Global socioeconomic carbon stocks in long-lived products 1900–2008

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Abstract

A better understanding of the global carbon cycle as well as of climate change mitigation options such as carbon sequestration requires the quantification of natural and socioeconomic stocks and flows of carbon. A so-far under-researched aspect of the global carbon budget is the accumulation of carbon in long-lived products such as buildings and furniture. We present a comprehensive assessment of global socioeconomic carbon stocks and the corresponding in- and outflows during the period 1900–2008. These data allowed calculation of the annual carbon sink in socioeconomic stocks during this period. The study covers the most important socioeconomic carbon fractions, i.e. wood, bitumen, plastic and cereals. Our assessment was mainly based on production and consumption data for plastic, bitumen and wood products and the respective fractions remaining in stocks in any given year. Global socioeconomic carbon stocks were 2.3 GtC in 1900 and increased to 11.5 GtC in 2008. The share of wood in total C stocks fell from 97% in 1900 to 60% in 2008, while the shares of plastic and bitumen increased to 16% and 22%, respectively. The rate of gross carbon sequestration in socioeconomic stocks increased from 17 MtC yr\(^{-1}\) in 1900 to a maximum of 247 MtC yr\(^{-1}\) in 2007, corresponding to 2.2%–3.4% of global fossil-fuel-related carbon emissions. We conclude that while socioeconomic carbon stocks are not negligible, their growth over time is not a major climate change mitigation option and there is an only modest potential to mitigate climate change by the increase of socioeconomic carbon stocks.

Keywords: carbon stocks, carbon sequestration, global carbon cycle, global carbon budget

Online supplementary data available from stacks.iop.org/ERL/7/034023/mmedia

1. Introduction

In order to improve our understanding of climate change and possible mitigation measures, it is imperative to better quantify important components of the global carbon (C) budget (Houghton 2007, Solomon et al 2007, Le Quéré et al 2009). Most discussions about the global C budget so far revolve around CO\(_2\) emissions from the burning of fossil fuels and the production of cement (e.g. Boden et al 2009, Friedlingstein et al 2010, Peters et al 2012), atmospheric CO\(_2\) concentration and fluxes (e.g. Tans et al 1990, Ciais et al 1995, Keeling et al 2011), terrestrial sources and sinks of CO\(_2\) (e.g. Schimel 1995, Houghton 1999, 2010, Bondeau et al 2007, Van Der Werf et al 2009) and the oceanic C sink (e.g. Sabine et al 2004, Le Quéré et al 2007, Takahashi et al 2009).

Much less information is available on another aspect of the global C cycle: the amount of C stored in socioeconomic stocks and their changes through time. The study of socioeconomic C stocks is an important element of the
interactions between the global C cycle and socioeconomic processes. In particular, it is related to the question, whether and to what extent an increase of socioeconomic C stocks can contribute to the mitigation of climate change by the sequestration of carbon in materials. Yet, socioeconomic C stocks are usually neglected in assessments of the global C balance (Marland et al. 2010).

Discussions related to socioeconomic C stocks currently are mostly separated between (1) C stocks in wood and wood-related products (e.g. Skog and Nicholson 1998, Hashimoto et al 2002, Churkina et al 2010, Ingeron 2010, Eriksson et al 2011) and (2) C stocks derived from the use of fossil fuels for petrochemicals such as plastic and bitumen (e.g. Gielin 1997, Neelis et al 2005, Weiss et al 2008, 2009). Furthermore, nearly all studies focus on a constrained geographic area, mostly the territory of nation states or a specific type of socioeconomic C stocks, e.g. those in human settlements.

Winjum et al (1998) was so far the only assessment that reports numbers on global C stocks in wood products. This seminal study compared the results from two methodologies for the calculation of the C budgets of wood products and the policy implications of the chosen calculation method for selected developed and developing countries. Our approach differs from that of Winjum et al (1998) in several important ways: (1) their focus was on C emissions while we focus on stocks, (2) their result refers to one year (1990) while we here present a centennial time series, (3) they did not consider carbon stocks from wood consumed before 1961, i.e. the start of the FAO database, (4) we consider not only C stocks and flows of wood products but also bitumen, plastic and livestock.

