Carbon sequestration and carbon emissions reduction through bamboo forests and products

van der Lugt, Pablo; Thanglong, T.; King, C.

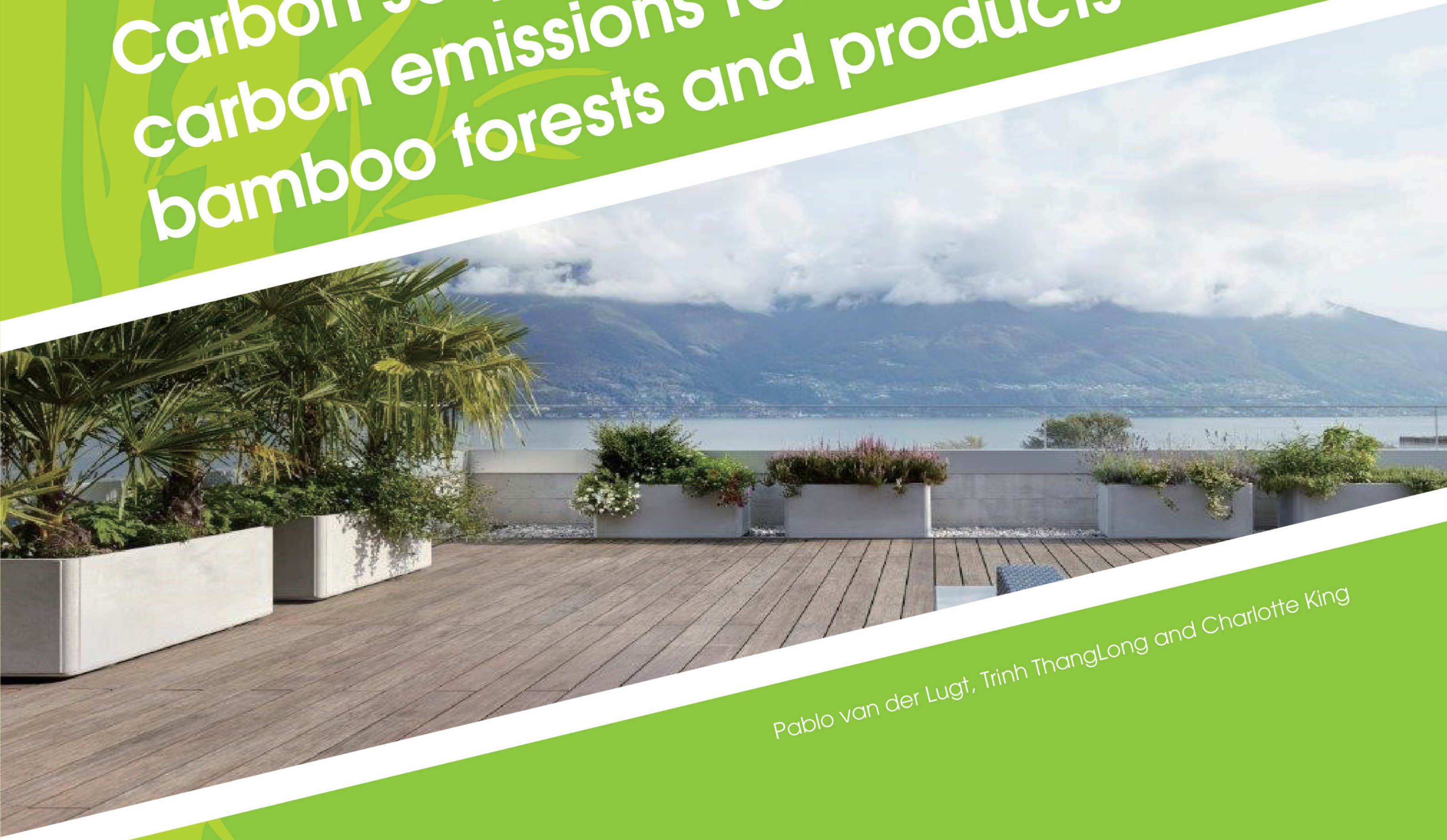
Publication date
2018

Document Version
Final published version

Citation (APA)
van der Lugt, P., Thanglong, T., & King, C. (2018). *Carbon sequestration and carbon emissions reduction through bamboo forests and products*. Inbar.

INBAR Working Paper

Carbon sequestration and carbon emissions reduction through bamboo forests and products



Pablo van der Lugt, Trinh ThangLong and Charlotte King

INBAR
INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

International Bamboo and Rattan Organisation

INBAR, International Bamboo and Rattan Organisation, is an intergovernmental organisation bringing together some 43 countries for the promotion of the ecosystem benefits and values of bamboo and rattan.

Authors:

Pablo van der Lugt,[1,2] Trinh ThangLong[3] and Charlotte King[3]

1.Delft University of Technology, Faculty of Architecture and the Built Environment, Climate Design & Sustainability Department, Julianalaan 134, 2628 BL Delft, the Netherlands. Contact: p.vanderlugt@tudelft.nl

2.MOSO R&D Center, Adam Smithweg 2, Zwaag, the Netherlands

3.International Bamboo and Rattan Organisation, 8 Fu Tong Dong Da Jie, Beijing, 100102, P.R. China

International Bamboo and Rattan Organisation (INBAR)

PO Box 100102-86, Beijing 100102, P. R. China
Tel: +86-10-6470 6161; Fax: +86-10-6470 2166;
Email: info@inbar.int
www.inbar.int

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AGC	Above-ground carbon
BGC	Below-ground carbon
C	Celsius
CDM	Clean Development Mechanism
FAO	Food and Agricultural Organization
HBP	Harvested Bamboo Products
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contributions
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SOC	Soil organic carbon
SWB	Strand woven bamboo
TEC	Total ecosystem carbon

ABSTRACT

Because of their fast growth rates, giant woody bamboos are already considered effective CO_2 absorbers. Carbon can be further sequestered in durable harvested bamboo products and even higher carbon emissions reduction is possible if bamboo products replace non-renewable, carbon-intensive alternatives.

