

## The role of carbon plantations in mitigating climate change: potentials and costs

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**Abstract** A methodology is presented to construct supply curves and cost–supply curves for carbon plantations based on land-use scenarios from the Integrated Model to Assess the Global Environment (IMAGE 2). A sensitivity analysis for assessing which factors are most important in shaping these curves is also presented. In the IPCC SRES B2 Scenario, the carbon sequestration potential on abandoned agricultural land increases from 60 MtC/year in 2010 to 2,700 MtC/year in 2100 for prices up to 1,000 \$/tC, assuming harvest when the mean annual increment decreases and assuming no environmental, economical or political barriers in the implementation-phase. Taking these barriers into consideration would reduce the potential by at least 60%. On the other hand, the potential will increase 55 to 75% if plantations on harvested timberland are considered. Taking into account land and establishment costs, the largest part of the potential up to 2025 can be supplied below 100 \$/tC (In this article all dollar values are in US dollars of 1995, unless indicated otherwise.). Beyond 2050, more than 50% of the costs come to over 200 \$/tC. Compared to other mitigation options, this is relative cheap. So a large part of the potential will likely be used in an overall mitigation strategy. However, since huge emission reductions are probably needed, the relative contribution of plantations will be low (around 3%). The largest source of uncertainty with respect to both potentials and costs is the growth rate of plantations compared to the natural vegetation.

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## 1 Introduction

There is mounting evidence that most of the global warming since the mid twentieth century is attributable to human activities, in particular to emissions of greenhouse gases (GHGs) from burning fossil fuels and land-use changes (Mitchell et al. 2001). Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states its ultimate objective as ‘Stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.’ A large number of scenario studies have been published that aim to identify mitigation strategies for achieving different stabilization levels of CO<sub>2</sub> (e.g. Morita et al. 2001). Most of these studies have concentrated on reducing the energy-related CO<sub>2</sub> emissions only, leaving aside abatement options that enhance CO<sub>2</sub>-uptake by the biosphere. This lack of attention to carbon sequestration in the scientific literature has been partly compensated since the Kyoto Protocol makes provisions for Annex B countries to partly achieve their reduction commitments by planting new forests or by managing existing forests or agricultural land differently.

Information made available before the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC; Metz et al. 2001) suggested that land has the technical potential to sequester an additional 87 billion ton carbon by 2050 in global forests alone (Watson et al. 2000). Since the IPCC’s TAR, many studies have addressed the possibility of carbon sequestration as part of mitigation strategies, although not many integral studies are available. Moreover, differences in terminology and scope make it difficult to compare the different carbon sequestration studies (Richards and Stokes 2004). Several sectoral studies suggest that land-based mitigation could be cost-effective compared to energy-related mitigation strategies and could provide a large proportion of total mitigation (Sohngen and Mendelsohn 2003; McCarl and Schneider 2001).

However, most of these studies work on crude assumptions for future land-use change, a crucial factor determining future land availability for other purposes than carbon plantations (Graveland et al. 2002) or land for modern energy crops (Hoogwijk et al. 2005). For example, Sathaye et al. (2006) based their future projections of carbon sinks on linear extrapolation of continuing deforestation and afforestation rates, whereas Sohngen and Sedjo (2006) only considered an increase in forest product demand, discarding future food demand, which is expected to increase immensely in the coming decades (Bruinsma 2003).

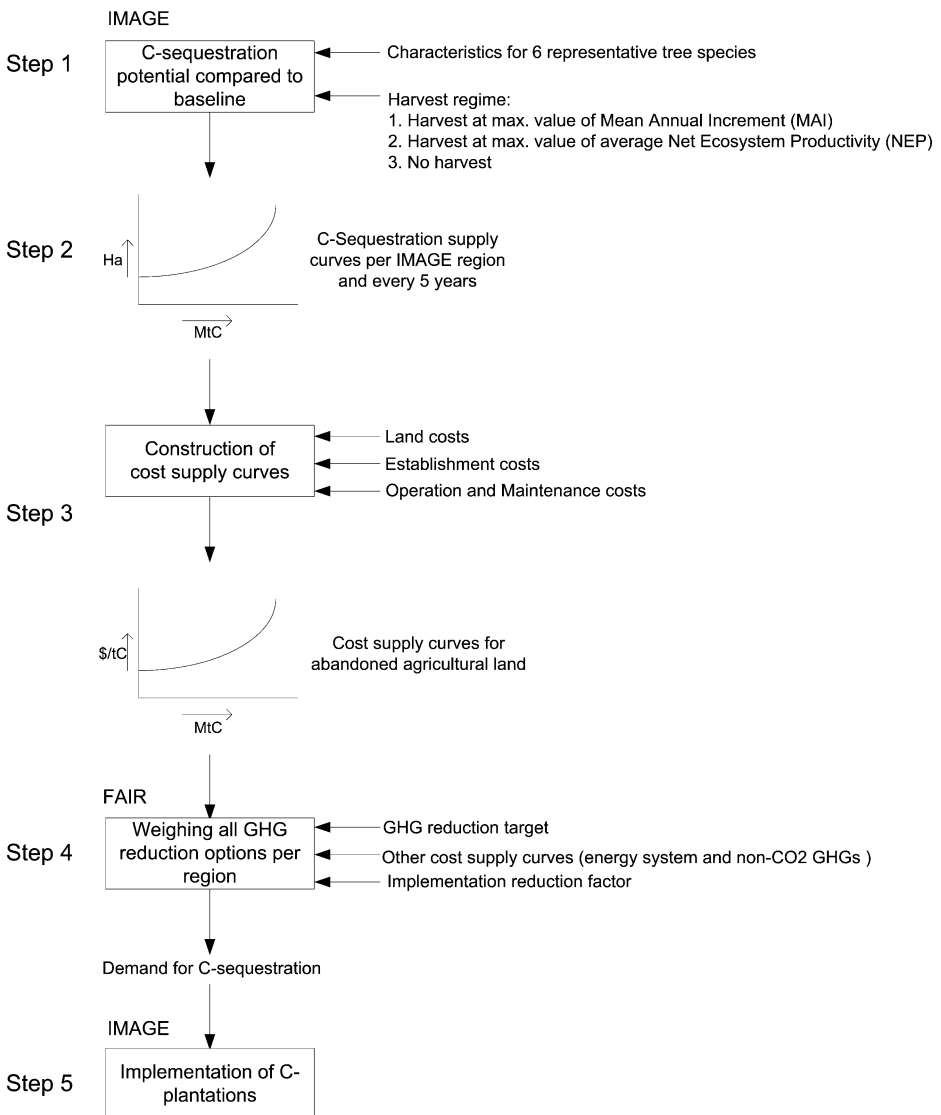
In this paper we present a new methodology to construct supply curves and cost–supply curves or Marginal Abatement Curves (MACs) for carbon plantations based on integrated land-use scenarios from the Integrated Model to Assess the Global Environment (IMAGE Team 2001; Strengers et al. 2004; Bouwman et al. 2006). This methodology builds on Van Minnen et al. (2007), in which a method is presented to quantify the sequestration potential of planting carbon plantations. Through this methodology, land use for food supply is taken into account and a more coherent carbon sequestration potential is obtained. Moreover, by basing the MACs on the land-use scenarios of IMAGE 2 and implementing the carbon plantations in IMAGE 2 itself, overestimation of carbon sequestration potential or unrealistic overruling of the food supply chain is not possible as it is in other studies. In these, MACs are used directly by Computable General Equilibrium models and the consequences for other land opportunities are not considered (Criqui et al. 2006; Jakeman and Fisher 2006).

In Section 2 we summarize the methodology to determine the carbon sequestration potential and present the methodology to construct cost supply curves. Section 3 consists of global and regional results to emphasize the regional specificity of our methodology. Here,

we also show the importance of different harvest regimes. In Section 4, we elaborate on the relative importance of different parameters in our methodology with a sensitivity analysis. In Section 5 we compare our results with other studies, and end with conclusions and recommendations.

## 2 Methodology and scenarios

An overview of the complete methodology is shown in Fig. 1.