Carbon emissions from socioeconomic C stocks are also included in several estimates of carbon fluxes by land use change (Houghton et al 1983, 1987, Houghton 1999, 2003, McGuire et al 2001). However, with the exception of Houghton (1999), who gives a number for socioeconomic carbon stocks in wood products in 1990, they only report C emissions from socioeconomic C stocks. In all publications, socioeconomic C stocks are constrained to wood products, they are based on a rough estimate on fractions of C stocks with different decay periods (10 and 100 years) and they do not differentiate between socioeconomic C stocks in use and C stocks in landfills. Thus, our study extends the previously available information for the small but nonetheless significant pool of socioeconomic C stocks in use considerably by providing a time series for global C stocks in different groups of products.

In this letter we present the first global time series of the main socioeconomic C stocks for the period from 1900 to 2008. We consider the following biomass- and fossil-fuel-based C pools on a global scale: wood and wood products, bitumen, plastic, livestock, humans and cereal stocks. C contained in humans, livestock and cereal stocks has so far not been quantified. The study is based on the most recent calculation methods, basic assumptions and data, e.g. IPCC standard factors for wood products. Our work is limited to the assessment of socioeconomic carbon stocks in use and thus does not include carbon stocks in disposal sites and their change over time. This not only allows a more specific look at the socioeconomic component of carbon stocks but also provides the basic data for an extension of the assessment to carbon stocks in disposal sites. Our work aims to contribute to an improved understanding of global C stocks and flows, as a precondition for effectively mitigating climate change. Our aims are (1) quantifying the development of global C stocks from 1900 to 2008, which allows us to determine the net carbon sink caused by an increase of socioeconomic C stocks and (2) discussing the relevance of these results for C mitigation measures.

2. Methods and data

Within the quantification of C stock in products, we considered C contained in the stocks of wood products, bitumen and plastic. Further synthetic C materials were not considered because no historical production data were available. Moreover, we quantified C stocks in livestock, humanes and cereals. Carbon stocks in products in use are calculated by the combination of inflows with half-lifes for six carbon pools (section 2.1), whereas carbon stocks in humans and livestock are derived from population numbers in combination with species-specific data on body mass (section 2.2). Carbon stocks in cereals are derived directly from numbers on global cereal stocks (section 2.2). In addition to the main calculation described below, we performed a sensitivity analysis based on the uncertainty ranges and variations of inflows of wood products (section 4.2 and the supplementary information available at stacks.iop.org/ERL/7/034023/mmedia).

2.1. Carbon stocks in products

We calculated the mass of C contained in the socioeconomic stocks of wood, wood products, bitumen and plastics for the period 1900–2008. The annual net carbon sink in long-lived products was then derived as the difference between the C stocks of two subsequent years.

The calculation of stocks in each year (including wood products, bitumen and plastic) is based on the tier 1 approach of the IPCC guidelines for harvested wood products (Pingoud et al 2006). C stocks in each year were derived from (1) inflows of C to socioeconomic stocks, (2) the fraction of C remaining on stock and (3) the fraction of C inflow actually entering the stock. Denoting as C(i), respectively C(i + 1), the carbon stock at points i, respectively i + 1, in time, one can write

\[ C(i + 1) = αC(i) + βI(i), \]

where \( α \) is the fraction of the C on stock in year \( i \) that is still on stock in the year \( i + 1 \) and \( β \) is the fraction of the inflow of year \( i \), denoted here as \( I(i) \), that enters the stock of year \( i + 1 \). In accordance with IPCC guidelines (Pingoud et al 2006), \( α \) can be described as \( e^{-k} \) and \( β \) as \((1 - e^{-k})/k\) with \( e \) as the Euler constant and \( k \) as the decay constant (dimension \( y^{-1} \)) of the product. The decay constant \( k \) can be described as
Stocks are therefore derived from the inputs \(i\) in bitumen and plastic.

\[\text{In}(2)/t_{1/2} \text{ with } t_{1/2} \text{ as the half-life of the respective product.}\]

Stocks are therefore derived from the inputs \(i\) for each year and the half-life \(t_{1/2}\) for each component of the carbon stock considered in this study, as summarized in table 1. We also apply this method to the calculation of carbon stocks in bitumen and plastic.