Research so far on the total carbon sequestration and carbon emissions reduction potential of woody bamboos is scattered and diffuse. This paper provides an overview of existing peer reviewed scientific literature on bamboo carbon sequestration and carbon emissions reduction potential from forests and through bamboo products.

The results of the literature overview show that, in general, bamboo has a lower total ecosystem carbon (TEC) (94-392 tonnes of carbon per hectare [tC/ha]) than timber forests (126-699 tC/ha), but a similar TEC as tree plantations (85-429 tC/ha). However, if the substitution of carbon-intensive materials with harvested bamboo products are included in calculations, the carbon emissions reduction potential of a managed giant bamboo species forest such as *Phyllostachus Pubescens* (Moso) can be significantly higher than for a Chinese fir (335 tC/ha versus 253 tC/ha) growing under the same conditions. Although dependent on the bamboo species, in a best case scenario, the combined carbon sequestration and carbon emissions reduction potential of reforesting degraded grassland with bamboo could reach 213.9 – 395.2 tC/ha of reforested land, or around 785 – 1450 tons CO_2/ha. The situation is reversed if the bamboo plantation is not managed, which relates to a combined carbon sequestration and carbon emissions reduction potential of only 49.5 tC/ha for unmanaged Moso bamboo, which shows the importance to bring bamboo forests under management.

To arrive at more robust conclusions, additional research is required, including the influence of various growth factors.

Keywords: bamboo, carbon sequestration, carbon emissions reduction, product displacement, climate change mitigation, durable products pool, reforestation

1.INTRODUCTION AND METHODOLOGY

Unsustainable consumption patterns are increasing the pressure on natural resources around the globe, leading to depletion of resources and increasing greenhouse gas emissions, in turn accelerating global warming. Under the Paris Agreement (known as COP 21), 195 countries have committed to keeping the increase in global temperature "well below 2° Celsius (°C) compared to pre-industrial levels", with a more ambitious aim to limit the temperature increase even further, to within 1.5°C.

However, despite accelerating technological innovations and the reducing cost of renewable energy, global mean temperatures are expected to rise above the 2°C goal (Raftery et al. 2017). According to the Intergovernmental Panel on Climate Change (IPCC), while decarbonisation of the global economy is a top priority, strategies to remove CO_2 from the atmosphere are also needed to meet climate goals (IPCC 2014). Deforestation and reforestation play an important role in meeting these climate objectives as it is estimated that deforestation of global forests alone contributes 10 to 15 per cent of global greenhouse gas emissions (FAO 2015).

In the Paris Agreement, REDD+ was officially recognised as a mechanism to mitigate climate change. REDD+ is closely linked to two mechanisms developed under the Kyoto Protocol: the Clean Development Mechanism (CDM) as well as the Joint Implementation mechanism. Further, according to Butarbar et al. (2016) REDD+ is strongly linked with the voluntary carbon market, including the Voluntary Carbon Standard and the Gold Standard. Under the Paris Agreement, countries must individually determine how to meet their climate goals through national action plans, called Nationally Determined Contributions (NDCs).

There are numerous ways in which forests and bio-based products, such as wood, as well as non-timber forest products, such as bamboo, can store carbon or can reduce carbon emissions. These include the prevention of deforestation and forest degradation, the better management of existing forests, afforestation, increasing use of durable, bio-based products, recycling and/or use as bio-energy sources during the End-of-Life phase. Proving bamboo-related carbon sequestration can be considered as an additionality, i.e. over and above current practice, requires complex calculation of the potential carbon emissions reduction and demonstration that this is not 'business as usual'. This is important, since some carbon emissions are already included in mandatory carbon reduction methodologies (for example, CDM, REDD+), others only in voluntary methodologies (such as VCS). Conversely, other carbon emissions are not included in any scheme, although they may have an absolute carbon benefit (e.g. displacing non-renewable materials with bio-based materials).

Because of their fast growth, giant woody bamboos are very effective CO_2 absorbers, not only in above ground carbon (AGC) but also in below ground carbon (BGC) such as roots, rhizomes and to a lesser extent in the soil organic carbon (SOC). This paper assumes bamboo biomass contains 50% carbon by weight (Chen et al. 2009; Yen and Lee 2011).

Most of the 30 million hectares of bamboo available worldwide grow in countries with tropical and sub-tropical climates across Africa, Asia and Latin America. Many of these countries also suffer from deforestation of their natural forests. Under the Paris Agreement, most countries have agreed to plant trees and other vegetation to increase their carbon sinks. Since bamboo is highly suitable for re/afforestation on unproductive agricultural land, degraded grassland or eroded slopes, it is potentially an effective tool to help implement country NDCs. However, for bamboo to be approved in NDCs through REDD+, it is first necessary for each country to justify the inclusion of bamboo as an appropriate carbon sequestration species.

At present, there is a real lack of research on the exact carbon sequestration of giant woody bamboos and bamboo products. This is hampering the effective adoption of bamboo in NDCs. Furthermore, existing information on the subject is scattered. This paper provides an overview of existing peer reviewed scientific literature on the carbon sequestration potential of bamboo forests, with a view to helping countries to include bamboo as a tool for national carbon sequestration and emissions reduction. In particular, the paper considers three mechanisms for calculating bamboo's carbon sequestration and carbon emissions reduction potential: total ecosystem carbon; the durable products pool; and potential product displacement.