**Fig. 1** Methodology to construct and apply MAC curves for carbon sequestration through plantations

## 2.1 Step 1: Global carbon sequestration potential

Using the carbon cycle model of IMAGE 2 (Alcamo et al. 1998 and Van Minnen et al. 1996), the carbon sequestration potential of carbon plantations is determined at a grid level of  $0.5^\circ$  longitude  $\times$   $0.5^\circ$  latitude, taking into account the agricultural land needed to meet the food and feed demand.<sup>1</sup> The carbon sequestration potential of the best growing trees out of six representative species is quantified by comparing their carbon uptake with the uptake of the natural vegetation that would otherwise grow at the same location. The growth of carbon plantation trees is determined by the Net Primary Production<sup>2</sup> (NPP) of the natural land cover type that best matches the tree species considered times an additional growth factor (AGF). AGF is defined as the additional growth of existing timber plantations compared to the average growth of the natural land cover types. The value attributed to the AGF per tree species is based on an extensive literature review (see Van Minnen et al. 2007). The potential is corrected for the carbon losses due to the conversion.

Two management options of the plantations are considered. If no harvest takes place, a plantation will grow to a stable level of carbon storage and then provide only little further sequestration over time. If a harvest takes place, we assume the wood is used to meet the demand for wood.<sup>3</sup> In the exceptional case, harvest exceeds the demand, the remaining wood can be used to displace fossil fuels. This is not modeled explicitly in the current version of the model, but mimicked by ‘storing’ all remaining useable stems and branches of harvested plantations so that they do not decompose. Leaves, roots and the non-harvested stems and branches enter the soil carbon pools. We assume no leakage, i.e. no changes in fossil fuel demand and/or wood demand. In the default settings we apply a harvest criterion, where the moment of harvesting takes place when the Above-Ground Biomass (AGB) has been maximized. This criterion is common in forestry and reflects the practice of harvesting a forest at the moment the Mean Annual Increment (MAI) decreases. In the IMAGE model this option is mimicked by harvesting when the age of the carbon plantation equals the ‘likely rotation length.’

## 2.2 Step 2: Supply curves

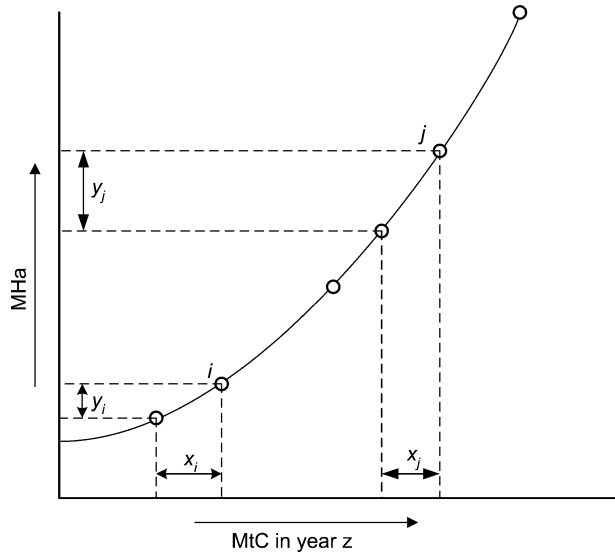
In step 1, the carbon sequestration potential for all 66,000 grid cells is computed. Since we consider the conversion of natural ecosystems to carbon plantations as being inconsistent with broader sustainability concepts, in this study we only use the potential on abandoned agricultural land to construct supply curves for each IMAGE 2 region. The curve for year  $z$  is constructed using all grid cells in a region where the average carbon sequestration, corrected for climate change and CO<sub>2</sub> fertilization effects, is positive in year  $z$ . In Fig. 2, grid cell  $i$  covers the  $y_i$  hectares that potentially sequester an average of  $x_i$  MtC in year  $z$ .

<sup>1</sup> In the Agricultural Economy Model (AEM), food products are associated with so-called ‘intensities,’ which indicate the amount of land needed to supply 1 Kcal per day of the product considered, taking into account the conversion from feed to meat. Because prices do not exist in the AEM, intensities are considered to be a proxy for prices. More details can be found in Strengers (2001).

<sup>2</sup> The Net Primary Productivity of an ecosystem is the rate at which it accumulates energy or biomass, excluding the energy it uses for the process of respiration. This typically corresponds to the rate of photosynthesis, minus respiration.

<sup>3</sup> The demand for wood products is based on a statistical relationship between wood production, population growth, industrial value added and the availability of forests (see Alcamo et al. 1998). The demand for fuel wood and charcoal is assumed to be a fixed fraction of the demand for traditional biofuels, as computed by the energy model TIMER (De Vries 2001).

**Fig. 2** A supply curve in year  $z$ ; grid cell  $i$  of size  $y_i$ ; Mha can potentially sequester  $x_i$  and MtC in year  $z$



Correction for climate change effects is needed because the amount of carbon sequestered should be based on stable conditions in terms of climate and  $\text{CO}_2$  concentration as also prescribed in the Kyoto Protocol.

Because it is unknown in advance *when* a certain potential is actually used in a mitigation effort and to allow for comparison with other greenhouse gas mitigation options using the FAIR model (see Step 4), we average the carbon sequestration over a predefined period of time. Therefore each point in a supply curve represents the average annual carbon sequestration potential of a grid cell as assigned to a certain time interval  $[t_s, t_t]$ , where  $t_s$  is the first year the total cumulative carbon sequestration is positive and  $t_t$  the final year of the simulation period. Especially in non-tropical latitudes,  $t_s$  can be up to 25 years after the planting year due to soil respiration exceeding the carbon uptake, especially when trees are young. The final year  $t_t$  is 2100, or, if no harvest takes place, the first year in which the annual carbon sequestration decreases below 40% of the overall average value. In case of harvest, the *average* carbon sequestration of a plantation between  $t_s$  and  $t_t$  equals the average value at the end of the simulation period. However, when this value at the end of the simulation period is less than 85% of the average value at the end of the last completed harvest cycle, we use the average carbon sequestration value at the end of the last completed harvest cycle for the whole plantation period.

### 2.3 Step 3 Cost–supply curves

In order to construct MACs out of the supply curves, costs of carbon plantations need to be assessed. When dealing with costs, it should be kept in mind that vastly different estimates of costs of sequestration in forests exist, even among studies that have focused on similar regions (especially the United States). In general, the single most important cost factor in producing or conserving carbon sinks is land (Richards and Stokes 2004). Here, we consider two types of costs: land costs, and establishment costs. Various other types of costs have been evaluated but not further considered. Operation and maintenance costs, for example, costs for fertilization, thinning, security and other activities are not considered in

most studies on forestry (for review, see Richards and Stokes 2004). We assume that operation and maintenance costs are either low (in the case of permanent plantations), or are compensated by revenues from timber or fuelwood (in the case of harvesting at regular time intervals) (Benítez-Ponce 2005). Likewise, transaction costs and costs of monitoring or certification are not considered since hardly any project experience is available at the time (Trines 2003).

#### 2.4 Land costs

Richards and Stokes (2004) indicate that land costs in a number of studies show a wide range of estimates. In our study, GTAP data (GTAP 2004) for land values of agricultural land in 2001 are used. Land costs in GTAP are defined as the sum of value added from crop production and land-based payments such as subsidies (see Table 1). The average value of *abandoned* agricultural land will probably be lower than the average value of *existing* agricultural land because of our assumption that grid cells with the lowest agricultural productivity are abandoned first. Therefore we might (slightly) overestimate the land costs in our analysis. We compared the annual GTAP land values (GTAP 2004) with capital values from the World Bank (Kunte et al. 1998) (see Table 1). These values are defined as the present discounted value of the difference between the world market value of three major agricultural crops (i.e. maize, wheat and rice) from these lands and crop-specific production costs. The present value of the annual land values from GTAP, computed with the same discount rate as in the World Bank study (i.e. 4%), has turned out to correlate very well for 7 out of 15 regions for which World Bank data exist: USA, South America, Northern Africa, Southern Africa, OECD Europe, Middle East and Oceania ( $R^2=0.99$ ; although GTAP values are about 1,000 US dollars higher than World Bank values). No data were available for Eastern Europe and Former Soviet Union. For another five regions (Canada, Western Africa, Eastern Africa, South Asia and Southeast Asia) GTAP values

**Table 1** GDP per ha of ‘useable’ area in 2000 and estimates of land costs based on two different sources: GTAP (GTAP 2004) and the World Bank (Kunte et al. 1998)

	IMAGE 2 Region	GTAP \$ ha <sup>-1</sup> year <sup>-1</sup>	GTAP <sup>a</sup> \$ ha <sup>-1</sup>	World Bank \$ha <sup>-1</sup>	GDP \$ ha <sup>-1</sup>	C <sub>R</sub>
1	Canada	87	2130	5224	960	2.8
2	USA	263	6450	6200	10150	2.6
3	Central America	324	7950	2650	2280	6.8
4	South America	153	3760	2160	860	5.2
5	Northern Africa	152	3720	2620	1840	3.5
6	Western Africa	31	760	1990	130	2.8
7	Eastern Africa	31	760	2000	120	2.8
8	Southern Africa	45	1110	500	310	2.6
9	OECD Europe	423	10370	10080	28250	2.5
10	Eastern Europe	263	6440	no data	3520	4.4
11	Former USSR	52	1280	no data	280	3.1
12	Middle East	100	2460	1710	2655	2.0
13	South Asia	304	7440	16515	1410	8.1
14	East Asia	458	11220	5273	2790	8.7
15	Southeast Asia	289	7085	24100	1815	6.8
16	Oceania	76	1870	1040	815	2.7
17	Japan	2150	52720	33470	150350	5.6

<sup>a</sup> The second GTAP column contains present-day values of the first column using a discount factor of 4%

come to about one-third of World Bank results (at  $R^2=0.91$ ). For the remaining three regions (Japan, East Asia and Latin America) GTAP values are considerably higher than the World Bank values. In the sensitivity analysis we show the importance of different land costs, which are considerable.

