most relevant for bamboo as it includes emission reduction projects through afforestation in developing countries.

Besides the so-called compliance carbon market, a voluntary carbon market has also developed, driven by corporate social responsibility. Eligible projects within the voluntary market are often small in scale and more focused on emissions related to related to agriculture, forestry and other land uses (AFOLU) than on the high emitting - large industry focus of the compliance market. The voluntary market is unregulated yet governed by several recognized international standards such as the Verified Carbon Standard and The Gold Standard, which are used to verify the quality of the carbon credits traded.

AFOLU accounts for more than 30% of total anthropogenic greenhouse gas emissions (IPCC, 2007), in particular through deforestation. Established in 2005, , REDD is a mechanism to reduce emissions from deforestation and degradation in developing countries. Later this was further broadened to REDD+ to reward afforestation and improved forest management. Whereas REDD+ has been readily adopted in the voluntary carbon market, it has not yet been adopted in the compliance market, although the CDM's latest recommendations support the inclusion of REDD+.

In general bamboo can contribute in two ways to carbon sequestration within the AFOLU scheme of the IPCC 2006 guidelines, i) on the forest / plantation level (chapter 4 Forest Land) or ii) contribution to the durable products pool (chapter 12, Harvested Wood Products).

Bamboo ecosystems as carbon sinks

Because it is botanically a grass — actually more than 1000 species of grass — bamboo is not classified as a tree in forestry evaluations and thus is often omitted from discussions of forests and climate change, including in the context of REDD+. Nevertheless, studies increasingly find that bamboo has important roles to play in sequestering carbon in forest ecosystems.

Attempts to determine how much carbon bamboo forests contain have shown great variation, demonstrating the need to harmonize the measurement of carbon density across different sites, species, climates and other conditions. Reliable estimates of global bamboo carbon stock await further research in Asia, Africa and the Americas, but recent research in China (Yiping et al. 2010, Kuehl 2013 et al.) has compared the dominant Moso bamboo species with the fast-growing Chinese fir tree, which grows in similar climatic conditions.

The results indicate that if Moso bamboo is well managed and harvested regularly to create durable products, it has a higher carbon sequestration capability over a fixed time period than does the Chinese fir (305.77 t C/ha vs 178.05 t C/ha over 60 years; per year this equates to annual carbon increments of 5.10 t C/ha for Moso bamboo and 2.97 t C/ha for Chinese fir). While Kuehl et al (2013), assumed that all harvested above-ground biomass is stored in durable products, such an assumption does not account for processing losses in transformation to industrial bamboo and wood products. Furthermore, the lifespan of the finished products will most likely be shorter than 60 years.

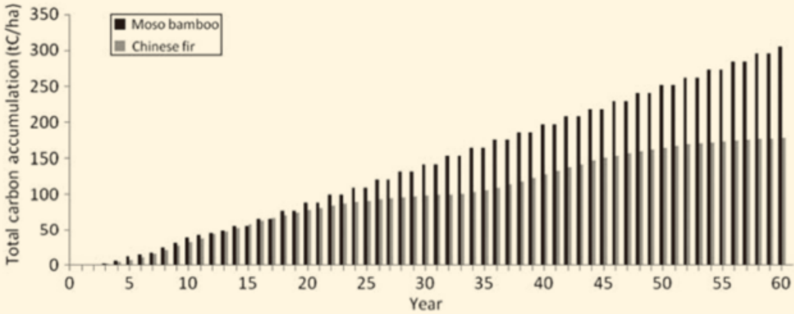

Figure 18. Patterns of modelled aggregated carbon accumulation of newly established Moso bamboo - regular harvest scenario - and Chinese fir plantations over 60 years. In a managed bamboo forest, where harvested bamboo is converted into durable bamboo products, a significantly higher amount of carbon is sequestered for the long term.

However, if the Moso bamboo forest is unmanaged and not harvested, e.g. for the production of durable products, the forest quickly comes to an equilibrium as the mature stems become old and decay, blocking space for new young culms. In this scenario, the carbon sequestration for Chinese fir will be higher than for bamboo over a fixed period of time (98.75 t C/ha vs 49.51 t C/ha over 30 years; per year this equates to mean annual carbon increments of 3.29 t C/ha for Chinese fir and 1.65 t C/ha for Moso bamboo).