1.1 Scope

There are over 1642 known species of bamboo (Vorontsova et al. 2016), with very different size and growth patterns. This paper considers only two giant bamboo species that, due to their size (biomass) and abundance, have sufficient potential for use in engineered bamboo products. These are:

- *Phyllostachys pubescens* (hereafter identified as 'Moso' bamboo) – a monopodial or 'runner' species, mainly found in China
- *Guadua angustifolia* (hereafter identified as 'Guadua') – a sympodial or 'clumper' species, mainly found in Latin America

For this study, it is assumed that the harvested bamboo is used to produce strand woven bamboo (SWB), also known as 'bamboo scrimber': very hard and dense bamboo boards and beams made from compression moulded bamboo strips, with a density of approximately 1050 kg/m^3 (of which bamboo content is 997.5 kg/m^3, remainder is resin). SWB is valued due to its hardwood-like aesthetic and hardness. Thermal modification of the input strips enables it to be used for exterior applications.[1]

1 For more detailed information on the SWB production process and raw materials, refer to MOSO (2016).

Figure 1: Strand woven bamboo for indoor (left) and outdoor (right) use. (Photo credit: MOSO International)

Figure 2: Ultra density SWB flooring in Bordeaux train station, France. This was used due to its hardness and wear resistance. (Photo credit: MOSO International)

Figure 3: Thermally modified exterior SWB decking, Switzerland.
(Photo credit: Danielle Kahr / MOSO International)

In the absence of standard methods, this paper calculates carbon sequestration potential based on:

1. Carbon locked in the ecosystem, defined as total ecosystem carbon (TEC);
2. Carbon locked in the harvested bamboo products (HBP), which is related to the annual rate of carbon sequestration in a bamboo forest.

In theory, each of these components may contribute to a country's NDC once bamboo has been registered by that particular country as an approved species for reforestation.

Furthermore, the potential to reduce carbon emissions is twofold when bamboo materials are used as a substitute for materials with a higher carbon footprint. This is known as the potential displacement factor (Rüter et al. 2016), or 'carbon emissions reduction through product displacement' (term used in this paper), which has considerable potential to further reduce a country's CO_2 emissions.[2]

Although carbon emissions reduction through product displacement is currently not considered in mechanisms approved under the Paris Agreement, such as CDM or REDD+ (Butarbar et al., 2016), it is particularly relevant where bamboo products are used, and might be included in future greenhouse gas

2 According to Oliver et al. (2014), substituting steel and concrete in construction with sustainably sourced wood would result in a 14 to 31 per cent reduction in global CO_2 emissions.

reduction protocols. For these reasons, we have included our calculations for product displacement in this paper.

Furthermore, energy generated from biomass may be included in CDM if it substitutes high-carbon intensity energy such as fossil fuel-based energy sources. As such, we have included calculations for carbon reduction via electricity production through the latest bamboo gasification technology.

1.2 Total ecosystem carbon

According to the Food and Agricultural Organization (FAO), the carbon in the world's forests and woodlands tends to be stored in various ways: 53 per cent is stored in living biomass, 8 per cent in dead wood and litter and 39 per cent in soil. To assist with an understanding of where carbon is stored, this paper uses the CDM methodology for re/afforestation activities, which categorises relevant carbon pools into three areas: AGC, BGC and SOC (United Nations Framework Convention on Climate Change 2016), combined under the TEC.

1.3 Durable products pool

In general, the carbon stored temporarily in harvested wood products (HWP) can be considered a net carbon sink "only in the case where a country can document that existing stocks of long-term forest products are in fact increasing" (IPCC 2006, IPCC 2014).

However, data on HWP commodities is usually derived from national and international statistics databases such as FAOSTAT or UN Comtrade, which is often not available for finished wood products (Rüter et al. 2016). Therefore, it is unclear to what extent HBP are included in this durable products pool. However, as bamboo may be included in NDCs, and the HWP pool is accepted under CDM, it seems likely that the HBP pool would also be eligible to contribute to a country's NDC.

Although a considerable part of the bamboo stem can be used for other applications, such as charcoal, chopsticks and fodder, these products usually have such a short product life that they do not significantly contribute to the durable products pool and are therefore not included in this analysis.

1.4 Carbon emissions reduction through product displacement

In the Climwood 2030 study, the potential displacement factor is defined as follows:

> The (absolute and relative) measure of the efficiency with which the increased use of forest biomass in the production of a given type of functional unit would reduce net GHG emissions, over the full life cycle of the functional units under consideration, e.g.: "Building a timber house instead of an equivalent, non-timber house would save X (per cent of) tCO_2e over the lifecycle of the houses." (Rüter et al. 2016)

Wood and bamboo absorb CO_2 during growth and have far lower CO_2 emissions during production (cradle-to-gate) compared to non-renewable, high-embodied energy materials such as plastics, metals and concrete. Over their life cycle, sustainably sourced wood and bamboo materials emit somewhere between -9 to -613 kg CO_2eq per m^3, compared to 503 to 19,012 kg CO_2eq per m^3 from non-renewable, carbon-intensive materials (van der Lugt 2017). According to Rüter et al. (2016) this can equate to as much as 1.5 to 3.5 tons CO_2 saved per ton of HWP used in the building industry to substitute non-renewable materials. This paper assumes an average displacement factor for (soft) wood of 2.5 tons CO_2 per ton HWP (equivalent to 0.68 tons C per ton HWP) and similar for SWB.[3]

In addition to engineered materials, the carbon emissions reduction through substitution of fossil based energy with bamboo based energy such as charcoal, biogas, pellets, ethanol, etc. is worth consideration in NDCs. Therefore, an example assessment of the carbon emissions reduction potential of using bamboo gasification technology instead of fossil fuel based electricity is included in this paper.

1.5 Carbon sequestration and carbon emissions reduction potential through new pools: bamboo reforestation and utilisation

Given the suitability of bamboo for reforestation (INBAR 2014), this paper also estimates the carbon sequestration and carbon emissions reduction potential of reforesting grassland (from T0 - baseline situation) with giant bamboo for 30 years (T1).

However, according to the IPCC (2003), conversion from forest to non-forest vegetation or vice versa does not lead to significant increases in soil carbon amount. The study by Yuen et al. (2017) confirms that the range of SOC for bamboo forest (70-200 tC/ha) is similar to grassland, pasture and shrub land (66-198 tC/ha) and therefore the SOC is omitted from the carbon sequestration calculation (T1-T0).

3 for detailed numbers see figure 4.7 in van der Lugt (2017).

2.RESULTS

2.1 Total ecosystem carbon

Table 1 presents estimated ranges of the various components of TEC for several types of land cover, including our selected giant bamboo species. For these bamboo species, the values are representative of mature stands growing under a range of climatic and environmental conditions in the subtropics and tropics.

Except for the data for Chinese fir plantations, the values have been derived from Yuen et al.'s peer reviewed meta-study based on 184 bamboo carbon and biomass studies (Yuen et al. 2017), thus providing a high level of confidence in the data presented in Table 1.