In order to derive the initial wood stocks in the year 1900 we considered inputs back to the year 1800 and neglected stocks in 1800, assuming that stocks before 1800 are almost irrelevant for those after 1900. For plastic and bitumen, inflows were assumed to be negligible before 1950 and 1920, respectively. At this starting point, bitumen inflows amount to 0.07% and plastic inflows to 0.6% of the corresponding inflows in 2008. The half-life and according parameters for the fractions going on stock and remaining in stock for the different materials are discussed below and summarized in table 1.

For plastic and bitumen, carbon inflows were derived from global production volumes in mass units. Global production data for bitumen after 1950 are from IEA (2010) and UN (2011a). Between 1900 and 1949, production figures for bitumen were extrapolated based on a time series for the non-energy use of oil from Grübler (1998), with the assumption of a constant share of bitumen in the non-energy use of oil of 19%, which was derived from the average share of bitumen in the non-energy use of oil during 1950–2008. The global inflow of plastics, starting in 1950, was derived from data given in PlasticsEurope (2009, 2010). The total mass of bitumen and plastics according to these sources was converted to carbon based on carbon content figures reported in table 1.

For all wood products, we use the default half-life recommended by the tier 1 approach of the IPCC guidelines for harvested wood products (Pingoud et al 2003).

For bitumen, the half-life and the factors \(\alpha\) and \(\beta\) based on this were derived based on the assumption that roads are resurfaced every 17 years in average, based on the average of several references (Birgisdóttir et al 2006, OECD 2005, Hashimoto et al 2007, Cochran and Townsend 2010, Huang et al 2009) and recycling ratios according to US DOT (1993).

Table 1. Parameters used for the calculation of socioeconomic carbon stocks of different fractions, with uncertainty ranges given in brackets. Sources and deduction of the parameters are summarized at the end of the table and described more detailed in the text.

| Forest biome         | Carbon density (kgC m\(^{-2}\))\(^a\) | Half-life \((t_{1/2})\) (yr) | Fraction of stock remaining in place \((\alpha)\) (kgC kgC\(^{-1}\)) | Fraction of inflows going on stock \((\beta)\) (kgC kgC\(^{-1}\)) |
|----------------------|-----------------------------------|------------------------------|-----------------------------------------------------------------|-------------------------------------------------|
| **Sawmwood**         |                                   |                              |                                                                 |                                                 |
| Temperate/boreal     | 225\(^b\) (184–276)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| Tropical             | 295\(^b\) (292–336)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| **Other industrial roundwood** |                             |                              |                                                                 |                                                 |
| Temperate/boreal     | 225\(^b\) (184–276)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| Tropical             | 295\(^b\) (292–336)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| **Wood-based panels**|                                   |                              |                                                                 |                                                 |
| Temperate/boreal     | 294\(^b\) (232–481)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| Tropical             | 294\(^b\) (232–481)\(^c\)         | 30\(^b\) (16–48)\(^c\)     | 0.977                                                           | 0.989                                           |
| **Paper and paperboards** |                               |                              |                                                                 |                                                 |
| Temperate/boreal     | 450\(^b\) \(^d\) (422–448)\(^c\)  | 2\(^b\) (1.7–3.3)\(^c\)   | 0.707                                                           | 0.845                                           |
| Tropical             | 450\(^b\) \(^d\) (422–448)\(^c\)  | 2\(^b\) (1.7–3.3)\(^c\)   | 0.707                                                           | 0.845                                           |
| **Bitumen**          |                                   |                              |                                                                 |                                                 |
| n.a.                 | 820\(^e\) \(^f\)                   | 96\(^f\) (57–129)\(^f\)   | 0.993                                                           | 0.996                                           |
| **Plastic**          |                                   |                              |                                                                 |                                                 |
| n.a.                 | 760\(^e\) \(^d\)                   | 12\(^e\) (9–15)\(^e\)     | 0.944                                                           | 0.972                                           |

\(^a\) Unit kg/ton of product in the case of paper and paperboards, bitumen and plastic.

\(^b\) According to IPCC guidelines for CO\(_2\) emissions of harvested wood products (Pingoud et al 2006).

\(^c\) According to PAIKY (2010).

\(^d\) Based on stoichiometric ratios of plastics weighted according to their current global production volumes (Shen et al 2009).