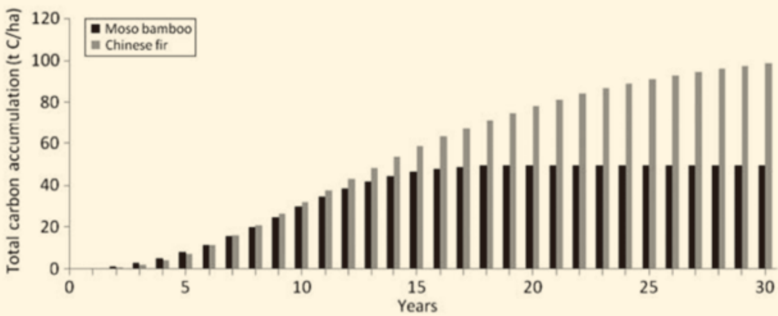

Figure 19. Patterns of modelled aggregated carbon accumulation of newly established Moso bamboo - no harvest scenario - and Chinese fir plantations (Kuehl et al, 2013)

The above implies that regular, annual harvests of Moso bamboo forests will increase carbon sequestration capacity through the biomass and soil on the plantation, as well as in the durable products pool and sequestration will be considerably higher for bamboo than for wood because of its high yield (see Bamboo's Durable Products Pool below). Bamboo also has an important role to play in reducing pressure on forests. Since a nationwide logging ban of certain forests came into effect in 1998, bamboo has increasingly been seen as a substitute for wood timber in China and has entered many markets traditionally dominated by wood.

Bamboo is slowly becoming recognized in some voluntary carbon offset programmes. . One high profile purchase made the news in 2009 when Alibaba, the Chinese internet retailing giant, bought offsets for 46,7 hectares of bamboo planted in Lin'an County of Zhejiang Province [for more information about the bamboo carbon accounting project see Zhou et al. (2013)]. Other carbon offset programmes, such as the Gold Standard, Panda Standard and Verified Carbon Scheme, have now accepted bamboo in some afforestation and reforestation projects. This means a start has been made, but a lot more work needs to be done as bamboo forests merit inclusion under REDD+ through conversion of degraded lands to bamboo plantations, but also through bringing unmanaged forests under management schemes.

The durable product pool

Each year the carbon stored in harvested bamboo stems is transferred to durable products such as panels, beams and flooring. Until these are discarded or burned, the carbon will remain locked in the product, serving as an important carbon pool. Because of its high annual yield, ,the products pool for bamboo will be significantly higher than for a fast growing tree species in the same climatic conditions such as Chinese fir. This is further amplified by the fact that it is more efficient to process industrial bamboo products (production efficiency of 42%) than wood (38%) for the production of high quality building materials (van der Lugt 2008, Werner et al. 2007). Processing efficiency can be even higher in the production of strand woven bamboo (56%), flattened bamboo (64%) or the stem (80%). See also Annex.

The total carbon stock of standing volume bamboo on a managed plantation plus the durable products pool is generally somewhat higher for Moso bamboo than for Chinese fir (see Figure 20), not taking into account the potentially larger area where bamboo could be used for landscape restoration. Figure 20 also clearly indicates that the carbon stock in the ecosystem is significantly higher than the carbon stock in the durable products pool.

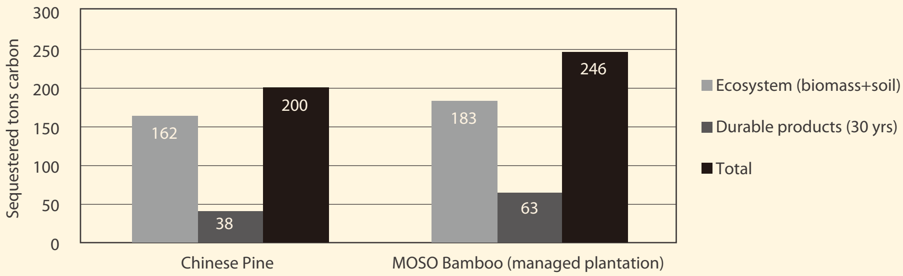

Figure 20: Average values for carbon stock over a 30 year time period on a managed plantation and durable products pool for Moso bamboo (Kuehl 2013, Zhou 2006, Qi 2009) and for Chinese fir (Kuehl 2013, Tu 2007, Xiao 2009)