The wide range in values reflects the differences in size of the bamboo species, as well as varying climates, soil conditions and management practices. Most studies focused on Moso bamboo, providing a total of 217 AGC and 127 BGC values. For Guadua bamboo, 8 AGC and 6 BGC values were provided.

Species	AGC	BGC	SOC	TEC
Bamboo (general)	16 - 128	8 - 64	70 - 200	94 - 392
Moso	33.2	14.8	120 (average)	168
Guadua	69.9	7.5	79 (average)	156.4
Forest (general)	40 - 400	11 - 74	75 - 225	126 - 699
Tree plantations (general)	15 - 200	5 - 33	65 - 196	85 - 429
Chinese fir plantation (after 30 years) (Kuehl et al. 2013; Yiping et al. 2010)	89		93.2 (including BGC)	182.2
Grassland / pasture	2 - 35	2 - 4	66 - 198	70 - 237

Table 1: *Estimated ranges of mean values (unless otherwise stated) of above ground carbon (AGC), below ground carbon (BGC), soil organic carbon (SOC), total ecosystem carbon (TEC = AGC + BGC + SOC) in tC/ha, based on Yuen et al. (2017).*

Table 2 provides the results from a carbon sequestration flux comparison study by Kuehl et al. (2013), comparing Moso bamboo with Chinese fir (*Cunninghamia lanceolata*), which grows in similar conditions and has similar uses. This is complemented with available carbon sequestration flux data for some other giant bamboo species. No data is available for Guadua.

Kuehl et al.'s data shows that giant woody bamboo forests and plantations only provide high mean annual carbon sequestration when they are intensively managed (intensive management includes regularly annual or biannual harvesting, annual management, maintenance and tending operations). If not intensively managed, the forest's carbon sequestration capacity quickly comes to an equilibrium as mature stems decay and block space for new culms. Because of this, the carbon sequestration flux of the above ground biomass is three times lower for unmanaged Moso than for managed Moso, but also lower than the mean annual carbon increment of Chinese fir under the same environmental conditions.

Species	Annual carbon sequestration flux (tC/ha/yr)		Source
	No management	Intensive management	
Moso	1.65 (AGC)	5.1 (AGC)	(Kuehl et al. 2013)
Bambusa bamboos		24 (AGC)	(Nath et al. 2015)
Bambusa oldhamii		16 (AGC)	(Nath et al. 2015)
Phyllostachys bambusoides		13 (AGC)	(Nath et al. 2015)
Bamboo (general)		2.5 – 25 (AGC + BGC)	(Yuen et al. 2017)
Chinese fir (*Cunninghamia lanceolata*) plantation	2.67 (AGC)		

Table 2: *Annual carbon sequestration flux for several bamboo species.*

2.2 Engineered bamboo materials

Table 3 considers carbon sequestration from the durable products pool, and carbon emissions reduction through product displacement, for Moso bamboo, Guadua and Chinese fir. All estimates are based on a durable product lifespan of 30 years (See Box 1 and Box 2 for sample sub-calculations.). Carbon stored in the durable products pool is not expected to increase after 30 years, as products are assumed to be discarded or burned, after which any captured CO_2 will be released, levelling the CO_2 stored in new durable products made from newly harvested bamboo . Note that compared to the annual carbon sequestration flux provided in Table 2, the durable products pool takes into account yield losses of approximately 50 to 60 per cent during manufacture of the engineered bamboo materials.

Box 1: Durable products pool calculation

As trade data for engineered bamboo products for specific production technologies, such as SWB, are still lacking, it is difficult to assess the size of the HBP pool. Nevertheless, based on known yields of bamboo for use in SWB products (yields after processing: 4.7 m^3/ha per year for Moso; 9 m^3/ha per year for Guadua[4]), an indicative estimate of carbon stored in the durable products pool per hectare can be made.

Moso

For a Moso SWB product of density 1050 kg/m^3, only 95 per cent is bamboo (5 per cent is glue); of this bamboo content, we can assume 50 per cent carbon content. Therefore the carbon stored in the durable products pool is calculated as 4.7 m^3/ha per year x 30 years x 1050 kg / m^3 x 95 per cent x 50 per cent = 70.3 tC/ha.

Guadua

Following the same assumptions as Moso, but at an annual yield of 9 m^3/ha per year, results in 134.7 tC/ha.

Chinese Fir

The density of Chinese fir is approximately 500 kg/m^3, and the annual yield in terms of semi-finished materials is 4m^3/ha per year (FAO 2006). The carbon stored in durable product pool is calculated as 4m^3/ha per year x 500 kg/m^3 x 50 per cent x 30 yrs = 30 tC/ha.

Carbon emissions from the manufacture of these products are not included in the calculation of the durable products component. As shown by van der Lugt and Vogtländer (2015), the net CO_2eq emissions for SWB products that are produced in China and used in the Netherlands is 0.3 tCO_2 per m^3.[5] Compared to 1.83 tCO_2/m^3[6] stored for 30 years, the amount of CO_2 emissions produced during the manufacturing does not have a significant effect on the outcome, and is therefore not included in this paper.

4 van der Lugt, 2008

5 Calculations include the conversion of SWBs into bioenergy for electricity production at the end of their lifecycle: a common practice in the Netherlands.

6 Calculated at: 1050 kg/m^3 x 95 per cent x 50 per cent carbon content x 3.667 mol ratio C – CO_2 = 1828 kg CO_2 locked into every m^3 of SWB

Box 2: Carbon emissions reduction through product displacement calculation

The potential displacement assumes that the full bamboo yield over 30 years is used to replace incumbent, non-renewable building materials.

Moso

4.7 m3/ha/yr * 30 years * 1,05 tons/m3 * 95 per cent (bamboo excluding glue content) * 0,68 t C/ t SWB (SWB displacement factor) = 95,6 tons C displaced per hectare over 30 years.

Guadua

Following the same assumptions as Moso, but at an annual yield of 9 m3 / ha / yr results in 183,1 tons C displaced per hectare over 30 years.

