

# Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo

Joost G. Vogtländer · Natascha M. van der Velden · Pablo van der Lugt

Received: 28 October 2012 / Accepted: 10 July 2013 / Published online: 6 August 2013  
© Springer-Verlag Berlin Heidelberg 2013

## Abstract

**Purpose** There are many recent proposals in life cycle assessment (LCA) to calculate temporary storage of carbon in bio-based products. However, there is still no consensus on how to deal with the issue. The main questions are: how do these proposals relate to each other, to what extent are they in line with the classical LCA method (as defined in ISO 14044) and the global mass balances as proposed by the IPCC, and is there really a need to introduce a discounting system for delayed CO<sub>2</sub> emissions?

**Methods** This paper starts with an analysis of the widely applied specification of PAS 2050 and the ILCD Handbook, both specifying the credit for carbon sequestration as ‘optional’ in LCA. From this analysis, it is concluded that these optional calculations give rather different results compared to the baseline LCA method. Since these optional calculations are not fully in line with the global carbon mass balances, a new calculation method is proposed. To validate the new method, two cases (one on wood and one bamboo products) are given. These cases show the practical application and the consequences of the new approach. Finally, the main issue is evaluated and discussed: is it a realistic approach to allocate less damage to the same emission, when it is released later in time?

**Results and discussion** This paper proposes a new approach based on the global carbon cycle and land-use change, translated to the level of individual products in LCA. It is argued that only a global *growth* of forest area and a global *growth* of application of wood in the building industry contribute to extra carbon sequestration, which might be allocated as a credit to the *total market* of wood products in LCA. This

approach is different from approaches where temporary storage of carbon in trees is directly allocated to a product itself. **Conclusions** In the proposed approach, there seems to be no need for a discounting system of delayed CO<sub>2</sub> emissions. The advantage of wood and wood-based products can be described in terms of land-use change on a global scale in combination with a credit for heat recovery at the end-of-life (if applicable).

**Keywords** Bamboo · Carbon sequestration · Carbon storage · LCA · Wood

## 1 Introduction

In the period 2006–2009, after a long debate on how to calculate biogenic CO<sub>2</sub> in life cycle assessment (LCA), it was decided by the majority of scientists and practitioners that the best approach in LCA is *not* to calculate biogenic CO<sub>2</sub>. The basic idea was, and still is, that biogenic CO<sub>2</sub>, once captured and stored by trees and other plants, will re-enter the atmosphere sooner or later after the use phase of the product. Hence, in computer programs like Simapro which use the Ecoinvent database (Hischier et al. 2010), biogenic CO<sub>2</sub> was removed from the lists of emissions of the Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential (GWP) midpoint indicators, and consequently from other leading indicator systems like CML-2 and ReCiPe (CO<sub>2</sub> emissions due to land transformation, however, are still counted in these systems). The new ISO 14067 on carbon footprint calculations based on the same logic (Section 6.3.9.2 of the standard, Note 1).

In the last few years, however, there is a feeling in the wood industry and in the industry of other bio-based products, that a credit should be given to bio-based renewable products, which is related to the temporary storage of carbon

Responsible editor: Matthias Finkbeiner

J. G. Vogtländer (✉) · N. M. van der Velden · P. van der Lugt  
Department of Design for Sustainability, Technical University  
Delft, Landbergstraat 15, 2628 CE Delft, The Netherlands  
e-mail: joost@vogtlander.nl

in these products (Brandao and Levasseur 2011; Brandao et al. 2013).

Two important parties reacted on the political will to incorporate carbon sequestration in LCA as an option: the team of the International Reference Life Cycle Data System (ILCD) Handbook (EC-JRC 2010) and the team of the Publicly Available Specification (PAS) 2050:2011 (BSI 2011). In both systems, it is possible to give a credit to temporary CO<sub>2</sub> storage by discounting delayed emissions. Both systems define the credit as optional<sup>1</sup> by the following statements:

- PAS 2050, Section 5.5.1: *‘Note 5. The use of a weighting factor to assess delayed emissions is no longer a requirement of this PAS. However, for entities wishing to undertake such assessment, provision is made in 6.4.9.3.2 and Annex E’.*
- ILCD Handbook, Section 7.4.3.7.3: *‘.i.e., per default, temporary carbon storage and the equivalent delayed emissions and delayed reuse/recycling/recovery within the first 100 years from the time of the study shall not be considered quantitatively’.*

Both systems restrict the calculations on CO<sub>2</sub> sequestration to the 100-year period after the manufacturing of the product (i.e., the 100-year assessment period). In the ILCD Handbook, the 100-year limit is argued to be in line with the decision of LCA scientists and practitioners to keep short- and long-term emissions (from leaching) separate in the LCA calculations (Hischier et al. 2010). The discussion on short- and long-term emissions has many issues (Hischier et al. 2010), but the main argument is summarised in (EC-JRC 2010), regarding the delayed emissions from landfills: *‘...will the inventory of landfills—if the emissions are modelled for e.g., 100,000 years—easily dominate the entire LCA results. This is important to know, but needs a separate interpretation. At the same time, does this issue illustrate one weakness of LCA: LCIA methods usually do not account for thresholds, but aggregate all emissions over time. Hence, even if the concentrations in the waste deposit leachate after 1,000 years might be below any eco-toxic effect, the total amount of these emissions over tenths of thousands of years will be summed up and be considered the same way as the same amount emitted at much higher concentrations over a few years’.* However, this argument for leaching does not hold for CO<sub>2</sub>; CO<sub>2</sub> has no toxicity threshold, and the 100-year assessment maximum for carbon sequestration is not only applied to ‘slow’ low level emissions but as well as to pulse (peak) emissions.

<sup>1</sup> The new ISO 14067 specifies that the calculation has to be done ‘without the effect of timing’; however, the effect of timing may be included in a separate report (section 6.3.8)

Another argument to use the 100-year cut-off period is the fact that the GWP midpoint weighting system of IPCC applies a time horizon as well. The 100-year time horizon is the most used in practice, since it was chosen as a basis for the Kyoto protocol. It should be realised that this was a political decision to balance the short term effect of CH<sub>4</sub> and the long-term effect of chlorofluorocarbons. The 100-year time horizon is a rather arbitrary choice (Kendall 2012).

However, there is no scientific reason to confuse the two sequential steps of the baseline LCA calculation, being the life cycle inventory (LCI), and the system to arrive at a single indicator in life cycle impact assessment (LCIA). The classical LCI is a relative straightforward calculation of mass and energy flows: the timing of emissions is not considered, and flows in the LCI are not discounted. Single indicator systems in LCIA, however, are complex and per definition, subjective, and have many time-related issues, sometimes with a long-time horizon, sometimes with a short one.