GDP per hectare of ‘useable’ area (see Table 1) is an important indicator for estimating how land costs evolve over time. The useable area is defined as the total surface area of a region minus the surface of hot desert, scrubland, tundra and ice. Adding other factors, such as population density or crop yields do not improve the correlation coefficient (of 0.74). Regional land costs over time ( $LC_R(t)$ ) are calculated as:

$$LC_R(t) = C_R \times \sqrt{\frac{GDP(t)}{Area_{2001}}} \tag{1}$$

where  $C_R$  is a regional normalization factor to make land costs in 2001 equal to the GTAP-land values (see Table 1).

Note that the period of application of carbon plantations is longer than the period of net sequestration. Therefore land costs of the complete period need to be assigned to the period in which carbon payments take place. Here, the period before cumulative carbon sequestration exceeds the sequestration of the natural vegetation is called the start-up period ( $sp_i$ ). For fast growing tree species, such as *Eucalyptus* and *Poplar*, this period is usually 0–5 years, whereas for other species it can be 25 years or more. The *annual* land costs,  $ALC_i(t)$ , are calculated by (in \$/ha/year):

$$ALC_i(t) = LC_R(t) \times \left( 1 + \frac{r \times \sum_{j=1}^{sp_i} (1+r)^{sp_i-j}}{1 - (1+r)^{-lt}} \right), t_s \leq t \leq t_t \tag{2}$$

where  $i$  is the index for a grid cell,  $r$  the discount rate (i.e. 4%), and  $lt$  the length of the period from  $t_s$  to  $t_t$  in years (see also Step 2).

### 2.5 Establishment costs

Establishment costs include costs for land clearing, land preparation, plant material, planting and replanting, fences and administrative and technical assistance. Costs of land clearing depend on the original type of vegetation and other (landscape and soil) factors. Estimates on establishment costs as summarized by IPCC (1996) have been translated to the IMAGE 2 regions (Table 2). These costs fall well into the range of the initial treatment costs, as reported in Table IX of Richards and Stokes (2004).

Because relatively small variations exist between the regions compared to the ranges within the regions, we decided to use one single average value (435 \$/ha) both in time and space. This assumption is supported by the overview study of Sathaye et al. (2001), who state that the cost of planting is relatively uniform and stable in time. The establishment costs are translated to annual establishment costs at the grid level as follows:

$$AEC_i(t) = 435 \times \frac{r \times (1+r)^{sp_i}}{1 - (1+r)^{-lt}}, t_s \leq t \leq t_t \tag{3}$$

**Table 2** Overview of regional establishment costs

	IMAGE 2 Region	Establishment costs \$ ha <sup>-1</sup> Source: IPCC 1996	Establishment costs \$ ha <sup>-1</sup> Source: Richards and Stokes 2004
1	Canada	456 (343–572) <sup>a</sup>	300–500
2	USA	473 (160–790) <sup>a</sup>	140–690
3	Central America	542 (172–890) <sup>a,g</sup>	387–700
4	South America	395 (290 <sup>b</sup> –500 <sup>c</sup> )	
5	Northern Africa	No carbon plantations	
6	Western Africa	456 (33–1,560) <sup>a</sup>	
7	Eastern Africa	343 <sup>d</sup> (33–1,560) <sup>a</sup>	
8	Southern Africa	456 (33–1,560) <sup>a</sup>	
9	OECD Europe	352 (296 <sup>b</sup> –408 <sup>c</sup> )	
10	Eastern Europe	352 (296 <sup>b</sup> –408 <sup>c</sup> )	
11	Former USSR	389 (370 <sup>f</sup> –408 <sup>c</sup> )	
12	Middle East	No carbon plantations	
13	South Asia	525 (420–630) <sup>a</sup>	367–550
14	East Asia	500 (50–950) <sup>a</sup>	46–828
15	Southeast Asia	515 <sup>c</sup>	
16	Oceania	395 (290 <sup>b</sup> –500 <sup>c</sup> )	
17	Japan	349 (290 <sup>b</sup> –408 <sup>c</sup> )	
	World average	435	400–450

<sup>a</sup> Table 9.29, IPCC (1996)

<sup>b</sup> Temperate afforestation, Table 7.9, IPCC (1996)

<sup>c</sup> Tropical reforestation, Table 7.9, IPCC (1996)

<sup>d</sup> Lower than African average because of lower per capita GDP

<sup>e</sup> Temperate reforestation, Table 7.9, IPCC (1996)

<sup>f</sup> Boreal reforestation, Table 7.9, IPCC (1996)

<sup>g</sup> Table C1, p. 77, Benítez-Ponce (2005)

<sup>h</sup> Here it is not clear to which year Richards and Stokes (2004) refer to

## 2.6 Step 4 Computation of a multi-gas abatement strategy

The MACs as described above are used as input in the FAIR model (Framework to Assess International Regimes) for differentiation of commitments (see Den Elzen and Lucas 2003) along with MACs from the energy system and non-CO<sub>2</sub> GHGs (Van Vuuren et al. 2007). The FAIR model was developed to explore and evaluate the environmental and abatement cost implications of various international regimes for differentiating future commitments to meet long-term climate targets. An implementation factor in the FAIR model (see Fig. 1) being lower than 1 mimics the fact that various socio-economic, environmental and political barriers may reduce the potential area that can actually be planted (see Discussion and conclusion). We use an implementation factor of 1 in the study presented here.

## 2.7 Step 5 Implementation of carbon plantations

Finally, the carbon sequestration demand as computed by a multi-gas mitigation simulation with FAIR is realized in a second IMAGE model run by simulating the actual establishment of carbon plantations. The sequestration by plantations in this run is often slightly higher than the sequestration demand since the MACs on carbon plantations as constructed in Step 2 were corrected for climate change and CO<sub>2</sub> fertilization effects.



## 2.8 Scenarios implemented

We used four IPCC SRES scenarios (Nakicenovic et al. 2000) to assess the importance of different baselines. These scenarios (A1b, A2, B1, and B2) explore different pathways for greenhouse gas emissions in the absence of climate policy on the basis of two major uncertainties: the degree of globalization versus regionalization and the degree of orientation on economic objectives versus an orientation on social and environmental objectives. New insights have emerged for some parameters: for example, both population scenarios and economic growth scenarios in low-income regions have been lowered (Van Vuuren and O'Neill 2006). In general, the B2 scenario focuses on possible events under medium assumptions for the most important drivers (i.e. population, economy, technology development and lifestyle). In terms of its quantification, the B2 scenario used here follows roughly the reference scenario of the World Energy Outlook 2004 in the first 30 years. After 2030, economic growth converges to the IPCC B2 trajectory. The long-term UN medium population projection is used for population (UN 2004). The demand for energy crops is determined according to Hoogwijk (2004). Trends in the regional management factors for agriculture, which reflects the difference between potential attainable yields and the actual yield level, have been taken from the 'Adapting Mosaic' scenario of the Millennium Ecosystem Assessment (Carpenter and Pingali 2005). The assumptions for population, economic growth and management factors in the A1b and B1 scenarios have also been taken from the respective scenarios, 'Global Orchestration' and 'Technogarden,' in the Millennium Ecosystem Assessment. All other assumptions are based on the earlier implementation of the SRES scenarios (Strengers et al. 2004; IMAGE team 2001).