Chinese fir

4 m3/ha/yr *30 years * 0,5 t/m3 * 0.68 tC / t HWP (softwood displacement factor) = 40,8 tons C displaced per hectare over 30 years.

Species	Durable products pool (tC/ha over 30 yrs)	Carbon emissions reduction through product displacement (tC/ha over 30 years)
Moso	70.3	95.6
Guadua	134.7	183.1
Chinese fir plantation	30	40.8

Table 3: *Carbon sequestration through HBP and carbon emissions reduction through product displacement of wood and bamboo, based on a product lifespan of 30 years.*

Figure 4 compares the data for all three of these carbon sequestration and reduction mechanisms for Moso, Guadua and Chinese fir.

To highlight the importance of active bamboo management, the data for an unmanaged Moso bamboo forest are included. In the unmanaged forest scenario, the combined effect of the carbon sequestration by the durable products pool and carbon emissions reduction through product displacement is nil.

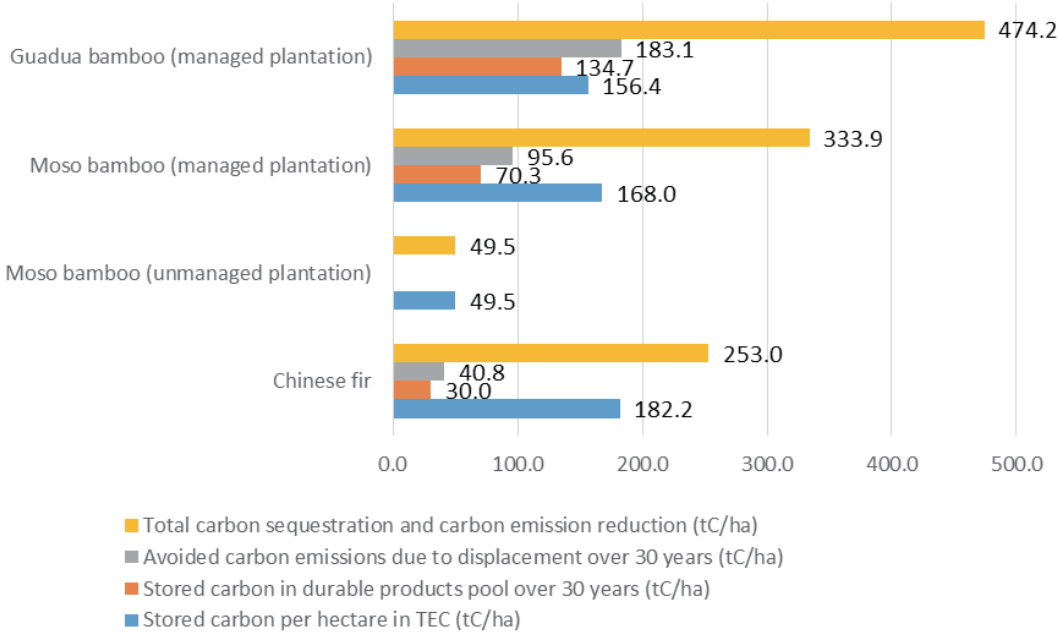


***Figure 4**: Carbon sequestration and carbon emissions reduction potential for bamboo (Moso, Guadua) and Chinese fir (tC/ha)*

Finally, Figure 5 presents the CO_2 emissions reduction potential of reforesting grassland (T0) with giant bamboo (Moso or Guadua), assuming optimal growing conditions and, once fully established, full utilisation of the harvest to produce SWB products in which carbon is stored for 30 years (T1), i.e an optimum carbon reduction scenario. The figure is similar to Figure 4, but since SOC for grassland and bamboo are about the same, SOC is not included in the ΔT.

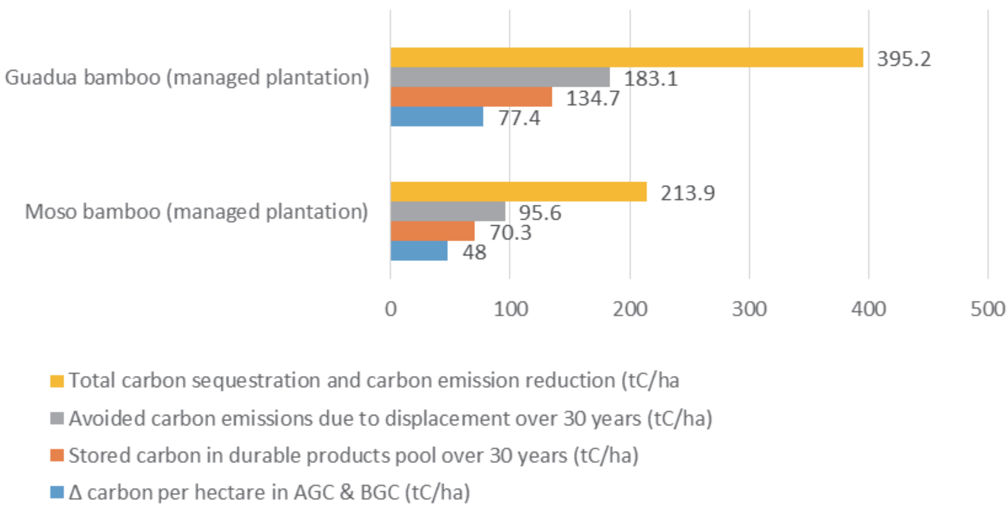


***Figure 5**: Combined carbon sequestration and carbon emissions reduction through product displacement for reforesting grassland (baseline = T0) with giant bamboo (Moso, Guadua) over a period of 30 years (T1).*

2.3 Bamboo for bio-energy

Bamboo biomass can also be converted into a source of energy for electricity or heating, either as fuelwood, gas or charcoal. If the bamboo biomass replaces fossil fuels for use as energy, then there is a carbon emissions reduction through product displacement. The magnitude of the displacement depends on many factors, such as the energy form which is being replaced, as well as the energy mix of the country, and the way in which the bioenergy is produced.