This paper will deal with the following issues:

- How do the optional calculations of PAS 2050 and the ILCD handbook relate to each other, and how do they relate to the global carbon mass balance as proposed by IPCC? (Section 2)
- To what extent is carbon sequestration dealt with in the baseline LCA method (as defined in ISO 14044)? (Section 3)
- What is the relevance of the global carbon mass balances from the IPCC for LCA? What is the new in the proposed system of this paper? (Section 4)

The consequences of the proposed calculation method are shown in a case on wood products (Section 5) and a case on bamboo products (Section 6). The conclusions and discussion can be found in Section 7 and 8. In these two last sections, the issue of the need for a discounting system for delayed CO<sub>2</sub> emissions is dealt with.

## 2 The credit for carbon sequestration in relation with the ‘delayed CO<sub>2</sub> pulse’

This section gives a summary of the background of the IPCC calculations on global warming (‘radiative forcing’ caused by CO<sub>2</sub>), which is a rather complex issue, however, necessary to understand the idea of the delayed CO<sub>2</sub> pulse. This delayed CO<sub>2</sub> pulse is the basis for the ‘optional’ calculation on carbon sequestration as given in PAS 2050 and the ILCD handbook. Readers who want more information on the issue of radiative forcing are referred to the literature references given in the text.

The 100-year cut-off (‘time horizon’), as mentioned in the previous section, has a fundamental impact on the calculation of the credit for carbon sequestration. This is depicted in

Fig. 1. In this figure the so called Lashof calculation (Fearnside et al. 2000; Clift and Brandão 2008) is given for the decay of a CO<sub>2</sub> pulse in the atmosphere, where the IPCC 2007 formula on the decay of CO<sub>2</sub> has been applied (Solomon et al. 2007) as follows:

$$\text{Decay} = 0.217 + 0.259 \times \text{EXP}\left(-T/172.9\right) + 0.338 \times \text{EXP}\left(-T/18.51\right) + 0.186 \times \text{EXP}\left(-T/1.186\right)$$

where  $T$  = time in years after the pulse

Figure 1 shows the effect of applying a time horizon in the calculation. When the CO<sub>2</sub> emission pulse is delayed with the carbon storage time (in the example 50 years), the shaded area will shift out of the time horizon of 100 years; this is the calculation credit which results from the time shift of the emission. The reality, however, is that the CO<sub>2</sub> is still there, so ‘omission’ would be a better word than ‘credit’.

The credit of a delayed-pulse emission as a function of time is given in Fig. 2. It is the result of the Lashof calculation in combination with the 100-year time horizon. The ILCD handbook and PAS 2050:2011 propose a linear approximation (where PAS follows the Lashof calculation for the first 25 years).

The result for both systems (for delay periods more than 25 years) is the same as a linear discounting system would have with a 1 % per year discount rate.

There is, however, no consensus at all on the credit system of Fig. 2, so there is need for further development (Brandao and Levasseur 2011; Brandao et al. 2013).

The Dynamic Life Cycle Assessment approach (Levasseur et al. 2010; Levasseur et al. 2013) seems to be one of the

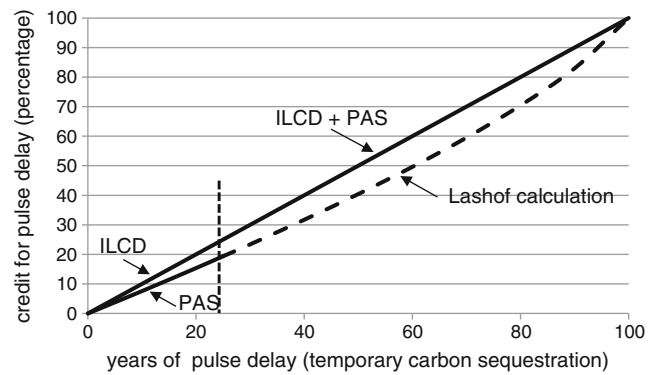


Fig. 2 The credit for a delayed CO<sub>2</sub> pulse in PAS 2050, the ILCD manual, and according to the Lashof calculation of Fig. 1

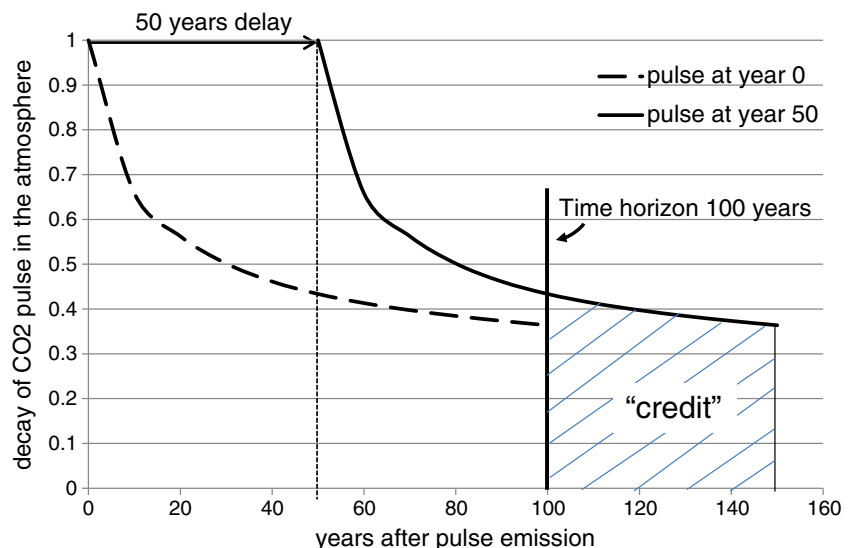
scientific answers on the aforementioned arbitrary credit problem: it has no specific time horizon. This system is based on an integrated radiative forcing calculation of a series of emissions over time. The disadvantage of this calculation system is, however, that the result of the calculation depends heavily on the sequence of pulse emissions in the given scenario. An example on the LCA of a wooden chair shows that there is a remarkable difference (300 %) between two scenarios:

- (1) The tree for the wood is planted 70 years *before* the chair is made
- (2) A new tree is planted at the moment (*after*) a tree is cut for the wood of the chair

The difference of the two scenarios is the period of carbon sequestration by the tree: in year minus 70 until year 0, or in year 1 until year 71.