\(^e\) Uncertainty range based on a review of case studies (see section 4.2 for sensitivity analysis and supplementary information for the deduction of the given range, available at stacks.iop.org/ERL/7/034023/mmedia).

\(^f\) Derived from averaged data on road resurfacing periods (Birgisdóttir et al 2006, OECD 2005, Hashimoto et al 2007, Cochran and Townsend 2010, Huang et al 2009) and recycling ratios according to US DOT (1993).

\(^g\) Derived from stock/flow data for plastic in Austria from 1960 to 2004 (Bogucka and Brunner 2007) and lifespan of different plastic products in Austria (Bogucka and Brunner 2007) and Germany (Patel et al 1999).
factors reported in table 1 from the mean value of three measures: (1) the best fit of the factor for half-lifes to the development of stocks and flows of plastic in Austria from 1960 and 2004 (Bogucka and Brunner 2007) and the mean of the lifespan of different plastic products, weighted according to their share of consumption according to (2) Bogucka and Brunner for Austria (2007) and (3) Patel et al (1999) for Germany.

In the case of wood and wood products, carbon inflows are accounted for on the country level. Following the tier 1 approach of the IPCC guidelines for harvested wood products (Pingoud et al 2006), carbon inflows from wood and wood products are derived from yearly production volumes plus yearly imports minus yearly exports for each country, differentiated between sawn wood, wood-based panels, other industrial roundwood and paper/paperboard. Data for volumes of production, imports and exports of the different wood product types since 1961 are from FAOSTAT (2011). The resulting consumption volumes for each country were converted from volume to dry weight on the basis of IPCC standard factors, differentiated between wood product types and tropical versus temperate/boreal forest in the case of sawnwood and other industrial roundwood (table 1). Factors that were used to convert dry matter to carbon and vice versa, as well as the fractions added to and remaining in stocks are IPCC standard values (Pingoud et al 2006). For sawn wood and other industrial roundwood, carbon fractions were differentiated between wood in boreal and temperate regions on the one and tropical regions on the other hand. In order to derive the appropriate carbon fraction, all countries were assigned to one of the three main forest biomes (see Haberl et al 2007).

Data on the global consumption of wood products in the time period between 1920 and 1960 are based on growth rates of wood harvest for 1920 and 1950 according to data from FAO (1955), Woytinsky (1926) and Zon and Sparhawk (1923). For the remaining periods, wood consumption was extrapolated based on population numbers according to Maddison (2010), assuming a constant per capita consumption of wood products before 1920.

2.2. Carbon stocks in humans, livestock and cereal stocks

Carbon stocks in humans and livestock were derived from global human population numbers, given by Maddison (2010) and from livestock numbers disaggregated among the main animal species and world regions, given by FAO (2011), combined with corresponding body weights. Maddison (2010) gives estimates for the global human population for each year from 1950 to 2008. Before 1950, we linearly interpolated population numbers between the population numbers given by Maddison for 1940, 1920, 1870, 1820 and 1700. Human population and livestock numbers were converted into total mass by multiplying their number with average human body mass and regionally specific body mass of animal species, respectively (see the supplementary information, tables S6 and S7 available at stacks.iop.org/ERL/7/034023/mmedia).

Data on average livestock mass per head after 1994, differentiated among the main animal species and world regions, were taken from Wint (1996). We assumed that in regions with a largely industrialized agriculture, average body mass of cattle and pigs increased during the 20th century along with their optimization for meat and milk output. Based on a comparison of carcass weights in 1910 according to Cuff (1992), Trow-Smith (2005) and Walton (1999) and carcass weights in 1994 according to FAO (2011), we estimated that in 1910, livestock body mass of cattle was one third and livestock body mass of pigs 17% lower than in 1994. This reduction was applied to cattle and pigs in the regions Northern America, Western Europe, Eastern/Southeastern Europe and Oceania/Australia. Before 1910, we held livestock body mass constant and extrapolated it linearly between 1910 and 1994.

The global average body mass of humans was based on global five year population cohorts for males and females in the year 2000 according to UN (2011b) combined with medium standard age-dependent mass per capita according to WHO (2007, 2011). For the age cohorts 10–14 yr and 15–19 yr, the average mass was derived from medium standard body mass indices (BMIs) for males and females of 12 and 17 yr, respectively, in combination with standard heights (WHO 2007). For the age cohorts above 19 yr, we derived average body weights from the global average BMI according to Finucane et al (2011), combined with heights for 19 yr old males and females according to WHO (2007).