The differences in socio-economic conditions and environmental conditions (see Table 3) have considerable effects on the demands for and growth rate of food, fodder, and energy crops and wood, thus on the area needed for agriculture. These different trends result in different areas being potentially available for carbon plantations, both cumulative and over time (Fig. 3). These areas are used as input for the simulation of different carbon sequestration potentials.

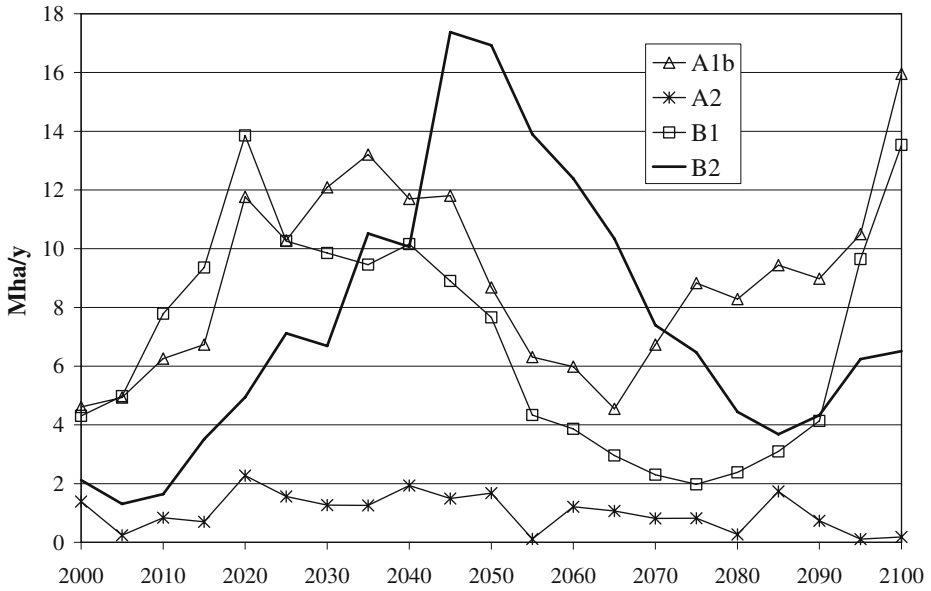
## 3 Results

### 3.1 Global potential carbon sequestration on abandoned agricultural land

The global sequestration potential on abandoned agricultural land is defined as the amount of carbon sequestered if *all* abandoned agricultural land in the world that remains abandoned until the end of the century were covered *entirely* by plantations, excluding

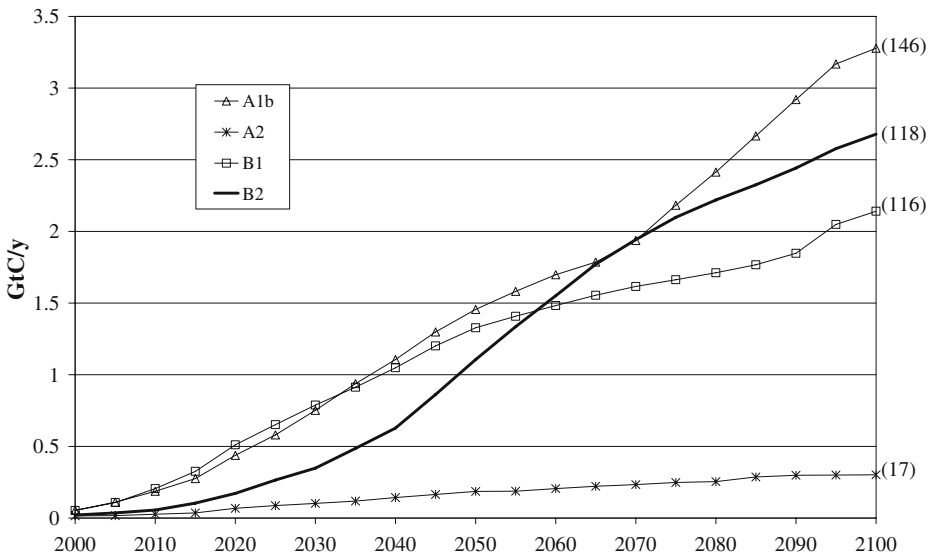
**Table 3** Five indicators in the year 2100 of the IMAGE implementation of four SRES scenarios

	Indicator	Unit	A1b	A2	B1	B2
1	GDP per capita	\$	75,100	17,690	54,232	36,000
2	Population	x billion	6.9	12.6	6.9	9.1
3	CO <sub>2</sub> equivalent	Ppmv	1,057	1,341	675	928
4	Temp. increase	°C	3.3	3.7	2.5	3.0
5	Agricultural land	Mha	2,004	4,512	1,859	2,671
6	Energy crop area	Mha	356	237	618	405
7	Potential CP area	Mha	938	109	724	790



**Fig. 3** Increase of abandoned agricultural land in the IMAGE implementation of four SRES scenarios, which can potentially be used for carbon plantations

locations where the plantations sequesters less carbon than the natural vegetation. Figure 4 shows the global potential annual carbon sequestration in the baseline scenarios used to construct the supply curves: i.e. based on average carbon sequestration values (see Step 2) and corrected for climate change effects.



**Fig. 4** Global potential annual carbon sequestration of plantations on abandoned agricultural land for four SRES-scenarios assuming harvest at Likely Rotation Length (LRL). The numbers between brackets equal the cumulative carbon sequestration in GtC

The sequestration potential is especially low in the A2 scenario, because of the limited amount of abandoned agricultural land. Compared to B2, the A1b and B1 scenarios have relatively high potential sequestration rates in the first part of the century, which is a direct consequence of relatively high land availability in this period (see Fig. 3).

### 3.2 Supply curves

In this section we show only the supply curve results for the B2-baseline scenario since it contains medium assumptions for the most important drivers (see [Scenarios implemented](#)).

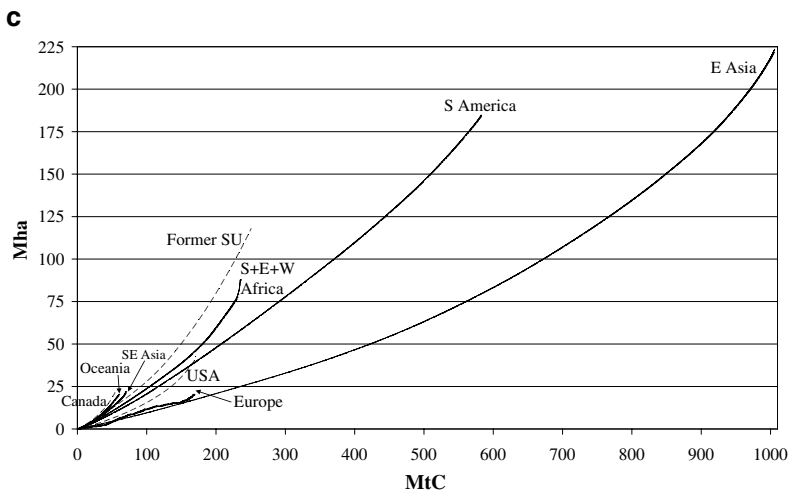
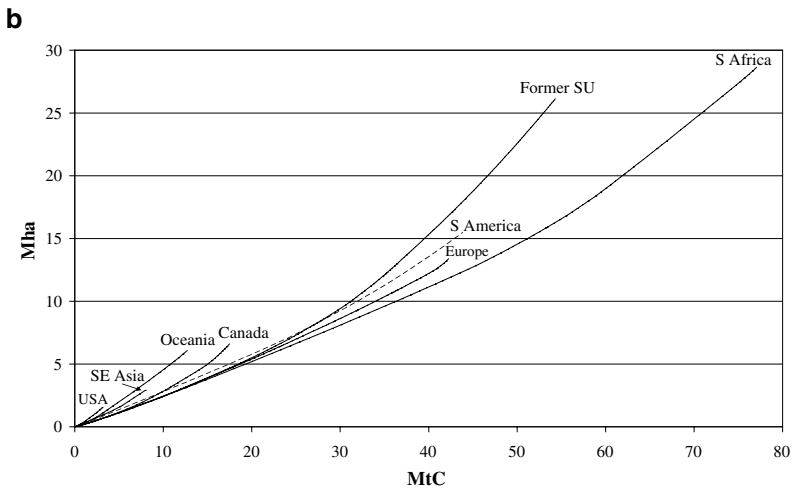
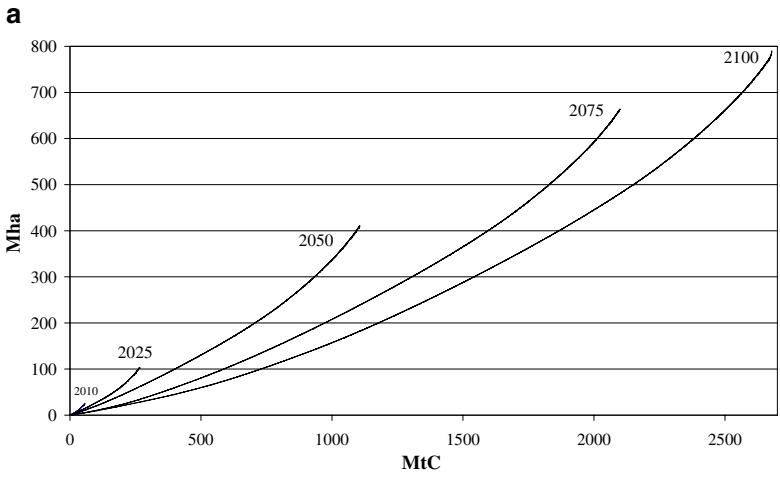
Figure 5 shows the world-level supply curves for the B2 scenario at five different moments in time. As explained in Fig. 2, the curves go from grids cells with a high sequestering potential at the beginning (i.e. a gentle slope) to low sequestration at the end (i.e. a steep slope). The *average* sequestration rates for the subsequent supply curves increase from 2.2 tC/ha in 2010 to 3.4 tC/ha in 2100. This is due to more productive areas becoming available later in the century. Note that the increase is *not* caused by climate change, since the carbon sequestration rates have been corrected for this.