Pingoud et al. (2003) and Marland et al. (2010) found that the annual inventories of CO2 emissions for major wood producing countries can change by as much as 30%, depending on how harvested wood products are treated in the inventory. The continuous growth of the size of the pool of harvested products is thus a key determinant in whether the system acts as a sink. As seen in chapter 5, for the Chinese situation, because of the increasing market demand the Moso bamboo area is growing as is the related durable products pool in buildings (step 4), which theoretically could be taken into account as an additional carbon stock worth valueing in carbon accounting systems. Nevertheless, as noted in INBAR Working Paper 73 (Zhou et al. 2013), "the current international climate negotiations have not yet reached a recognized measurement, monitoring, verification methodology for harvested forest product carbon storage. Existing domestic methodology research on Harvested Bamboo Product carbon storage measurement, monitoring, and verification is not yet mature and lacks systematic structure (…). However, it is not covered in the present methodology due to insufficient current knowledge about bamboo product applications, losses during production and the unknown course of product degradation and release of carbon into the atmosphere."

Thus, the work presented in this report including the detailed production steps as reported in van der Lugt (2008) and van der Lugt et al. (2009) will be of value in the validation of the Chinese Harvested Bamboo Product carbon pool which then may be included already in voluntary credit systems and hopefully also soon in mandatory carbon crediting regulations.

Furthermore, although not yet included in the AFOLU guidelines, if the substitution effect of building with materials with a low or negative carbon footprint such as wood (Gustavsson 2001) but also bamboo (see figure 20) instead of high carbon intensive materials (such as steel, concrete, brick, PVC) would be included in the future, this could have a large influence on carbon accounting mechanisms and become a major incentive for further implementation of durable bamboo products in the building industry.

Landscape restoration

In addition to its potential carbon sequestration benefits, bamboo provides several opportunities for landscape restoration due to its fast growth, potential for soil binding and erosion control, ability to grow on degraded and marginal soils, nutrient and water conservation on land and provision of a continuous and permanent canopy (Mishra et al. 2014, Rebelo and Buckingham 2015).

Although bamboo provides many opportunities for landscape restoration, as with any crop, appropriate management and propagation techniques are needed. Monoculture plantations should be avoided to reduce susceptibility to pests and prevent soil degradation and biodiversity loss (Buckingham 2014). Furthermore, restoration benefits particularly apply on degraded lands and should never come at the expense of natural forests.

The potential of bamboo for landscape restoration has been actively exploited by INBAR in the scope of the Bonn Challenge. This global movement was launched at a ministerial conference in Germany in September 2011 with the goal of restoring 150 million hectares of degraded and deforested land by 2020. The movement gained momentum when the target was extended to 350 million hectares by 2030 through the New York Declaration on Forests (UN 2014). According to Laestadius et al (2015), if this goal is reached it would result in an annual carbon sequestration of up to 1,6 -3,4 Gt CO_2 / year, totalling 11,8 – 33,5 Gt CO_2 sequestered over the period 2011-2030.

Following the Bonn Challenge and New York Declaration, the World Resources Institute (Minnemeyer et al. 2011) has identified 2 billion hectares suitable for so-called mosaic restoration, which integrate forests (including bamboo forests and plantations) with other land uses, such as agroforestry and agriculture. Much of the bamboo growing area worldwide overlaps with the 2 billion hectares identified by WRI. Given the ability of bamboo to restore degraded land for productive use, there is a clear worldwide potential for bamboo afforestation (Rebelo and Buckingham 2015). See Figure 21.

A "Sea" of bamboo in eastern China

Figure 21. The World Resources Institute identified 2 billion hectares of degraded land that offer opportunities for restoration.

Figure 22. Bamboo growth areas worldwide

INBAR'S member countries have agreed[11] to restore 5 million hectares with bamboo by 2020, recognizing that this could grow to 10 million as national plans and initiatives progress over the coming decade.

The challenge: Getting bamboo included in domestic and international carbon accounting and forestry regulations

Although bamboo is included in most – but not all – international definitions of forests, bamboo silviculture is poorly served by existing international agreements on forests. Furthermore, bamboo is often a feature of agroforestry systems, which fall outside the scope of government departments of agriculture or forestry. New approaches that emphasize landscape approaches to sustainable rural development promise to change these perceptions — and the sooner the better.