The interesting aspect of the sequence issue of the Dynamic Life Cycle Assessment approach is that the dilemma of the sequence vanishes when the calculation is made for a manufacturer of wooden chairs: when the manufacturer

Fig. 1 Residence time of CO<sub>2</sub> in the atmosphere and the resulting credit of a delayed pulse as a consequence of the 100-year criterion, according to the Lashof calculation



makes several chairs per year over several decades, the problem can be modelled as a steady-state mass flow calculation. The forest is then regarded as steady state as well: continuously, a small part of the trees is cut and replanted, the major part consists of growing trees, and a small part is ready to be cut. The same steady state applies then to the end-of-life: the combustion of chairs (with or without heat recovery) or the landfill of chairs is regarded as a continuous flow. With this reasoning, we are back to the original way of calculation in LCI. The remaining issue then is how to cope with the aspect of land-use change (afforestation, reforestation, better forest management and deforestation) when the steady-state flow increases or decreases. This will be dealt with in Sections 5 and 6.

A remarkable issue in the approach of the ILCD Handbook and PAS 2050:2011 is that the credit of delaying emissions is to be applied to bio-based products as well as fossil-based products like polymers ('the atmosphere does not differentiate between the two types of CO<sub>2</sub>'). Since many polymers have a higher ratio of 'kg carbon'/kg product', many polymers seem to benefit more from the credit for delayed emissions. Neither the industry nor the politicians seem to be aware of this issue (Brandao and Levasseur 2011; Brandao et al. 2013).

The advantage of carbon sequestration in wood and other bio-based products (over oil based polymers) in the baseline LCA, however, is not related to the delayed emissions, but is related to the end-of-life scenario, as explained in Section 3.

### 3 The relevance of carbon sequestration at product level in LCI

Although the biogenic CO<sub>2</sub> is not counted in LCIA, it is required to keep track of the biogenic CO<sub>2</sub> in LCI (EC-JRC 2010), see Fig. 3.

Biogenic CO<sub>2</sub> is first taken out of the air in the forest (plantation), and then released back to the atmosphere at the end-of-life. So, biogenic CO<sub>2</sub> is recycled, sooner or later in time. When a wood product or a bamboo product, however, is burnt with energy recovery at end-of life (e.g., in an electrical power plant), the total system of Fig. 3 generates an output flow (e.g., electricity). This heat or electricity replaces energy production from other sources, including

fossil fuels. In other words: the use of fossil fuels and the related emissions is avoided, which results in a reduction of the potential global warming effect. In LCI calculations, this can be modelled as a system credit: the production of heat or electricity from wood waste has a negative carbon footprint. This is the so called substitution approach in consequential modelling, see Section 14.5 of the ILCD Handbook (EC-JRC 2010).

The conclusion of this section is that there is no system credit for the biogenic CO<sub>2</sub> cycle, unless the wood (or any other bio-product) is burnt for electricity and/or heat, and unless the trees are replanted. A better efficiency of the production of electricity results in a higher credit.

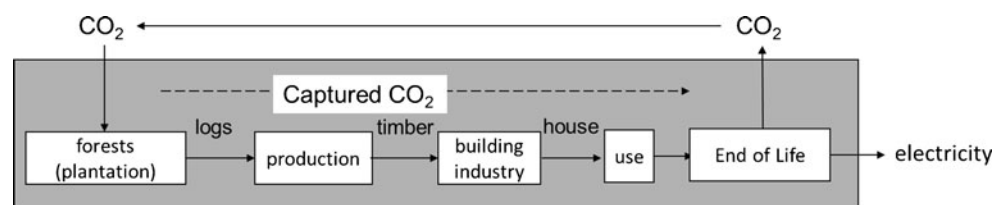
### 4 A general description of carbon sequestration at global level

The effects of carbon sequestration can be understood when studying it at a global system level (Vogtländer 2010). On a global scale, CO<sub>2</sub> is stored in forests (and other vegetation), in the ocean, and in products (e.g., buildings and furniture). The details of carbon mass balances are very complex; however, an understanding of the basics of the proposed LCA method in this paper requires a system approach which starts from the highest possible aggregation level (the so called "Tier 1" and "Tier 2" approach of the IPCC). In this approach, we look at vast forest areas (e.g., Scandinavia, the Baltic countries, European Russia, Siberia, Canada, New Zealand). At this aggregation level, there is a continuous rotation of the forests. The local time-dependent carbon sequestration effects caused by harvesting are levelled out within the region since only a small proportion of the trees are harvested each year. Figure 4 is a simplified schematic overview of the highest aggregation level of the global carbon cycle.

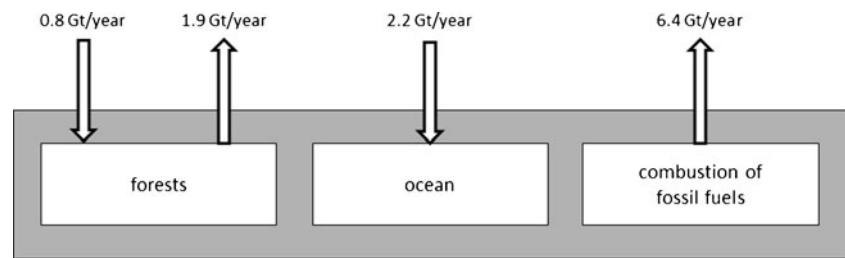
The issue is that the anthropogenic CO<sub>2</sub> emissions on a global scale can be characterised by three main flows:

- Carbon emissions per year caused by burning of 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)

**Fig. 3** The life cycle of biogenic CO<sub>2</sub>



**Fig. 4** Global anthropogenic fluxes of CO<sub>2</sub> (Gt/year) over the period 2000–2010



- Carbon sequestration per year by re-growth 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 significantly be improved in the short term by the following changes (1) burn less fossil fuels, (2) stop deforestation, (3) intensify the use of forest on the Northern Hemisphere by better management and wood production in plantations, (4) afforestation (plant trees on soils that have not supported forests in the recent past), (5) increase application of wood in durable (construction) products, such as buildings.

However, it is far too simple to claim that application of wood in design and construction will lead to carbon sequestration and therefore it will counteract global warming. It depends on the origin of wood and the growth of the wood markets. One should realise that, if there is *no change* in the area of forests and *no change* in the volume of wood in buildings there is *no change* in sequestered carbon on a global level and hence *no effect* on carbon emissions. This means that only when *more* carbon is being stored in forests (either by area expansion with an increase of net carbon storage on that land, or by increased productivity in existing forests by improved management), and when the *total volume* of wood in buildings is *increasing*, there will be extra carbon sequestration.