According to Chang (2007), the carbon content of the human body is 18% of live body mass. We applied this value to humans as well as livestock.

Carbon in cereal stocks are based on numbers on global cereal stocks from 1961 to 2008 according to USDA (2012). Carbon values are derived by combining these numbers with crop specific dry weight fractions (see Haberl et al 2007) and an assumed carbon content of 50% for dry matter biomass. Before 1961, we extrapolate cereal stocks based the cereal stock/population ratio in 1961, applying this ratio to population numbers prior to 1961 taken from Maddison (2010). In order to smooth the high year to year volatility of cereal stocks, we used the three year moving average for carbon in cereal stocks.

3. Results

According to our calculations, total global socioeconomic carbon stocks increased by a factor of 5.0, from 2.31 GtC in 1900 to 11.52 GtC in 2008 (figure 1(b)). While in 1900, nearly all C stocks consisted of wood products and to a minor part cereals, bitumen and plastic gained increasing importance in the second half of the 20th century, with a share of 22% for bitumen and 16% for plastic at the end of the period. Our data shows that compared to other C stocks, human and livestock contribute only a very minor part to socioeconomic C stocks during the whole period.

Inflows to, and outflows from socioeconomic carbon stocks are shown in figure 1(a). According to our results, inflows to socioeconomic stocks increased by a factor of 7.6
and thus much stronger than C stocks, from 85 MtC yr\(^{-1}\) in 1900 to 677 MtC yr\(^{-1}\) in 2007 and decreased to 650 MtC yr\(^{-1}\) from 2007 to 2008. Whereas in 1900, inflows were limited to wood products, up to 2008 plastic and bitumen increased their share of inflows to 29% and 13%, respectively. Due to our methodology, which does not allow to separate in- and outflows for humans, livestock and cereals, numbers for in- and outflows only refer to wood products, bitumen and plastic.

The annual net carbon sink or source resulting from this growth or decline of socioeconomic C stocks is shown in figure 1(c). The global socioeconomic carbon sink increased from 17 MtC yr\(^{-1}\) in 1900 to 247 MtC yr\(^{-1}\) in 2007, decreasing again to 243 MtC yr\(^{-1}\) in 2008. As shown in figure 1(d), the sequestration of carbon in socioeconomic stocks expressed as percentage of global fossil-fuel-based C emissions fluctuated around 2.2–3.4% during the whole period. The current yearly net C sink in socioeconomic stocks in use is about 8% of the residual terrestrial C sink which is estimated to be approximately 2900 MtC yr\(^{-1}\) (Richter and Houghton 2011).

A comparison of the development of C in- and outflows (figure 1(a)) with the development of socioeconomic C stocks (figure 1(b)) shows that although plastic amounts to 29% of C inflows in 2008, with a high per capita increase in the considered period (figure 2(a)), it contributes only 17% to the according socioeconomic C stocks in 2008. Bitumen, on the other hand, contributes only 13% to C inflows but 22% to socioeconomic C stocks and wood products contribute 58% to C inflows and 61% to socioeconomic C stocks in 2008 (excluding cereals, humans and livestock). The relation between C inflows and socioeconomic C stocks shows the strong impact of service life and recycling ratios on the share of inflows that is accumulated in different compartments of socioeconomic C stocks, with a relatively low average lifetime in the case of plastic and a high average lifetime and recycling ratio in the case of bitumen.

Socioeconomic carbon stocks per capita decreased between 1900 and 1965 from 1.49 tC/cap to 1.36 tC/cap 1965 and afterwards increased to 1.73 tC/cap in 2008. The decrease of carbon stored in wood products from 1.43 tC/cap to 1.03
Figure 2. (a) Annual carbon in- and outflows to/from socioeconomic stocks per capita and (b) socioeconomic carbon stocks per capita for the period 1900–2008. For underlying data, see the supplementary information (available at stacks.iop.org/ERL/7/034023/mmedia).

tC/cap in 2008 was more than counterbalanced by the growth of bitumen stocks (0.38 tC/cap in 2008) and plastic stocks (0.28 tC/cap in 2008).