At the regional level (Fig. 5b), four regions make up the lion's share of the supply in 2025: Southern Africa, the former Soviet Union, South America, and Europe (sum of OECD Europe and Eastern Europe). Southern Africa has the largest potential due to crop yields that increase faster than food and fodder demand, resulting in a decreasing need for agricultural land from 226 Mha in 2000 to 168 Mha in 2025. The large potential available in the former Soviet Union is mainly due to decreasing population numbers (−6%) and slightly increasing crop yields, again both resulting in less land needed for agriculture. The relative high potential of Europe is due to stabilizing population numbers while yields go up, especially in Eastern Europe (+23%). In South America, slowly decreasing population growth combined with a relatively fast increase in crop yields results in a decreasing need for agricultural land, starting in 2020. This trend continues in the remainder of the twenty-first century making South America the second largest supplier of carbon sequestration in 2100 (Fig. 5c). In our analysis, the largest supplier in 2100 is East Asia (mainly China). Population size peaks in 2030 at almost 1.6 billion and decreases to 1.3 billion in 2100, while average crop yields increase by 22% in the same period. This results in a 65% decrease in agricultural land. Over 220 Mha becomes available for carbon plantations, which potentially sequesters 1 GtC per year. In 2100 the former Soviet Union, Africa (excl. North Africa), USA, and Europe supply around 200 MtC each. Europe shows the highest sequestration potential per hectare, comparable to East Asian levels. Relatively fertile agricultural land is abandoned in Europe, potentially supporting fast-growing plantations of mainly poplar.

The potential in South Asia (incl. India) is zero during this century because population growth remains high up to 2075 and only decreases slowly afterwards.

### 3.3 Cost–supply curves

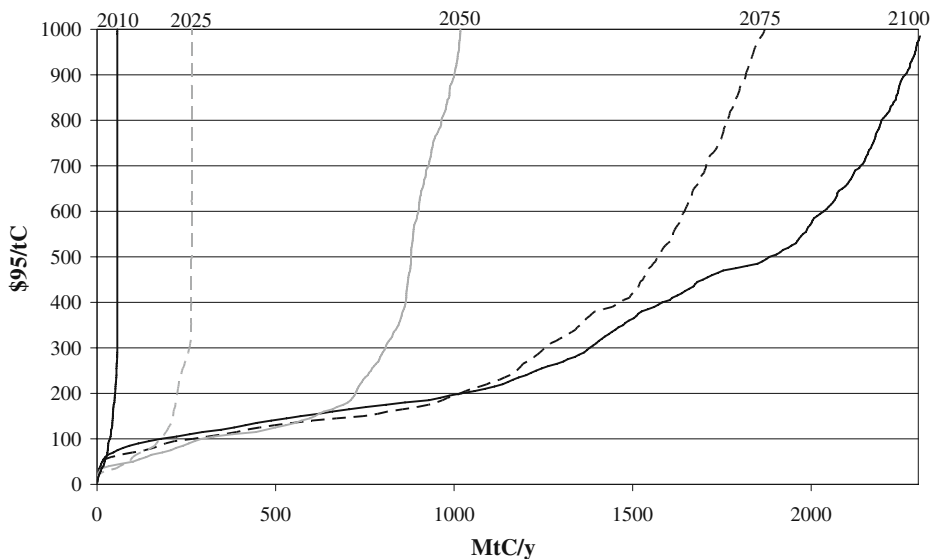
Figure 6 shows the global carbon sequestration cost supply curves for abandoned agricultural land in the B2-scenario. For 2010 and 2025 the largest part of the carbon sequestration potential can be supplied at costs of less than 100 \$/tC. This is relatively cheap compared to other mitigation options. In the FAIR model, these are Carbon Capture and Storage (CCS), fuel switch, use of energy crops, energy efficiency improvement, reduction of non-CO<sub>2</sub> greenhouse gas emissions, renewable energy, nuclear energy and a category of other measures (see Van Vuuren et al. 2007 for more details). In 2050, less than



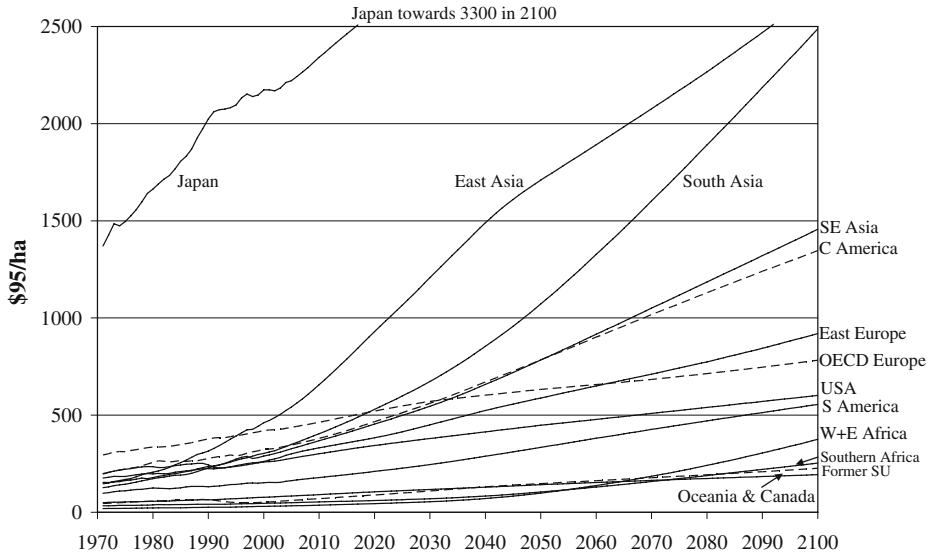
◀ **Fig. 5** Supply curves in the B2-scenario for: **a** the world in 2010, 2025, 2050, 2075 and 2100, **b** regional supply curves in 2025 and **c** in 2100. North Africa, South Asia, Central America, the Middle East and Japan are omitted because they have low or zero potentials. East Asia, Eastern and Western Africa are omitted in 2025 because their potentials are zero or close to zero in that year

30% of the carbon sequestration potential can be supplied below 100 \$/tC and 75% below 200 \$/tC. Even that is reasonably low compared to other options. Beyond 2050 the costs of carbon plantations increase considerably. In 2075 only 14% of the sequestration potential is achievable for less than 100 \$ and 54% for less than 200 \$/tC. In 2100 these percentages are 8 and 44, respectively. So prices will go up early in the second half of this century.