In boreal and temperate regions such as in Europe and North America, the forest area is increasing steadily for several decades due to afforestation and reforestation (see Fig. 5), which results to increased carbon storage over the last decennia (see Fig. 6).

Figure 6 shows that carbon storage in tropical areas is decreasing. The demand for tropical hardwood is higher than the supply from plantations (only 35–40% of Forest Stewardship Council (FSC)-wood is from plantations). This leads to deforestation, resulting in carbon emissions caused by less carbon sequestration. This mechanism is depicted in Fig. 7.

The conclusion in regard to the production side of wood is:

- Extra demand of boreal and temperate softwood from Europe and North America leads to a better forest management and an increase in forest area therefore more sequestered carbon (Fig. 5)

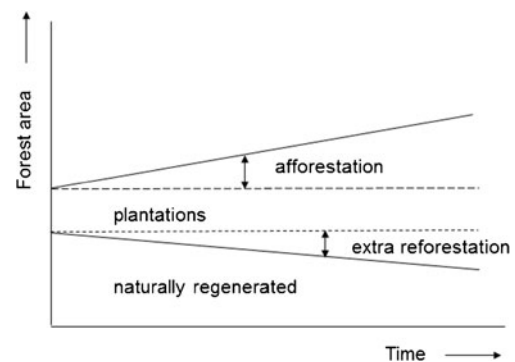
- (Extra) demand of tropical hardwood leads to a decrease in forest area, therefore less sequestered carbon (Fig. 7)

Extra demand of bamboo in China has an effect on carbon sequestration which is similar to that of European and North American wood: it leads to a better forest management and an increase in bamboo forest area (Lou Y et al. 2010).

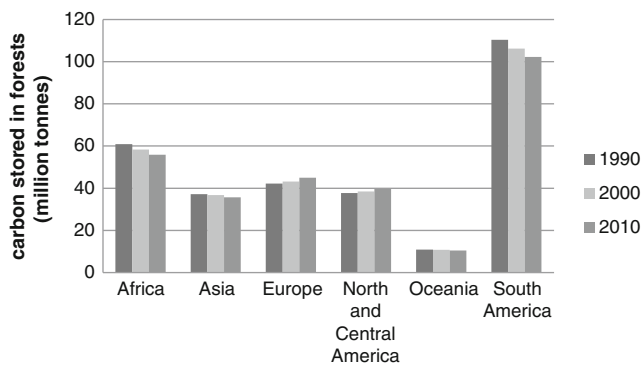
The carbon sequestration in wood in houses and offices is slowly rising on a global scale (because of increasing population), which is as such positive in terms of extra carbon sequestration. This volume of carbon sequestration, however, is low in comparison with the volume of standing trees in the forests: less than 30 % of the carbon above the ground (= less than 24 % of the carbon above plus under the ground) ends up in housing, which is explained in Section 5, steps 1 and 4.

The conclusion is that carbon sequestration is enhanced when more boreal or temperate softwood from Europe and North America and/or bamboo is applied in housing, since more carbon is sequestered in the forests as well as in the houses. On the contrary, the application of tropical hardwood is damaging carbon sequestration, since the decrease of carbon in the tropical forests is more than the increase of carbon in the wood products.

*Another key issue of the global mass balance is that carbon sequestration is not increasing per house which is built, but per extra house that is built above the number of houses that are required to replace discarded, old, houses.* This is an important consequence of the global mass balance,



**Fig. 5** Higher demand of boreal and temperate softwood from Europe and North America leads to more carbon sequestration because of afforestation (extra forests) and reforestation (converting naturally regenerated forests to plantations and better forest management)



**Fig. 6** Trends in carbon storage in forests from 1990–2010 (Source: FAO 2010)

which is often overlooked by LCA practitioners when they study carbon sequestration at product level in the LCI phase of the assessment.

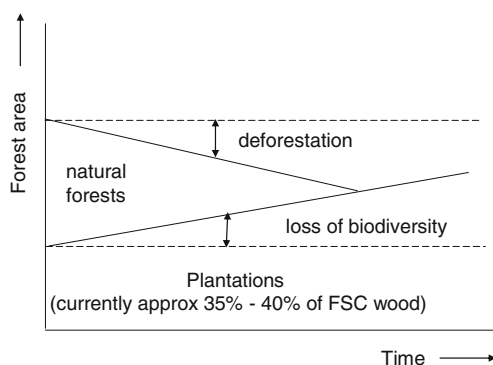
In LCA, the aforementioned global aspect of carbon sequestration in forests is defined in terms of land-use change. The remaining question then is: how to allocate the positive or negative effect of carbon sequestration in forests on global scale to the wood or bamboo at product level?

In this paper, we propose an *allocation of the extra global carbon sequestration in forests to the total global production of wood products*. Such an allocation method is applied since it is not realistic to assign the extra trees to specific wooden products. This allocation method is different from the way the optional calculations are specified in PAS 2050 and the ILCD manual.

The way the proposed allocation method of this paper is done in practice is explained in Step 3 of the examples in Sections 5 and 6.

### 5 Example 1: calculation of carbon sequestration caused by land-use change for European softwood

The aim of the calculation in this section is to illustrate how the proposed method is done in practice, and to validate the



**Fig. 7** Higher demand of tropical hardwood leads to deforestation and less carbon sequestration

method as such (by checking the impact on the output of each calculation step).

The scope of the calculation is the carbon sequestration in boreal softwood from cradle-to-grave, excluding emissions from forest management equipment, product manufacturing, transport, and end-of-life operations (a so called “streamlined” LCA approach). The geographical system boundary is Europe, as defined in (FAO 2010)

The calculation of carbon sequestration caused by land-use change for wood is done in five steps:

- (1) The calculation of the relationship (ratio) of carbon stored in forests and carbon stored in end-products (planed timber); this first step is in compliance with baseline LCA
- (2) The calculation of a land-use change correction factor (to cope with the fact that there was another type of biomass before the area was changed to forests); this step is in compliance with the IPCC standards
- (3) The calculation of the *extra* stored carbon in forests (see Fig. 5), because of *growth of wood production*, and its allocation to the end-products (i.e., planed timber); this step, and the way of allocation, is proposed in this paper by the authors
- (4) The calculation of the *extra* stored carbon in houses and offices, because of *growth of the volume*; this step is in compliance with PAS 2050 and the ILCD handbook optional credit
- (5) The final calculation of the total result of carbon sequestration: the multiplication of the results of steps 1, 2, 3, plus the result of step 4.