Per capita inflows to socioeconomic carbon stocks increased from 55 kgC cap\(^{-1}\) yr\(^{-1}\) in 1900 to approximately 97 kgC cap\(^{-1}\) yr\(^{-1}\) at the end of the period (figure 1(a)). Between 1900 and 1960, per capita carbon inflows remained fairly constant at 55 to 58 kgC cap\(^{-1}\) yr\(^{-1}\), whereas from 1961 to 2008, they increased with an average annual growth rate of 1.1%, however with large fluctuations. Per capita carbon outflows show a reversed but similar development, increasing from 53 kgC cap\(^{-1}\) yr\(^{-1}\) in 1900 to 82 kgC cap\(^{-1}\) yr\(^{-1}\) in 2008.

4. Discussion

4.1. System boundary

The socioeconomic C stocks discussed in this letter were defined as the socioeconomic C stocks in use. Although C stocks in landfills were not considered, they may be significant: according to Kohlmaier et al. (2007), global C stocks of wood in landfills may perhaps be as high as half of the wood C stock in use. As the degradation of bitumen and plastics is very slow, the amount of bitumen and plastics stored in landfills depends on the fraction of bitumen and plastic wastes that is incinerated. Although plastics stocks are smaller than those of wood (figure 1(b)), the C stocks in landfills can be assumed to be considerable compared to the stocks in use reported here. Over the considered period, 76% of all C inflows from wood products, 47% of all C inflows from plastic and 16% of all C inflows from bitumen did not accumulate in socioeconomic C stocks and therefore were incinerated or landfilled. Inclusion of C stocks in landfills would therefore yield higher C stock numbers and, due to the growth of outflows from stocks in use, also to a larger estimate of C sequestration.

Natural fibres and natural rubber were excluded due to their relatively low annual production. In 2008, global fibre crop production was 28 Mt yr\(^{-1}\) (FAO 2011) and natural rubber 10 Mt yr\(^{-1}\) (World Bank 2009), which would correspond to a C inflow of approximately 19 MtC yr\(^{-1}\) (assuming a C content of 50%). This would be approximately 3% of all C inflows in 2008 which were considered here. We also did not include several non-plastic synthetic carbon materials, such as lubricants and solvents. According to a study by Patel et al. (1999), in 1990 these materials accounted for 41% of the total synthetic carbon materials in Germany. Assuming the same carbon content as plastic, this would amount to 12% of the total C inflows accounted for in this study. However, the underestimation of stocks is probably much smaller because lubricants and solvents are used relatively fast and hence have a low residence time. Finally, including the C content of iron would increase the C inflows by approximately 2% (calculated from Rauch and Pacyna (2009) assuming a C content of global socioeconomic iron stocks of 1%). We therefore estimate that this study covered about 83% of all carbon inflows but a larger percentage of the C stocks in use.

It is important to note that our data on C outflows do not provide an estimate of CO\(_2\) emissions to the atmosphere, as parts of the C go to other, long-lived compartments such as landfills. However, the data we present here can potentially be used to derive atmospheric CO\(_2\) emissions from socioeconomic C stocks if combined with fractions of the outflows landfilled and incinerated as well as the degradation of wood products over time. e.g. see the IPCC guidelines for greenhouse gas inventories of waste (Eggleston et al. 2006b). In addition, CO\(_2\) emissions from carbon stocks would need to consider emissions occurring in the processing steps from industrial roundwood harvest to final wood products and accordingly between the processing of fossil fuels to final products such as bitumen and plastic.

4.2. Sensitivity to uncertainty of parameters

As explained in section 2, our calculations of socioeconomic C stocks in wood products were largely based on the
Table 2. Sensitivity of socioeconomic carbon stocks in 2008 to modifications of the applied parameters and uncertainty ranges of half-lifes, carbon densities and production numbers for harvested wood products. The variations are explained in the footnotes below the table. See the supplementary information for a more elaborate discussion of the sensitivities and the review of case studies (available at stacks.iop.org/ERL/7/034023/mmedia), from which the uncertainty ranges are derived.