With respect to the costs of sequestering carbon, large differences exist between world regions (Fig. 7). These differences are mainly driven by land costs and differences in growth rates. For example, in 2025 the full potential of the largest supplier, Southern Africa, can be obtained at the lowest costs (see Fig. 8a). This due to the low land costs in Southern Africa (see Fig. 7) and the highest potential average carbon plantation sequestration rates (see Fig. 5b). On the contrary, although European growth rates are higher than in the former Soviet Union and South America (see Fig. 5b and c), costs per hectare are much higher due to land being relatively expensive. A general trend is that higher availability of land coincides with lower land costs and higher carbon sequestration rates, and thus larger potentials against lower costs result. A remarkable exception is East Asia. In 2025 the sequestration potential is almost zero due to the lack of available land, resulting in high costs. In 2100, the carbon sequestration is still expensive, despite the large increase in land available. Costs start around 300 \$/tC and less than 50% can be obtained below 500 \$/ha. This is because land costs are already high in 2025 and increase relatively fast in the course of the century, even if more land becomes available. One could argue that land costs in East Asia should not keep going up so much, since decreasing land scarcity should result in lower land prices. In this case, the assumed relationship between GDP and land costs (see Eq. 1) should be reconsidered for that region. On the other hand, since East



**Fig. 6** Carbon sequestration cost-supply curves for abandoned agricultural land at the world-level in the B2-scenario for 2010, 2025, 2050, 2075 and 2100



**Fig. 7** Land costs of some major regions in the B2 baseline-scenario

Asia remains very densely populated and land is needed for many more purposes, land prices might indeed remain high.

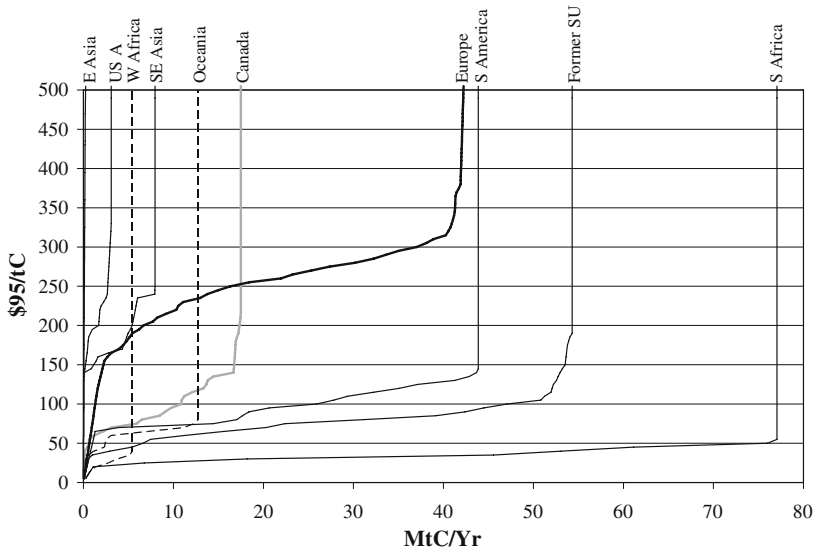
### 3.4 Carbon plantations in a multi-gas abatement strategy

Carbon sequestration on plantations is a rather cheap option compared to other mitigation options. For example, Van Vuuren et al. (2007) shows that in a 650 ppmv CO<sub>2</sub> equivalent stabilization scenario carbon prices could be between 150 and 200 \$/tC in the period in which the largest reductions are needed. In a 550 ppmv stabilization scenario these prices are between 250 \$/tC and 450 \$/tC, while a stabilization level of 450 ppmv results in prices of 500 \$/tC to 1000 \$/tC. Given these prices, 50 to 100% of the useable carbon sequestration potential will be utilized. However, since large emission reductions are needed, the relative contribution of carbon plantations in an overall mitigation strategy will always be low. In Van Vuuren et al. (2007), starting from the same B2 baseline scenario as in this analysis, it is shown a 450, 550 and 650 ppmv stabilization level need a cumulative emission reduction in this century of 1200, 850, and 650 GtC, respectively. Respectively, only 37, 29, and 19 GtC of these amounts (or around 3%) can be achieved through the establishment of carbon plantations, given an implementation factor of 0.1 in 2005, increasing to 0.4 in 2030 and thereafter. Note that although the contribution in the mitigation effort might be limited, harvested wood from these carbon plantations could cover up to 40% and more of the global wood demand in 2100 (assuming no leakage effects).

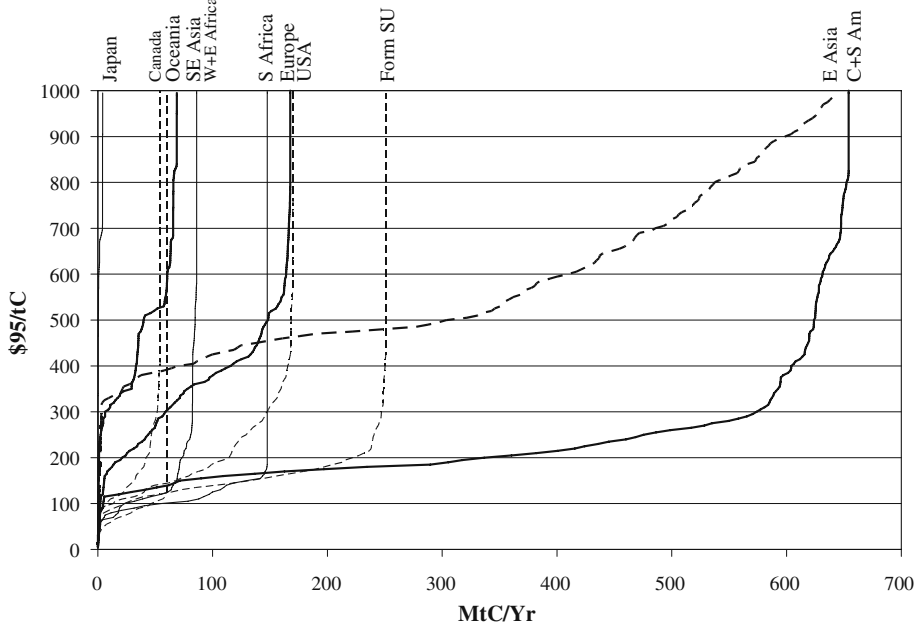
## 4 Sensitivity analysis

Table 4 shows the consequences of varying seven crucial parameters on the supply and costs of carbon sequestration in plantations in the B2 baseline-scenario: (1) the CO<sub>2</sub>

**a**



**b**



**Fig. 8** Regional cost supply curves in the B2 scenario in: **a** 2025 and **b** 2100. The potentials of North Africa, South Asia and the Middle East are zero this century and therefore not mentioned, while Eastern Africa and Central America have zero potentials in 2025. In 2100 the (low) potentials of the latter two regions have been added to Western Africa and South America, respectively

**Table 4** Sensitivity analysis of crucial parameters and their impact on costs in the B2-scenario in 2100

Parameter	Range of values	Agric. Land Mha	Pot. CP Area Mha	Total supply MtC	Costs per tC <sup>a</sup> \$	CO <sub>2</sub> eq. ppmv
Baseline values		2671	790	2679	138	928
CO <sub>2</sub> fert. (excl. agriculture)	-50%	-0.7%	+1.9%	+0.2%	+1.2%	+6.7%
	-100%	-1.3%	+5.9%	+1.7%	+3.8%	+15%
Additional growth factor	-20%		-2.2%	-37%	+126%	
	+20%		0.0%	+33%	-35%	
Management Factor	High	-17%	+14%	+15%	-12%	-2.4%
	Low	+7.6%	-14%	-13%	+12%	+0.8%
Harvest regime	No harvest		-19%	-20%	+10%	
	NEP		+0.1%	+7.5%	-11%	
Establishment costs	-20%				-0.5%	
	+20%				+0.4%	
Land costs	-20%				-19.5%	
	+20%				+19.6%	
Discount factor	2%				-10%	
	8%				+22%	
Baseline scenario	A1b	-25%	+19%	+22%	0.0%	+14%
	B1	-30%	-8.4%	-20%	+11%	-27%
	A2	+69%	-86%	-89%	+200% <sup>b</sup>	+45%

<sup>a</sup> Costs per tC refer to the average costs of the cheapest first GtC. In the baseline scenario this is up to 200 \$/tC.

<sup>b</sup> The supply in A2 is 250 MtC. Therefore average costs have been compared with the average costs of the cheapest 250 MtC of the B2 baseline scenario

fertilization factor, which has been shown being as one of the most sensitive parameters of the carbon cycle (Leemans et al. 2003); (2) the additional growth factor (AGF), which is the crucial parameter in the growth rate of a carbon plantation (see Step 1) (3) the management factor that has a strong impact on the actual yield of agricultural crops; (4) the harvest regime, which has a significant effect on the global potential carbon sequestration (see Fig. 4); (5) establishment costs; (6) land costs, and (7) the discount factor, which influences both annual establishment and land costs through Eqs. 2 and 3.