#### Step 1 Calculation of the carbon ratio

It is important to realise that 1 kg of a wooden end-product relates to many kilograms of wood in the forests, which has been calculated according to the baseline LCA procedure, applying Ecoinvent data:

- 1-kg biomass, dry matter (d.m.) in standing trees, is equivalent to 0.65 kg of logs (Werner et al. 2007)
- 0.65-kg d.m. of logs, is equivalent to  $0.65 \times 0.585 = 0.38$  kg of sawn timber (Werner et al. 2007)
- 0.38-kg d.m. sawn timber is equivalent to  $0.38 \times 0.87 = 0.33$  kg of planed timber (Werner et al. 2007)
- 1-kg d.m. biomass in standing trees is equivalent to 1.25-kg d.m. total biomass, since the root/shoot ratio is 0.25 (Aalde 2006)
- 1-kg d.m. of planed timber originates from  $1.25/0.33 = 3.79$ -kg d.m. biomass in the forests
- The carbon content is 0.5-kg C per 1-kg wood (Aalde et al. 2006; Verchot et al. 2006)

- Therefore, 1-kg d.m. planed timber, is equivalent to the storage of  $3.79 \times 0.5 = 1.9$ -kg carbon in the forest

The result of step 1 is that 1-kg d.m. planed timber is related to  $1.9 \times 3.67 = 6.97$  kg CO<sub>2</sub> storage in the forest.

#### Step 2 Calculation of the land-use change correction factor

The next step in the calculation is related with the land-use change: before the afforestation, the land had also stored biomass. So the ‘Tier 2 Gain–Loss Method’ (Verchot et al. 2006) of the IPCC has to be applied (it must be mentioned that this method is not described in the ILCD Handbook, Annex B (EC-JRC 2010); however, it is fully in line with the requirement of section 7.4.4.1 page 234). The essence of this gain–loss method is a comparison of the steady state *before* and *after* the of land-use change. For European boreal softwood, we assume that there was grass before the afforestation since the boreal areas are hardly used for agriculture (agriculture is concentrated in warmer areas).

The ‘total above-ground and below-ground non-woody biomass’ for grass is 7.5-t d.m./ha (it ranges from 6.5 to 8.5), with a carbon content of 47 % (Verchot et al.2006).

The biomass of softwood forests, is assumed at 120-t d.m./ha (Aalde et al. 2006) for the above-ground biomass, with a root/shoot ratio of 0.25 and a carbon content of 50 %.

The land-use change correction factor for afforestation is therefore:

$$\frac{\{(120 \times 1.25 \times 0.50) - (7.5 \times 0.47)\}}{(120 \times 1.25 \times 0.50)} = \mathbf{0.953}$$

For reforestation, the situation is different when the land-use change is from ‘naturally generated’ forests to plantations. Data on biomass in the Global Forest Resources Assessment 2010 of the Food and Agriculture Organisation of the United Nations (FAO 2010) and Aalde et al. (2006) suggest that the biomass in plantations might be about twice the biomass in naturally generated forests. The land-use change correction factor is 0.5 for such cases, based on the total wood production, and 1.0 based on the *extra* wood production.

#### Step 3 Calculation of *extra* stored carbon in forests and its allocation

In Section 4, it was explained that only the *extra* biomass in forests makes a differences in terms of less CO<sub>2</sub> in the atmosphere. The total biomass in the European forests was 88,516 million tonnes in 2005

and 90,602 million tonnes in 2010 (FAO 2010). So there was a growth in biomass of 2,086 tonnes, or 2.36 % in 5 years. This is about 0.47 % per year.

For the calculation in step 5, the authors propose to base the yearly growth of the total biomass in forests on the expected average growth of European timber production of 2.3 % (UNECE 2005). There are two arguments to take the market growth of European timber production: (1) The growth of biomass may not always be in balance with the timber production, since the stock of biomass is very high (the turnover of stock is very low). (2) The measurement of biomass in forests is quite problematic, and therefore less accurate than the market growth of timber production (FAO 2010).

The related growth of yearly extra carbon storage in the forests is to be allocated to the total yearly production of wooden products.

#### Step 4 Calculation of the *extra* stored carbon in houses and offices

The extra carbon sequestration in houses and offices is related to the planed timber minus ‘application losses’, which we estimate at 10 %. This results in  $0.9 \times 0.5 \times 3.67 = 1.65$  kg CO<sub>2</sub> storage in the houses per 1-kg d.m. planed wood. The *extra* storage is related to the market growth given in step 3. This extra carbon sequestration is:

$1.65 \times 0.023 = 0.038$  kg CO<sub>2</sub> per kilogram dry matter planed timber

#### Step 5 Calculation of the total result

The effect on carbon sequestration caused by land-use change can be calculated now as follows:

$$\text{carbon sequestration} = 6.97 \times 0.953 \times 0.023 + 0.038 = \mathbf{0.19 \text{ kg CO}_2 \text{ per kilogram diameter planed timber}}$$

### 6 Example 2: calculation of carbon sequestration caused by land-use change for Chinese bamboo (*Phyllostachys pubescens*)

The aim of the calculation in this section is to illustrate how the proposed method is applied in practice in the case of bamboo products, and to validate the method as such (by checking the differences compared to European softwood in each calculation step).

The scope of the calculation is the calculation on carbon sequestration in Chinese bamboo from cradle-to-grave, excluding emissions from forest management, product manufacturing, transport, and end-of-life operations (a so called ‘streamlined’ LCA approach). The geographical system boundary is China, as defined in (FAO 2010)

The calculation is made for *Phyllostachys pubescens* (density 700 kg/m<sup>3</sup>, length up to 15 m, diameter on the ground 10–12 cm, wall thickness 9 mm), also called Moso, from the Anji region, the province of Zhejiang, China. It is processed to planed bamboo products like plywood and strand woven bamboo (SWB) in Huangzhou, the province of Zhejiang. SWB is a relative new industrial bamboo product with a high Janka hardness (12,500 N) and density (1,080 kg/m<sup>3</sup>), made from compressed bamboo strips plus resin. For LCI data of the production processes, see (Vogtländer et al. 2010; Van der Lugt 2009).

The calculation for Chinese bamboo is done via the same steps as given in Section 5.