| Sensitivity to modifications (GtC) | Sensitivity to uncertainty ranges (GtC) |
|----------------------------------|---------------------------------------|
| Results (GtC) | IPCCb | Winjumc | Casesd | Totale | Half-lifef | C densityg | Productionh |
| 11.5 | 11.2 | 11.7 | 11.9 | 6.9–19.0 | 7.2–12.6 | 10.6–13.6 | 10.4–13.5 |

a Results according to our calculation (see section 3).
b Use of IPCC tier 1 default factors for industrial roundwood production prior to 1961.
c Carbon densities of different wood products taken from Winjum et al (1998), who differentiate carbon densities with more detail among different wood types.
d Parameters for half-lifes and carbon densities as shown in table S1 and S2 of the supplementary information (available at stacks.iop.org/ERL/7/034023/mmedia) (mean values), based on a review of case studies.
e Combined variation of half-lifes, carbon densities and FAO production values according to uncertainty ranges shown in table 1 in brackets, based on a review of case studies and the uncertainty of FAO production numbers for harvested wood products according to Eggleston et al (2006a) (see the supplementary information available at stacks.iop.org/ERL/7/034023/mmedia).
f Variation of half-lifes according to uncertainty range shown in table 1 in brackets, based on a review of case studies (see the supplementary information available at stacks.iop.org/ERL/7/034023/mmedia).
g Variation of C densities of wood products according to uncertainty range shown in table 1 in brackets, based on a review of case studies (see the supplementary information available at stacks.iop.org/ERL/7/034023/mmedia).
h Variation of FAO production numbers for wood products according to uncertainty range given by Eggleston et al (2006a) (see the supplementary information available at stacks.iop.org/ERL/7/034023/mmedia).

5. Conclusions

In absolute terms, socioeconomic C stocks grew steadily throughout the 20th century, while in per capita terms, they decreased slightly until 1965 and increased afterwards. In the second half of the 20th century, the share of wood-based products declined while bitumen and plastic contributed an increasing share to the growth of carbon stocks.

The current yearly increase of socioeconomic C stocks amounts to approximately 8% of the ‘residual terrestrial C sink’ and hence is a non-negligible component of the global C emissions from the non-energetic use of fossil fuels, i.e. their study did not give numbers on C stocks and had entirely different system boundaries. These results are thus not directly comparable to our results for bitumen and plastic.

Global C emissions from the decay and burning of wood and wood products have been estimated by Winjum et al (1998). According to this study, carbon ‘emissions’ from wood products were 0.207 GtC yr⁻¹ in 1990, a number that is very close to our estimate of C outflows from wood products of 0.219 GtC yr⁻¹ in 1990 (figure 1(a)). The small difference is not surprising due to differences in methodologies and assumption. These two numbers are directly comparable because both of them include wood products flowing into landfills and not only C emissions to the atmosphere. Global C inflows of wood products to socioeconomic stocks estimated by Winjum et al (1998) were 0.252 GtC yr⁻¹ in 1990; our corresponding estimate is 0.310 GtC yr⁻¹. This difference can in part be explained by the fact that the estimate of Winjum et al (1998) only included wood products with a lifetime of more than five years while we included all wood products, irrespective of their lifetime.
cycle. A consideration of non-used C stocks in landfills would increase this share. Still, the role of enhanced C sequestration in long-lived products does not appear as a major climate change mitigation option, as the carbon sink by the change of carbon stocks in use currently only amounts to about 3% of the yearly C emissions from fossil fuel combustion. Moreover, fossil fuel derived plastic and bitumen, which account for about one third of this carbon sink, cannot be included in such a potential as their increased use is in no case linked to the reduction of carbon in the atmosphere.

In general, the increase of socioeconomic C stocks as a climate mitigation strategy has to be considered in the context of the trajectory of natural as well as social C stocks and flows (Karjalainen et al. 1999, Ingerson 2010, Eriksson et al. 2011). This includes the consideration of carbon stocks in the biosphere (e.g. forests), which are reduced when biomass such as wood is harvested, and the CO₂ emissions in production processes. Previous research suggests that substitution of building materials such as bricks and concrete which are replaced with wood results in overall a positive carbon balance in the life cycle (Buchanan and Levine 1999, Börjesson and Gustavsson 2000). Finally, the C balance is crucial, but not the whole story. The land, which is needed for C sequestration in biomass, is limited and is the basis for the provision of vital ecosystem services. Thus, an integrated assessment of C sequestration strategies that takes a multitude of factors into account is required.

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