Box 3 provides an example of bamboo gasification technology based on an ongoing INBAR and PROSPERER project in Madagascar, which uses small gasification plants (25 kWh) run by rural communities (INBAR 2017). In these projects, the processes of bamboo management, harvesting and transport are completed manually, and so operational emissions are not included in the calculation. Because of the short lifespan there is no carbon sink in the durable products pool assumed, except if the charcoal would be buried underground.

Box 3: Carbon emissions reduction potential of electricity production using bamboo gasification

Bamboo based energy production

The gasification of 1.2 kg of dry bamboo produces 1 kWh of electricity plus 0.06 to 0.16 kg charcoal as a by-product.

Once the generator consumption of 0.12 kWh electricity is deducted, this gives a net production of 0.88 kWh of electricity from 1.2 kg of dry bamboo, i.e. 0.72 kWh/kg dry bamboo plus approx. 0.1 kg of charcoal.

Assuming that there is no processing loss from the harvesting of Moso bamboo for energy production - i.e. that the full AGC harvest is utilised annually, and a full annual carbon sequestration capacity of 5.1 tC/ha per year (Kuehl et al. 2013), the dry bamboo biomass is equal to 10.2 t/ha per year. This can produce 10.200 kg x 0.72 kWh = 7344 kWh/ha + 1020 kg charcoal per year.

Fossil fuel-based energy displacement

The CO_2 emission factor for electricity from the Chinese grid is 0.925 kg CO_2eq/kWh electricity produced. (data from Eco-invent 2018, data entry “Electricity, high voltage {CN}| production mix | Alloc Rec, S”)

As such, substituting electricity from the Chinese grid with electricity from bamboo gasification would reduce CO_2 emissions by 7344 kWh x 0.925 kgCO_2eq/kWh = 6795 kg CO_2/ha per year, or 6.8 tCO_2.

Over 30 years, the CO_2 emissions reduction would be 203.8 tCO_2/ha, or 55.5tC/ha. This is even without including the figure for carbon emissions reduction through the product displacement effect of the bamboo charcoal by-product.

In case the charcoal is buried underground assuming it will remain there for at least 30 years, carbon locked in bamboo charcoal (assuming 100% C content) over 30 years could be 30.6 tC/ha or 112 tCO_2/ha. Total carbon emissions reduction potential could then be 86.1 tC/ha, and in total 254,1 tC/ha.

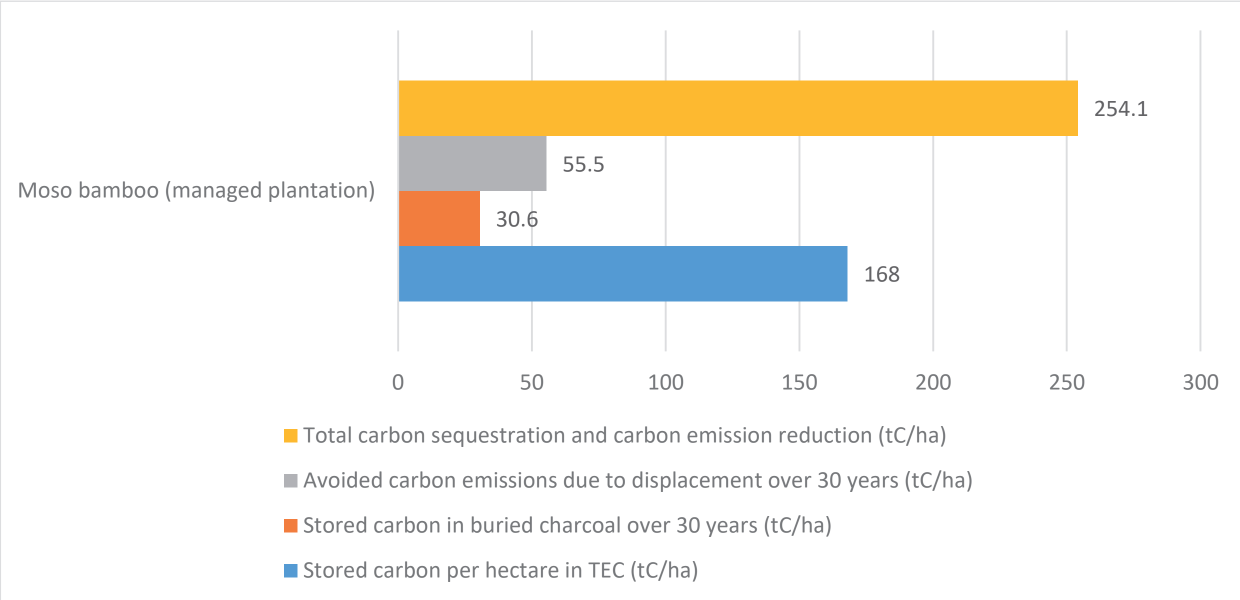


***Figure 6:** Combined carbon sequestration and carbon emissions reduction potential if the full yield of Moso bamboo is used for bamboo biomass gasification technology and if the charcoal by-product is buried underground (tC/ha)*

3.DISCUSSION

This paper has shown that bamboo has a lower TEC (94 to 392 tC/ha) than natural forests (126 to 699 tC/ha), but a similar TEC to managed tree plantations (85 to 429 tC/ha). This is consistent with previous literature on the subject (see, for example, Yiping et al. 2010).

However, there are large differences in TEC depending on the bamboo species and growing conditions. Under ideal growing conditions, the carbon storage of a managed Moso bamboo forest has been measured at between 169–259 kg C/ha. The carbon sequestration potential at any site will depend heavily on the management practices (intensity, weeding, irrigation, fertilisation, etc.), climatic conditions (temperature, soil conditions, precipitation, etc.) and importantly, the bamboo species used.

When compared with tree species which grow in similar climatic conditions and are also suitable for production of building materials, bamboo can have significant potential as a carbon sink, as a comparison of managed Chinese fir plantations versus managed Moso bamboo forests reveals. Although the TEC of a managed Moso bamboo forest growing in similar circumstances is lower or similar to Chinese fir plantations (168 tC/ha versus 182 tC/ha), the bamboo's higher growth rate means the resulting higher yield can be converted into durable products. This provides countries with a significant carbon sink in the durable products pool. Furthermore, if these bamboo products replace non-renewable, carbon-intensive building products, there is a further carbon reduction impact through displacement of those products – for example, using engineered bamboo flooring or window frames instead of PVC flooring or aluminium window frames.