#### Step 1 Calculation of the carbon ratio.

One kilogram of a bamboo end-product relates to many kilograms of wood in the bamboo plantation:

- 1-kg biomass, d.m. above the ground in the bamboo plantation, is equivalent to 0.42 kg of bamboo in the end-product (Van der Lugt et al. 2009)
- 0.42-kg d.m. of bamboo, is used in 0.44-kg d.m. plywood (the resin content is 5 % of the weight of plywood) and in 0.546-kg d.m. SWB (the resin content is 23 % of the weight of SWB) (Van der Lugt et al. 2009)
- 1-kg d.m. biomass above the ground in the bamboo plantation is equivalent to 3.1-kg d.m. biomass above + below the ground, since bamboo has a vast root system<sup>2</sup>
- 1-kg d.m. of bamboo plywood originates from  $3.1/0.44=7.05$ -kg d.m. biomass in the bamboo plantation, and 1-kg d.m. of SWB originates from  $3.1/0.546=5.7$ -kg d.m. biomass in the bamboo plantation
- The carbon content is 0.5 kg C per 1-kg bamboo (Aalde et al. 2006; Verchot et al. 2006)
- Therefore, 1-kg d.m. bamboo plywood is equivalent to the storage of  $7.05 \times 0.5 = 3.5$  kg carbon in the plantation, and 1-kg d.m. SWB is equivalent to the storage of  $5.7 \times 0.5 = 2.85$  kg carbon in the plantation

The result of step 1:

- 1-kg d.m. bamboo plywood is related to  $3.5 \times 3.67 = 12.85$  kg CO<sub>2</sub> storage in the plantation
- 1-kg d.m. SWB is related to  $2.85 \times 3.67 = 10.5$  kg CO<sub>2</sub> storage in the plantation

<sup>2</sup> Besides the trunks, branches, and shrub, there is CO<sub>2</sub> 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.

#### Step 2 Calculation of the land-use change correction factor

It is assumed that the additional permanent plantations are established on grassland and do not come at the expense of natural tree forests. This is a plausible assumption as a large portion of the Moso bamboo resources comes from the industrialised provinces around Shanghai (Zhejiang, Anhui, Jiangxi). Furthermore, this assumption fits well in the current policy for afforestation and natural forest protection of the Chinese Government controlled by the Chinese State Forestry. More information on this issue can be found at (CSF 2013).

Similar to the calculation of this step in Section 5, the Tier 2 Gain–Loss Method (Verchot et al. 2006) of the IPCC has to be applied. The ‘Total above-ground and below-ground non-woody biomass’ is 7.5-t d.m./ha (it ranges from 6.5 to 8.5) with a carbon content of 47 % (Verchot et al. 2006).

The biomass of bamboo plantations is  $35.8 \times 3.1 = 111$  t d.m./ha for biomass above + below the ground (Van der Lugt 2009; Zhou and Jiang 2004), and a carbon content of 50 %.

The land-use change correction factor for afforestation is therefore:

$$\{(111 \times 0.50) - (7.5 \times 0.47)\} / (111 \times 0.50) = \mathbf{0.936}$$

Much of the extra Chinese bamboo production in the past comes from better management (Lou Y et al. 2010) of existing bamboo forests. In such a case the land-use change correction factor is 1 for the *extra* bamboo production.

#### Step 3 Calculation of *extra* stored carbon in forests and its allocation

The Seventh Chinese National Forestry Inventory provides data on the growth of bamboo plantations in China. In the period 2004–2008, bamboo plantations have grown from 4.84 to 5.38 million hectares, or 11.2 % in 5 years or 2.24 % per year. The growth of tree forest area in China is at a similar level (11.7 %).

It does make sense, however, to base the future yearly growth of the total biomass in bamboo forests on the average growth of Chinese timber production,<sup>3</sup> which is expected to be at least 5 % for the coming decades, given the high GDP of the Chinese economy. The related growth of yearly extra carbon storage in the

<sup>3</sup> Here is a similar argumentation as in footnote 2 for European wood. It must be mentioned here that this growth does not require extra agricultural land. Much of the bamboo production in the past comes from better forest management (Lou et al. 2010). Moreover, bamboo is planted in areas where farming is not feasible, e.g., at slopes for erosion prevention, and for rehabilitating land (Kuehl Y et al. 2011)



plantation is to be allocated to the total yearly production of bamboo products.

#### Step 4 Calculation of the *extra* stored carbon in houses and offices

The extra carbon sequestration in houses and offices is related to the bamboo products minus application losses, which we estimate at 10 %. Taking into account the resin content in the end-product (5 % for plywood and 23 % for SWB), this results in:

- $0.95 \times 0.9 \times 0.5 \times 3.67 = 1.57$  kg biogenic CO<sub>2</sub> storage in the houses per 1-kg d.m. bamboo plywood. The *extra* storage, related to the market growth in step 3, results in the *extra* carbon sequestration of  $1.57 \times 0.05 = 0.0785$  kg CO<sub>2</sub> per kilogram dry matter bamboo plywood.
- $0.77 \times 0.9 \times 0.5 \times 3.67 = 1.27$  kg biogenic CO<sub>2</sub> storage in the houses per 1-kg d.m. SWB. The *extra* storage, related to the market growth in step 3, results in the *extra* carbon sequestration of  $1.27 \times 0.05 = 0.0635$  kg CO<sub>2</sub> per kilogram dry matter SWB.

#### Step 5 Calculation of the total result

The effect on carbon sequestration caused by land-use change can be calculated now as follows:

- Carbon sequestration =  $12.85 \times 0.936 \times 0.05 + 0.0785 =$  **0.68 kg CO<sub>2</sub> per kilogram dry matter bamboo plywood**
- Carbon sequestration =  $10.50 \times 0.936 \times 0.05 + 0.0635 =$  **0.55 kg CO<sub>2</sub> per kilogram dry matter SWB**

## 7 Discussion

The discussion on how to deal with the carbon sequestration in LCA reveals that some important issues in the LCA methodology are still not resolved (Finkbeiner 2009). This paper shows that methodological choices highly influence the outcome of the LCA calculations.

Table 1 shows the data on the baseline LCA method of Section 3 (the first four columns), compared to the land-use

change approach of Section 4 (the last column). Ecoinvent LCIs are used for softwood, and the Idemat 2012 LCI is used for bamboo plywood (Vogtländer et al. 2010; Van der Lugt et al. 2009). Idemat is a database which is used at the Delft University of Technology, additional to Ecoinvent.