#### 4.1 CO<sub>2</sub> fertilization

We evaluated the consequences of lowering the CO<sub>2</sub> fertilization factor on *natural* ecosystems by 50 to 100% (i.e. no fertilization at all). The reason of doing this is the current scientific debate on the large-scale response of ecosystems to increasing atmospheric CO<sub>2</sub> levels (e.g. Heath et al. 2005; Körner et al. 2005). The CO<sub>2</sub> fertilization in *agriculture* has been left unchanged, because this has to our knowledge not been questioned in the literature. Reducing the fertilization factor, lowers the global Net Primary Production to 10–24%, resulting in 23–50% reduced carbon net uptake of natural ecosystems. This is equivalent to more than 6 GtC per year by the end of the century. The potential carbon plantation area increases by 2 to 6% because slightly less agricultural land is needed to cover the food and feed demand. This is because higher atmospheric CO<sub>2</sub> concentrations stimulate agricultural production. The total potential carbon sequestration in carbon plantations ('Total supply' in Table 4) increases less than the potential area because the lower CO<sub>2</sub> fertilization factor reduces the additional carbon sequestration of carbon plantations compared to the natural vegetation. Costs per tC (for the first Gt reduction



potential) substantially change for the same reason. In fact, this factor has the least impact on costs compared to the other factors. On the other hand, the mitigation effort will be much higher if CO<sub>2</sub> fertilization is 50 to 100% lower than we now assume in IMAGE, since, as indicated above, the natural ecosystems will then sequester far less CO<sub>2</sub>.

#### 4.2 Additional growth factor

As previously mentioned, the additional growth factor (AGF) is defined as the growth rate of a plantation compared to the average growth of the natural land cover type that best matches the tree species considered. It is one of the most sensitive variables in our model in assessing the global sequestration potential and its costs. This in line with the findings by Richards and Stokes (2004) and Benítez-Ponce (2005).

When reducing the AGF values by 20%, the cumulative net carbon sequestration up to 2100 decreases by 37%, whereas it increases by one-third when assuming a 20% higher additional growth. This large effect is caused mainly by a changed uptake of the plantations. The uptake changes are larger than the changes in AGF, because what counts is the *additional* uptake of a carbon plantation compared to what the underlying natural vegetation would do. For example, if the AGF is increased from 1.8 to 2.16 (= +20%) this implies a 45% increase in the uptake of a plantation compared to the natural land cover ( $2.16 - 1 = 1.16$  instead of  $1.8 - 1 = 0.8$ ). The potential plantation area also slightly decreases under a lower AGF, because a plantation becomes less effective and might no longer be able to sequester more carbon than the natural vegetation. Costs per tC more than double when the additional growth factor is reduced by 20%, which shows its extremely high sensitivity to the AGF.

#### 4.3 Management factor

The management factor for crops reflects the difference between potential attainable and actual crop yields. This factor therefore has an impact on the agricultural land needed to produce the food and feed demanded, and thus on the abandonment of agricultural area. In the sensitivity runs, we used management factors from the ‘Global Orchestration’ and ‘Order from Strength’ scenarios taken from the Millennium Assessment. ‘Global Orchestration’ has a higher management factor and ‘Order from Strength’ a lower one, respectively.

‘Order from Strength’ results in 200 Mha (or almost 8%) additional agricultural land needed in 2100, leading to a decrease of about 110 Mha (or –14%) potential available for carbon plantations. The reason of a lower decrease in plantation area is that the additional agricultural land comes not only from reduced abandoning, but also from clearing new land in some regions. ‘Global Orchestration’ shows a substantial decrease in agricultural land demand of 450 Mha (–17%), while the potential plantation area increases by 125 Mha (+16%). This difference occurs because large areas never become agricultural land at all and are therefore never abandoned. Both total potential carbon sequestration (‘Total Supply’) and costs per tonne carbon change by about the same percentage as the change in potential plantation area, where high management factors also significantly reduce the eventual atmospheric CO<sub>2</sub>-concentration, implying less mitigation effort.

#### 4.4 Harvest regime

Next to harvesting the plantations when MAI decreases, two alternative harvest criteria are used to determine the importance of harvesting: (1) no harvest and (2) harvest when the net

carbon sequestration of the plantation (or NEP) averaged over stand age decreases. The pattern of the potential sequestration rate is similar between the three harvest regimes, but the total sequestration amounts differ considerably. The highest potential will be achieved when harvesting at the moment NEP decreases. The lowest sequestration potential is reached if plantations are permanently grown. The differences (in terms of GtC/yr) between the harvest options occur mainly in the second half of the century. Permanent plantations have the highest sequestration rates at 25 to 50 years after an initial period of 0 to 10 years. After these 25 to 50 years the sequestration potential decreases, while it remains high or even increases when harvest takes place. Table 4 shows that harvesting when NEP decreases leads to an additional supply of 7.5% compared to harvesting when MAI decreases (see Fig. 4), while costs per tC decrease by 11%. Therefore, harvesting when NEP decreases, is most logical from the incentive of mitigating climate change but hard to implement in practice, because the NEP of a plantation is almost impossible to verify.

Furthermore, it should be realized that regularly harvested plantations sequester more carbon than permanent plantations only if the harvested does not disturb the wood market (i.e. leakage) and if the displacement factor is not (much) smaller than 1. As indicated by Schlamadinger and Marland (1997) and Nabuurs et al. (2003) in time horizons up to 100 years, the net carbon benefit can actually be higher in cases considering reforestation only.

#### 4.5 Establishment and land costs

As indicated earlier, both establishment costs and land costs are uncertain. Since establishment costs are much lower than land costs (see Step 3), varying establishment costs change costs per tonne carbon only marginally. To the contrary, varying land costs has a nearly linear effect on the total costs per tonne.

#### 4.6 Discount rate

The discount rate determines how annual land costs in the start-up period are valued thereafter, and how establishment costs are translated to annual costs during the sequestration period (see Eqs. 2 and 3). Because the costs of carbon sequestration programs occur early and the carbon sequestration benefits are substantially delayed, high discount rates produce higher unit costs of sequestration. Choosing an appropriate discount rate is always a major source of discussion. Nilsson and Schopfhauser (1995), for example, suggest discount rates in the range of 0–10% for long-term forestry projects. But there is no rational consensus on how to set the rate. They even propose using an array of interest rates in global analysis in order to catch regional specifics. To get an idea of the importance of the discount rate for the results shown above, we repeated the calculation with a discount rate of 2 and 8%, instead of 4% in the B2 baseline scenario. Table 4 depicts that the costs per tC change about 5% for each percent change in discount rate.

#### 4.7 Baseline scenario

Although the potential area for carbon plantations and thus the potential carbon sequestration supply is different in the A1b and B2 scenarios, the impact on costs is very limited. In case of A2, costs increase by a factor 2. However, this is an extreme scenario where high population numbers and low crop yields result in only 109 Mha being available for carbon plantations. This area has probably been taken out of production because of very low yields and will also result in low carbon sequestration rates and thus (very) high costs.

## 5 Discussion and conclusion

We constructed supply curves and cost-supply curves for carbon sequestration for plantations in 17 world regions. In this section we synthesize our results and place them in a broader context by comparing them with other global and regional studies.

### 5.1 Carbon sequestration potential and costs

Using the IPCC B2 Scenario, and assuming harvest at the moment that the mean annual increment (MAI) decreases, we observed the carbon sequestration potential on abandoned agricultural land to increase from almost 60 MtC/yr in 2010 to 2,700 MtC/yr in 2100. Geographically speaking, the largest contributors in the coming 20 years are South Africa and the Former SU. By the end of the century, the lead is taken over by East Asia (China) and South America.

Assuming permanent plantations, the potential carbon sequestration *decreases* up to 44%.

If harvest takes place when average Net Ecosystem Production decreases the potential *increases* by 8 to 10%, but in practice the NEP criterion is almost impossible to verify.

The potential would *increase* by 55 to 75% if carbon plantations were allowed on harvested timberland. It is, however, questionable whether this can be considered as a sustainable option.