It is time for the United Nations Framework Convention on Climate Change to explicitly recognize bamboo's existing and potential contribution to mitigating climate change by ensuring that bamboo-based carbon accounting methodologies for afforestation and reforestation projects are included in the agreements on carbon market mechanisms. In addition, the UNFCCC should support the development of new methodologies for incorporating bamboo into REDD+ programmes and national greenhouse inventory accounting for harvested wood products. In this way, the huge contribution that bamboo can make climate change mitigation and adaptation, landscape degradation and improving rural income and livelihoods can finally be realized.

[11] For more information see http://www.wri.org/blog/2014/12/rebranding-bamboo-bonn-5-million-hectare-restoration-pledge

Annex
Yield of land

Land use

Land is rapidly becoming more scarce and degraded, posing a profound constraint to feeding a growing global population.

A useful indicator for the scarcity of land is its ecological footprint, which is defined as "a measure of how much biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates using prevailing technology and resource management practices (WWF 2012)."

In 2008 the global ecological footprint was 18,2 billion hectares, whereas the global productive area was only 12,0 billion hectares. This means that humans are currently consuming more than 1.5 times the amount of resources that the Earth can produce. Clearly, renewable materials with a high yield of land are required. See Figure 23.

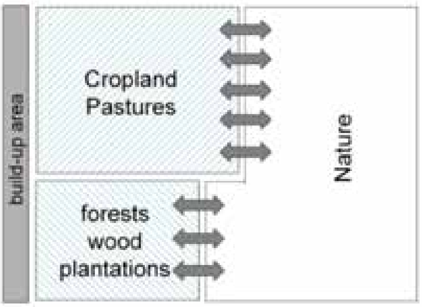

Figure 23. The yield of land must be as high as possible to achieve a minimum ecological footprint.

Bamboo appears to be a good solution:

- It can grow in areas that are currently non-productive (e.g. on eroded slopes).
- It is fast-growing and has a high yield.
- Its root structure stays intact after harvesting, generating new shoots.

The yield (in this report: annual increase in harvestable standing volume minus processing losses) calculations below are based on numbers for average wood and plantation sites and processing facilities. Note that yields may be considerably higher or lower, depending on geographical and climatic circumstances (e.g. soil, precipitation, elevation, etc.); the data are thus only indicative of the average yields of the species in question.

Annual yields have been calculated for Moso bamboo from China and Guadua (*Guadua Angustifolia*) from Latin America. Guadua is larger than Moso, reaching heights of 20-25 metres and diameters up to 22 cm. Like most bamboos, Guadua reaches its final height in the first half year of its growth and will come to maturity in the following four to five years. Guadua has a higher yield (approximately by a factor of two) than Moso. However, the biodiversity of the areas where Guadua grows (Colombia, Ecuador) is two and a half times higher than the biodiversity of the Zhejiang area, which is home to Moso. Therefore, from the point of view of saving biodiversity, it seems wiser to expand Moso plantations to meet future demand for bamboo products (unless reforestation with Guadua takes place on degraded lands).

The annual yield of bamboo and wood may differ depending on the kind of materials that are produced because of varying processing efficiencies. Calculations have been made in van der Lugt (2008) on three different production scenarios, which are depicted in Figure 24:

A. High value products (sawn timber, veneer, plybamboo, strand woven bamboo, taped mats)
B. Medium value products (MDF, chipboard)
C. For combustion as an energy source and for pulp e.g. for paper production