From Table 1, it can be concluded that the credit for the carbon sequestration caused by the land-use change, as presented in this paper, is relevant in comparison to the emissions caused by the production. The calculation for production is made for the default method of the ILCD handbook: biogenic CO<sub>2</sub> has not been taken into account, so the production data in the Table is for fossil CO<sub>2</sub> only. The credit for combustion with heat recovery has been calculated for two different levels of efficiency: an efficiency of a modern coal fired electrical power plant of 45 % (IEA 2007), and an efficiency of a modern municipal waste incinerator of 24.75 %. The ‘avoided fossil fuels’ are calculated for the grid average energy mix of the Ecoinvent ‘electricity, medium voltage, production Union for the Coordination of the Transmission of Electricity (UCTE), at grid/UCTE S’ LCI.

Table 2 provides some additional data with regard to the issue of linear discounting of a delayed CO<sub>2</sub> pulse in 100 years (a 100-year time horizon). The issue here is whether or not discounting brings additional information which cannot be missed.

The discounting of a delayed CO<sub>2</sub> pulse results in a credit in LCA (column 1 of Table 2), but reduces the credits for combustion with heat recovery (column 2 and 3 of Table 2 compared to column 3 and 4 of Table 1), so the overall effect of discounting is limited. Note also that the effect of discounting in Table 2 is an overestimation of the benefit in reality since there is still a considerable amount of CO<sub>2</sub> in the atmosphere after the 100-year cut-off criterion of in the Lashof calculation (see Fig. 1, Section 2).

Given the fact that the result of the discounting is limited, and that it gives an overestimation of the resulting credit, the discounting system of the delayed CO<sub>2</sub> pulse does not make sense in LCA, since it does not fulfil the precautionary principle (which should be applied in LCA).

Furthermore, the traditional LCA accounting system has the advantage that the approach on the level of one product is

**Table 1** Traditional LCA data on European softwood and Chinese bamboo

|   | Production                          |                         | Combustion                             | Municipal                              | Land-use change                       |
|---|-------------------------------------|-------------------------|--|--|---------------------------------------|
|   | kg CO <sub>2</sub> e/m <sup>3</sup> | kg CO <sub>2</sub> e/kg | Power plant<br>kg CO <sub>2</sub> e/kg | Waste incin<br>kg CO <sub>2</sub> e/kg | this paper<br>kg CO <sub>2</sub> e/kg |
| Sawn timber, softwood, planed, air dried, at plant/RER S (d.m. 80 %)  | 85                                  | 0.21                    | −1.08                                  | −0.59                                  | −0.15                                 |
| Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90 %) | 104                                 | 0.26                    | −1.21                                  | −0.67                                  | −0.17                                 |
| Idemat2012 Plywood Bamboo (including transport to Europe, d.m. 90 %)  | 811                                 | 1.16                    | −1.13                                  | −0.62                                  | −0.61                                 |

**Table 2** The effect of a discounted CO<sub>2</sub> pulse at the end-of-life (after 50 years, linear discounting 1 % per year) on LCA data of European softwood and Chinese bamboo

| All data in kg CO <sub>2</sub> equivalent, IPCC 2007 GWP 100a         | Optional<br>Carbon sequestration<br>ILCD 50 years<br>kg CO <sub>2</sub> e/kg | Heat recovery<br>In power plant<br>ILCD after 50 years<br>kgCO <sub>2</sub> e/kg | Heat recovery<br>In munic waste incin<br>ILCD after 50 years<br>kgCO <sub>2</sub> e/kg |
|---|--|--|--|
| Sawn timber, softwood, planed, air dried, at plant/RER S (d.m. 80 %)  | -0.734   | -0.540   | -0.295   |
| Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90 %) | -0.826   | -0.605   | -0.335   |
| Idemat2012 Plywood Bamboo (d.m. 90, 5 % resin)                        | -0.785   | -0.565   | -0.310   |

in line with the approach of a continuous flow of products (of the same type), which makes it robust for a wide range of scenarios (from a local to a global level). The traditional LCA is also less vulnerable for different assumptions on the decay of wood in landfill: in wet regions the decay is fast, in dry regions slow, which has a big impact in calculations with a time horizon.

An important issue is how to implement the proposed method of this paper in practice. What are the implications for LCA practitioners and to what level of detail land-use change should be addressed?

A practical aspect is the availability of data. For the 12 global regions in (FAO 2010) enough data are available to make a Tier 2 calculation on the *average* forests in that region. At the level of specific types of timber in the global trade (e.g., spruce, scots pine, radiata pine, etc.), however, data are not readily available. The most practical approach to resolve that problem might be that FAO includes the required information in their FAOSTAT database (at the level of the 233 countries), an initiative that should be done in close cooperation with the developers of ILCD, USLCI and Ecoinvent.

The accuracy of the Tier 2 calculations on specific types of timber in the global trade cannot be high since wood is a natural product with a rather high variation of the main growth characteristics of the trees. It is important, however, that data become available: data with low accuracy is better than no data at all.

With regard to the accuracy of calculations on carbon sequestration, it is important to realise that the carbon footprint is only one of the environmental indicators related to land-use change. Two other important issues with regard to land-use change are:

- The albedo effect of deforestation and reforestation in boreal areas. The change in albedo (surface reflection) in areas with snow has an effect on global warming which is of the same magnitude as the effect of carbon sequestration in forests (Cherubini et al. 2012).
- The reduction of biodiversity caused by deforestation of tropical rain forests. Reduction of biodiversity of natural forests is one of the main issues in the debate on tropical

hardwood, making a difference between illegal logging, reduced impact logging, FSC-certified logging and logging from plantations. This is one of the main arguments to use an indicator system that takes this important aspect into account (as a midpoint), like the ReCiPe system or the system of the eco-costs (Vogtländer et al. 2001; Vogtländer et al. 2004).

## 8 Conclusions

The conclusions with regard to the issue of carbon sequestration are as follows:

- The afforestation and reforestation related to a growing application of boreal softwood, wood from temperate regions, and bamboo products have a significant contribution to carbon sequestration on a global level
- An even bigger contribution is the reduction of fossil CO<sub>2</sub> emissions by combustion with heat recovery (production of electricity) of the wood and bamboo products at the end-of-life

The conclusions with regard to the LCA methodology are as follows:

- Proper modelling of the end-of-life stage results in a considerable credit for wooden products in the case of combustion with heat recovery. There is no reason to deviate from this ‘default’ method in the ILCD Handbook and PAS 2050:2011.
- The ‘optional’ method in the ILCD manual and PAS 2050:2011 (i.e., discounting of the delayed CO<sub>2</sub> emissions) results in an overestimation of the benefits of temporary fixation of biogenic CO<sub>2</sub>. This optional method does not fulfil the precautionary principle, and should therefore be avoided in LCA
- It is advised to reconsider the calculation procedure to deal with carbon sequestration in wood (and other bio-based products), as described in the ILCD Handbook Section 7.4.3.7.3, 7.4.4.1, and Section 13, and bring it in line with Section 4 and the examples in Section 5 of this paper

- Land transformation data of general LCI databases should be applied with great care, since they cannot simply be applied to single products (as explained in Section 4).