Up to 2025 the largest part of the (limited amount of) carbon sequestration potential can be supplied for costs of less than 100 \$/tC. But the costs are projected to rise during this century. We project that in the second half of this century more than 50% of the potential can be supplied only at costs over 200 \$/tC. Compared to the costs of other mitigation options in the energy system (including energy crops) and for non-CO<sub>2</sub> emissions this is still a rather cheap option. As a result a large part of the carbon sequestration potential will likely be used in an overall mitigation strategy (Van Vuuren et al. 2007). However, since large emission reductions are needed, the relative contribution of carbon plantations will be low.

### 5.2 Implementation factor

The presented potential is based on an implementation factor of 1, implying no restrictions due to shortage of planting material, limited availability of nurseries, lack of knowledge and experience, unavailability of credit facilities, land tenure, distrust in governmental policies, and other priorities for the land (e.g. energy crops), and so on. Nilsson and Schopfhauser (1995) estimated, for example, that only 275 Mha carbon plantations will actually be available out of the global total of 1.5 billion ha (=18%), due to social, political, cultural and infrastructural barriers. Likewise, in a study on Clean Development Mechanisms (Waterloo et al. 2001), eight implementation criteria are distinguished, including additionality, verifiability, compliance and sustainability. If all eight criteria were to be applied, they estimated that only 8% of the potential area would actually be available. This number increase in time and with increasing permit prices. Benítez-Ponce and Obersteiner (2006) introduced ‘country risk considerations,’ stressing that investments in many developed countries are more preferred than in ‘risky’ countries from a political, financial and economic point of view. They showed that applying this country risk concept, carbon sequestration potential may be reduced by approximately 60%. Although such geographically differentiated implementation rates are interesting, it may be difficult to apply in our method because of its perspective up to 2100 for which political considerations are highly uncertain. Nevertheless, we will evaluate the use of regional implementation factors in the

near-term future. Right now we have evaluated the effect of using lower exogenous implementation factors throughout the world (see Van Vuuren et al. 2007).

### 5.3 Cost comparison at the global level

Richards and Stokes (2004) provided an overview by comparing 36 forest carbon sequestration cost studies. A major problem highlighted is that a comparison is often difficult to make due to ‘inconsistent use of terms, geographic scope, assumptions, program definitions, and methods.’ Nevertheless, ‘after adjusting for variations among the studies,’ they concluded that in the cost range of 10–150 \$/tC it may be possible to sequester 250–500 MtC/yr in the USA and up to 2 GtC/yr globally (see Table 5).

It is, however, not directly clear how they adjusted data for variations among studies, which complicates comparison with our results. When looking at the underlying studies in more detail it seems that:

- The time-frame of most studies is between 50 and 140 years
- Land costs form the most important cost factor and are always included
- Initial treatment costs (or establishment costs) are almost always included
- Revenues from timber have been included to a limited extent
- Administration costs and maintenance costs have either not been included or only to a limited extent
- Most studies refer to afforestation of former agricultural land *and* reforestation of harvested or burned timberland
- Most ecosystem carbon components are included
- Additionality of the carbon sequestration is *not* taken into account
- Secondary benefits have not been taken into account

Unfortunately, it remains unclear to what extent:

- Their estimate applies to the full time-frame, or whether this level is reached at the end of the period
- The baseline scenarios used differ from the baseline scenarios in the study presented

A major difference between most other studies and our methodology is the exclusion of timberland. If, however, we were also to include harvested timberland, the global potential between 10 and 150 dollars would be 75 MtC in 2010 and about 1.2 GtC/yr in 2075 and 2100 (see Table 5). More than 2 GtC would be obtained only at costs above 235 \$/tC. The potential for the USA in the same cost range would be 3 MtC/yr in 2010 and 150 MtC/yr in 2100. A potential of 250–500 MtC/yr could be obtained in 2100 at cost levels around 300 \$/tC. This would bring our results to the low end of the range in these other studies. The main

**Table 5** Carbon sequestration potential: comparison with other studies

Study	Time Years	Costs \$/tC	USA MtC/year	World MtC/year
This study	50–100	<150	75	600
Richards and Stokes 2004	50–140	<150	250–500	2,000
This study incl. timberland	50–100	<150	150	1,200
Benítez-Ponce and Obersteiner 2006	20	<400		450
This study incl. country risk	20	<400		450
Benítez-Ponce and Obersteiner 2006	100	<400		650
This study incl. country risk	100	<400		1,080

reasons for this are that we: (1) largely excluded revenues from harvested wood, (2) only account for the *additional* carbon sequestration compared to the natural vegetation, and (3) do not convert *existing* agricultural land to carbon plantations, i.e. there is no interference with the food and feed production.

Benítez-Ponce and Obersteiner (2006) present a global country-risk adjusted<sup>4</sup> cost-supply curve based on a grid cell analysis for the next 20 and 100 years. They consider croplands, grasslands, shrublands and savannas, excluding (potentially) highly productive land. They show that in the next 20 years, about 9 GtC can be sequestered below 400 \$/tC. In the next 100 years, this will be about 65 GtC. If we include these land classes in our analysis and also apply a country-risk adjustment of minus 60%, our cumulative potential carbon sequestration in the first 20 years is almost 9 GtC below 400 \$/tC and 108 GtC in the first 100 years (see Table 5). Thus the results are almost equal in the first 20 years, but differentiate in the longer term. The difference is caused mainly by the differences in method: i.e. an analysis based on land cover changing over time instead of using the land cover as it is now. Furthermore, we explicitly model the carbon cycle, while Benítez uses the carbon uptake from spatial databases.

#### 5.4 Cost comparison at the regional level

Differences are more pronounced at regional level due to the reasons mentioned by Richards and Stokes (2004). For example, on the basis of a study from Xu (1995), both Sathaye et al. (2001) and Richards and Stokes (2004) indicate that China has reasonable potentials against *negative* costs. Up to 2060, the computed sequestration potential for China (or actually East Asia) in our analysis is comparable to theirs (see Fig. 5), but only for considerably higher costs (Fig. 7). The negative costs in Sathaye et al. (2001) are caused by high timber prices in China, something that is not included in the study presented.

Another interesting region is South Asia (including India). In our analysis this region has practically no potential. Sathaye et al. (2001), on the contrary, estimate for India that plantations can sequester about 300 MtC until 2030, whereas Richards and Stokes mention a potential of 3.7 Gt, based on a study from Ravindranath and Somashekhar (1995). The main reason for our much lower estimate is the fundamental requirement of not allowing interference with agriculture. Benítez-Ponce and Obersteiner (2006) conclude that ‘most least-cost afforestation projects are located in Africa, South America and Asia.’ Our analysis confirms this result for Africa and South America (see Fig. 8). For Asia we only have low-cost projects in the Former SU. As discussed above, the remainder of Asia is relatively expensive.

## 6 Summary

Here, we have presented supply curves and cost–supply curves for carbon sequestration for plantations in 17 world regions. These curves have been used in an overall framework comparing different CO<sub>2</sub> emission mitigation options. We have shown that a potential of up to 2,700 MtC/yr by the end of the twenty-first century is possible, depending on assumptions made. The associated costs are low up to 2025, but are projected to substantially increase afterwards. Still, the costs remain low compared to the costs of other

<sup>4</sup> Benítez et al. assess that risks associated with political, economic, and financial circumstances reduces the global carbon sequestration potential by approximately 60%.

mitigation options in the energy system (including energy crops) and for non-CO<sub>2</sub> emissions.

Although direct comparison with other studies is not straightforward, the range of supply and costs presented falls well in the range of other (regional and global) carbon sequestration cost–supply studies. An exception is East Asia, where our land prices might be too high and where revenues from timber extraction are more important than in other regions.

The largest source of uncertainty for the projected sequestration potential and associated costs is the assumed growth of carbon plantations compared to the natural vegetation, as expressed in the Additional Growth Factor (AGF). Especially if growth falls short, costs per ton of carbon will strongly increase. A different baseline scenario than B2 has a limited impact on costs, suggesting that costs do not strongly depend on the baseline scenario used.

Next steps will deal with comparing the potential of energy crops and carbon plantations, including revenues from harvested wood and their impact on the wood and land market (i.e. leakage), the inclusion of regional implementation factors and of other cost components such as maintenance and monitoring. Regional consequences will also be evaluated in more detail, especially for East Asia. To improve the carbon cycle modelling (and thus the carbon sequestration computation), we are currently working on the inclusion of a Dynamic Global Vegetation Model (DGVM). Also, an AOGCM of intermediate complexity will be incorporated in IMAGE to allow for the simulation of climate–vegetation feedbacks, such as albedo and precipitation changes due to changing vegetation patterns (see Bouwman et al. 2006 for more details).

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