Therefore, considering both the larger amount of carbon stored in the durable products pool (70.3 tC versus 30 tC for Chinese fir) and the carbon emissions reduction through product displacement (95.7 tC versus 40.8 tC for Chinese fir). The total combined carbon sequestration and carbon emission reduction potential of a managed Moso bamboo forest is significantly higher than for a Chinese fir plantation (334 tC/ha versus 253 tC/ha).

It is important to emphasise that this situation is reversed if the bamboo plantation is not managed. In this case, Chinese fir has a far higher combined carbon sequestration and carbon emissions reduction potential (49.5 tC/ha for unmanaged Moso bamboo compared to 253 tC/ha for Chinese fir plantation). This highlights the importance of active management of bamboo forests, for maximum carbon sequestration and carbon emissions reduction.

In the case of a giant sympodial bamboo such as Guadua, which has considerably higher yields than Moso, the potential for combined carbon sequestration and carbon emissions reduction is even higher: 474.2 tC/ha. This is in line with the conclusions of Nath et al. (2015), who found that sympodial bamboos have highest annual carbon sequestration rates (see also table 2).

Use of giant bamboo for bio-energy production through gasification also yields a net CO_2 emissions reduction through substitution, as seen in this paper's calculations for China's electricity grid (box 3). However, this reduction is not as high as when the bamboo harvest is used to produce engineered bamboo products. This is because the long lifespan of engineered building products enables the additional carbon storage of the durable products pool to be included, whereas the short cycle of bio-energy does not. For example, Moso bamboo HBPs yield 333.6 tC stored over 30 years, compared to 223.5tC (168 tC/ha + 55.5 tC/ha) saved through fuel substitution over the same period. In case the charcoal by-product is fully buried, over a 30-year timeframe the total carbon sequestration and carbon emissions reduction potential could be as high as 254.1tC.

This paper also assessed the potential for carbon sequestration and carbon emissions reduction through product displacement in the scenario of reforesting grassland. If the full yield of a managed bamboo harvest is used to produce SWB products and displace non-renewable, carbon-intensive materials, this could achieve a reduction of between 785 to 1450 tons CO_2/ha. This is excluding carbon stored in the SOC, as the baseline situation was assumed to be grassland, which has a similar SOC as bamboo / tree forests (table 1).

This study has identified several limits to bamboo's effectiveness. Firstly, the above figures represent the combined carbon sequestration and carbon emissions reduction potential of some of the largest bamboo species under ideal conditions. In many cases, such conditions are not always possible and the annual carbon sequestration flux rate of bamboo forests may well be under 2.5 tC/ha per year. This is especially true for unmanaged stands where, even for giant bamboo species such as Moso, the carbon sequestration flux rate can drop from 5.1 tC/ha per year to as low as 1.65t C/ha per year in the same location (Kuehl et al. 2013). As such, it is important not to overestimate bamboo's potential for climate change mitigation.

Another issue, which has not been discussed in the above, is the policy aspect of bamboos' adoption into national NDCs. At this time, it seems that the TEC may only be eligible for inclusion in a country's NDC under the CDM, and then only once bamboo has been approved as an eligible species for reforestation by the applicant country. Due to lack of bamboo-specific trade data, it is not yet possible to include the HBP pool in national climate policies as effective climate change mitigation measure. For these reasons, bamboo is unlikely to be eligible for inclusion in NDCs in the near future, apart from through the TEC (CDM), or via voluntary carbon schemes on a project-by-project basis. Similar issues affect the uptake of sustainably sourced bamboo construction materials (as well as other bio-based building materials) as a sustainable replacement for commonly used, carbon-intensive building materials in CDM or REDD+ (Rüter et al. 2016).

CDM will come to an end in 2020. Hopefully its successor, the Sustainable Development Mechanism, which was initiated during the UN Framework Convention on Climate Change's 21st Conference of the Parties, will include the durable products pool and carbon emissions reduction through product displacement as eligible pathways to meet National Climate goals. However, the Sustainable Development Mechanism's rules, institutional arrangements and eligibility criteria for countries and projects are still unclear at the time of writing.

4.RECOMMENDATIONS

This paper has shown that bamboo has a very large potential to reduce CO_2 emissions, and could be a strategic resource for countries' NDCs. Bamboo reduces carbon through carbon sequestration in bamboo re/afforestation, as well as through the creation of durable products which store carbon and at the same time can substitute carbon-intensive building materials. Alternatively, it can be used as a source of renewable energy which can replace fossil fuel-based sources. However, the results also show that there is large variation in the carbon sequestration and carbon emissions reduction potential of bamboo, and that many factors may influence the outcomes.

More accurate data, and a wider understanding of different bamboo species, will facilitate the inclusion of bamboo into national NDCs and/or voluntary carbon crediting schemes, which in turn could attract more institutional and climate change-related funding for bamboo activities. This literature review covered two primary species of giant bamboo which are commonly used in engineered bamboo products: *Phyllostachus Pubescens*, or 'Moso' bamboo, and *Guadua Angustifolia*. In the future, research into bamboo carbon sequestration and carbon emissions reduction should identify more species that are suitable for reforestation and have high potential for industrial utilisation in value-added products, such as engineered building materials and bio-energy.

In order to estimate the carbon reduction effects with a higher degree of accuracy, the effect of different management, harvesting, thinning and planting schemes should be investigated, to better understand the effect on yields and consequently carbon sequestration and carbon emissions reduction potential. For example, Li et al. (2013) concluded that long-term intensive management of Moso bamboo forests reduced the total SOC over time, and recommended alternative management regimes.

Another important lesson is the need to improve international trade data on bamboo products. The International Bamboo and Rattan Organisation estimates that international trade of bamboo and rattan products reached USD 1741 million in 2015 (INBAR, in press). The trade of bamboo products is likely much higher, but due to the incorrect classification of many HBPs as 'woods', numbers appear small. It is important that trade data on engineered bamboo materials from bamboo producing countries is well mapped using the appropriate trade codes, in order to accurately define the size of the HBP pool. As seen above, these statistics can also influence the inclusion of a bamboo durable products pool in international mechanisms for climate change mitigation.