The way that carbon sequestration in wood products is dealt with in LCA, needs further refinement. In the proposed approach there seems to be no need for a discounting system of delayed CO<sub>2</sub> emissions. The advantage of wood and wood-based products can be described in terms of land-use change on a global scale in combination with a credit for heat recovery at the end-of-life (if applicable). However, the availability of data on transformation of land is limited (on the level of specific types of timber), so systematic collection of reliable data is required.

## References

- Aalde H, Gonzalez P, Gytarsky M, Krug T, Kurz WA, Ogle S, Raison J, Schoene D, Ravindranath NH, Elhassan NG, Heath LS, Higuchi N, Kainja S, Matsumoto M, Sánchez MJS, Somogyi Z (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4, Chapter 4 Forest Land. Available at [www.ipcc.ch](http://www.ipcc.ch). Accessed 6 Feb 2013
- Brandao M, Levasseur A (2011) Assessing temporary carbon storage in life cycle assessment and carbon footprinting: outcomes of an expert workshop JRC 63225. Publications Office of the European Union, Luxembourg
- Brandao M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Vedel Jørgensen S, Hauschild MZ, Pennington DW, Chomkamsri K (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *Int J Life Cycle Assess* 18(1):230–240
- BSI, British Standards Institution (2011) PAS 2050: 2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, London
- Cherubini F, Bright RM, Strømman AH (2012) Site-specific global warming potentials of biogenic CO<sub>2</sub> for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environ Res Lett* 7:045902. doi:10.1088/1748-9326/7/4/045902
- Clift R, Brandão M (2008) Carbon storage and timing of emissions. University of Surrey. Centre for Environmental Strategy Working Paper Number 02/08. ISSN: 1464–8083, Guildford
- CSF (2013) website Chinese State Forestry, <http://english.forestry.gov.cn/web/index.do>. Accessed 6 Feb 2013
- European Commission–Joint Research Centre and Institute for Environment and Sustainability (2010) International reference life cycle data system (ILCD) handbook—general guide for life cycle assessment—detailed guidance. Publications Office of the European Union, Luxembourg
- FAO (2010) Global forests resources assessment, Forestry Paper 163. Food and Agriculture Organisation of the United Nations, FAO. Available at [www.fao.org/forestry](http://www.fao.org/forestry). Accessed 6 Feb 2013
- Fearnside PM, Lashof DA, Moura-Costa P (2000) Accounting for time in mitigating global warming through land-use change and forestry. *Mitig Adapt Strateg Glob Chang* 5:239–270
- Finkbeiner M (2009) Carbon footprinting—opportunities and threats. *Int J Life Cycle Assess* 14(2):91–94
- Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Margni M, Nemecek T (2010) Implementation of life cycle impact assessment methods. Ecoinvent report No. 3, v2.2. Swiss Centre for Life Cycle Inventories, Dübendorf
- IEA (2007) Biomass for Power Generation and CHP. Available at <https://www.iea.org/techno/essentials3.pdf>. Accessed 6 Feb 2013
- Kendall A (2012) Time-adjusted global warming potentials for LCA and carbon footprints. *Int J Life Cycle Assess* 17:1042–1049
- Kuehl Y, Henley G, Lou Y (2011) The climate change challenge and bamboo: mitigation and adaptation. IMBAR, Beijing. Available at <http://www.inbar.int/publications/?category=1&sortby=title&dlpage=4>. Accessed 6 Feb 2013
- Levasseur A, Lesage P, Margni M, Deschenes L, Samson R (2010) Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environ Sci Technol* 44(8):3169–3174
- Levasseur A, Lesage P, Margni M, Samson R (2013) Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *J Ind Ecol* 17(1):117–128
- Lou Y, Li Y, Buckingham K, Henley G, Zhou G (2010) Bamboo and Climate Change Mitigation. IMBAR, Beijing. Available at <http://www.inbar.int/publications/?category=2>. Accessed 6 Feb 2013
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) IPCC Fourth Assessment Report: Climate Change (AR4), The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge. Available at [www.ipcc.ch](http://www.ipcc.ch). Accessed 6 Feb 2013
- UNECE, United Nation Economic Commission for Europe (2005) European Forest Sector Outlook Study 1960–2000–2020, Geneva Timber and Forest Study Paper 20. Available at <http://www.unecce.org/forests-welcome/publications.html>. Accessed 6 Feb 2013
- Van der Lugt P, Vogtlander J, Brezet J (2009) Bamboo a sustainable solution for Western Europe. VSSD, Delft
- Verchot L, Krug T, Lasco RD, Ogle S, Raison J, Yue Li, Martino DL, McConkey BG, Smith P (2006) IPCC guidelines for national greenhouse gas inventories. Volume 4, Chapter 6 Grass Land. Available at [www.ipcc.ch](http://www.ipcc.ch). Accessed 6 Feb 2013.
- Vogtlander J, Brezet J, Hendriks CF (2001) The Virtual Eco-costs '99, a single LCA-based indicator for sustainability and the Eco-costs/Value Ratio (EVR) model for economic allocation. *Int J Life Cycle Assess* 6(3):157–166
- Vogtlander JG, Lindeijer E, Witte J-PM, Hendriks C (2004) Characterizing the change of land-use based on Flora: application for EIA and LCA. *J Clean Prod* 12:47–57
- Vogtlander J, Van der Lugt P, Brezet J (2010) The sustainability of bamboo products for local and Western European applications LCAs and land-use. *J Clean Prod* 18:1260–1269
- Vogtlander J (2010) A practical guide to LCA for students, designers and business managers, cradle-to-grave and cradle-to-cradle. VSSD, Delft
- Werner F, Althaus H-J, Künninger T, Richter K, Jungbluth N (2007) Life cycle inventories of wood as fuel and construction material. Ecoinvent Report No. 9. Swiss Centre for Life Cycle Inventories, Dübendorf
- Zhou GM, Jiang PK (2004) Density, storage and spatial distribution of carbon in *Phyllostachys pubescens* forest. *Sci Silvae Sin* 6:20–24 (in Chinese with English summary)