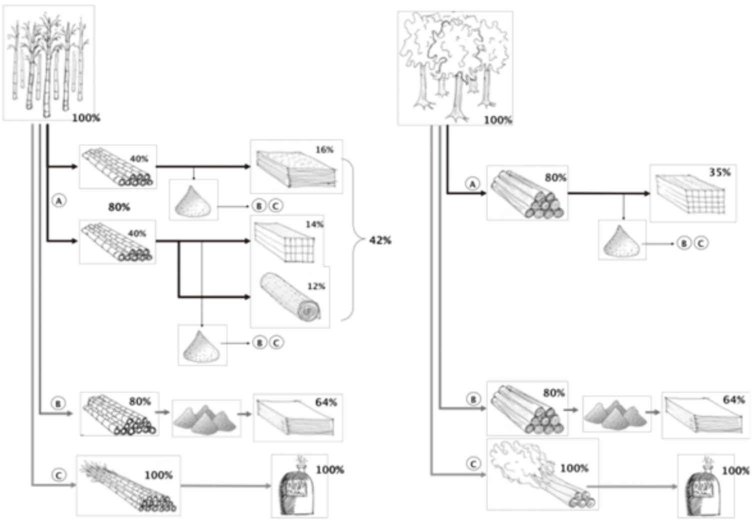

Figure 24. Efficiency during the conversion of bamboo (left) and wood (right) resources to semi-finished materials under A, B and C scenarios; all percentages related to harvestable standing volume (100%), taken from van der Lugt (2008).

Under the A scenario, the comparison is made between bamboo, the hardwood species teak and European oak and the softwood species Scandinavian Scots pine, North American western red cedar and eucalyptus. For detailed calculations on the annual yield of various bamboo products, the reader is referred to section 5.2.2 in van der Lugt (2008). In this report flattened bamboo is included following the SWB calculation in table 5.22 of van der Lugt (2008) but with a higher processing efficiency of 80% as there is little waste during processing this product (the stem is the final product in flattened form).

Figure 25 shows that industrial bamboo materials have a larger annual yield than hardwoods (with which they compete in terms of material properties), especially in the case of strand woven bamboo and / or flattened bamboo because of their higher processing efficiency, and even more so in the case of giant bamboo species such as Guadua (with an annual yield almost twice as high as Moso). Industrial bamboo products are competitive or even outperform eucalyptus – one of the fastest growing wood species worldwide – depending on the production scenario.

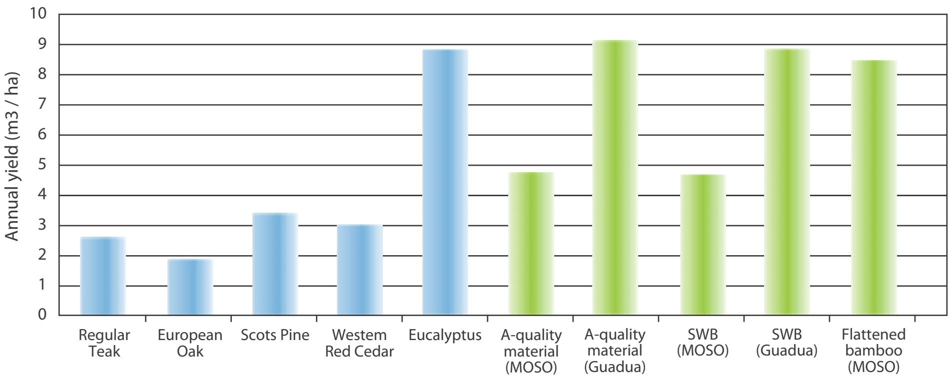

Figure 25. Annual yield of various wood and bamboo species in cubic metres produced per hectare per year (FAO 2006, MAF 2008, van der Lugt 2008, USDA 2013).

A general benefit of bamboo as a reforesting crop is the short time required to establish a bamboo plantation. While the time needed for a plantation of species such as Moso and Guadua to come to maturity is not longer than ten years, the time required to take a wood plantation to maturity may range from 15 years (eucalyptus), 30 years (plantation teak), 70 years (regular teak) and up to 80 years (European oak).

In terms of annual yield of the end product, combined with the biodiversity of the area, it can be concluded that bamboo is one of the best performing renewable resources around, especially if used as semi-finished material in a durable application (e.g., for housing and use outdoors).

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The **International Network for Bamboo and Rattan (INBAR)** is the multilateral development organisation of 41 Member States for the promotion of bamboo and rattan. INBAR supports its members to include bamboo and rattan in their sustainable development action plans and green economy strategies. It promotes innovative ways of using bamboo and rattan to improve rural livelihoods, protect the environment, address climate change and issues of international bamboo and rattan trade and standards. INBAR connects a global network of partners from government, private and NGO sectors to promote a global agenda for sustainable development using bamboo and rattan.

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