In summary, bamboo has a high potential to reduce carbon emissions, through TEC, the durable products pool and the displacement of carbon-intensive materials or as an alternative source of energy. This total carbon benefit can be even greater than most wood species, if the bamboo is well-managed. However, if left unmanaged, the situation reverses and bamboo has low carbon reduction potential. This shows the necessity of bringing bamboo stands worldwide under management.

REFERENCES

Butarbutar, T., Köhl, M., Neupane, P.R. 2016. Harvested wood products and REDD+: looking beyond the forest border. *Carbon Balance Management*. Available online at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4875948/ (Last accessed March 21, 2018)

Chen X.G., Zhang X.Q., Zhang Y.P., Booth T. and He X.H. 2009. Changes of carbon stocks in bamboo stands in China during 100 years. *Forest Ecology and Management.* 258. 1489–1496.

Del Lungo A., Ball J., Carle J. 2006. *Global planted forests thematic study - Results and analysis.* Planted Forests and Trees Working Paper 038. FAO: Rome, Italy.

Eco-invent. 2018. 'The Model of the Eco-costs / Value Ratio (EVR)'. Available online via http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html (Last accessed March 21, 2018)

FAO. 2015. *Global Forests Resources Assessment 2015*. Food FAO: Rome, Italy.

INBAR. 2014. *Greening Red Earth: Restoring landscapes, rebuilding lives.* INBAR Working Paper 76. INBAR: Beijing, China.

INBAR. 2017. 'South-South knowledge transfer strategies for scaling up pro-poor bamboo livelihoods, income generation and employment creation, and environmental management in Africa'. Available at: http://www.inbar.int/project/south-south-knowledge-transfer-strategies/ (Last accessed March 21, 2018)

INBAR. 2018. *Trade Overview 2015. Bamboo and Rattan Products in the International Market*. INBAR: Beijing, China.

IPCC. 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Institute for Global Environmental Strategies for the IPCC: Hayama, Japan.

IPCC. 2006. *IPCC Guidelines for Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and other Land Use*. Institute for Global Environmental Strategies for the IPCC: Hayama, Japan.

IPCC. 2014. 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol. IPCC: Geneva, Switzerland.

Kuehl Y., Li Y., Henley G. 2013. Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (*Phyllostachys pubescens*) plantations. *Forests, Trees and Livelihoods*. 22. 1-18.

Li Y., Zhang J., Chang S.X., Jiang P., Zhou G., Fu S., Yan E., Wu J., Lin L. 2013. Long-term intensive management effects on soil organic carbon pools and chemical composition in Moso bamboo (*Phyllostachys pubescens*) forests in subtropical China. *Forest Ecology and Management*. 303. 121-130.

MOSO. 2016. Environmental Product Declaration MOSO Density. CAPEM. Available online at www.moso.eu/epd (Last accessed March 21, 2018)

Nath A.J., Lal R., Das A.K. 2015. Managing woody bamboos for carbon farming and carbon trading. *Global Ecology and Conservation*. 3. 654–663.

Oliver C.D., Nassar N.T., Lippke B.R., McCarter J.B. 2014. Carbon, fossil fuel, and biodiversity mitigation with wood and forests. *Journal of Sustainable Forestry.* 33. 248-275.

Raftery A.E., Zimmer A., Frierson D. M. W., Startz R., Liu, P. 2017. Less than 2 °C warming by 2100 unlikely. Nature Climate Change volume 7, pages 637–641 (2017)

Rüter S., Werner F., Forsell N., Prins C., Vial E., Levet A.-L. 2016. *ClimWood2030, Climate benefits of material substitution by forest biomass and harvested wood products: Perspective 2030 – Final Report*. Braunschweig: Johann Heinrich von Thünen-Institut.

UNFCCC. 2016. *CDM Methodology Booklet*. 8th edition. Available online via https://cdm.unfccc.int/methodologies/ (Last accessed March 21, 2018)

van der Lugt P . 2008. *Design interventions for stimulating bamboo commercialization*. PhD thesis. Delft University of Technology: Delft, the Netherlands.

van der Lugt P., Vogtländer J.G. 2015. *The Environmental Impact of Industrial Bamboo Products - Life-cycle Assessment and Carbon Sequestration*. INBAR Technical Report 35. INBAR: Beijing, China.

van der Lugt P. 2017. *Booming Bamboo: the (re)discovery of a sustainable material with endless possibilities*. Materia: Naarden, the Netherlands.

Vorontsova M.S., Clark L.G., Dransfield J., Govaerts R., Baker W.J. 2016. *World Checklist of Bamboos and Rattans*. INBAR and the Board of Trustees of the Royal Botanic Gardens, Kew: Beijing, China.

Yen T.M. and Lee J.S. 2011. Comparing aboveground carbon sequestration between Moso bamboo *(Phyllostachys heterocycla)* and China fir *(Cunninghamia lanceolata)* forests based on the allometric model. *Forest Ecology and Management.* 261. 995–1002.

Yiping L., Li Y., Buckingham K., Henley G., Guomo Z. 2010. *Bamboo and Climate Change Mitigation*. INBAR Technical Report 32. INBAR: Beijing, China.

Yuen J.Q., Fung T., Ziegler A.D. 2017. Carbon stocks in bamboo ecosystems worldwide: Estimates and uncertainties. *Forest Ecology and Management.* 393. 113–138.

Because of their fast growth rates, giant woody bamboos are already considered effective CO_2 absorbers. Carbon can be further sequestered in durable harvested bamboo products and even higher carbon emissions reduction is possible if bamboo products replace non-renewable, carbon-intensive alternatives.

Research so far on the total carbon sequestration and carbon emissions reduction potential of woody bamboos is scattered and diffuse. This paper provides an overview of existing peer reviewed scientific literature on bamboo carbon sequestration and carbon emissions reduction potential from forests and through bamboo products.

Cover illustration: Thermally modified exterior SWB decking, Switzerland.

Photo credit: Danielle Kahr / MOSO International