Journal of Forest Economics 19 (2013) 384–401

Contents lists available at ScienceDirect

Journal of Forest Economics

journal homepage: www.elsevier.com/locate/jfe

Consequences of carbon offset payments for the global forest sector

Joseph Buongiorno*, Shushuai Zhu

Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 25 September 2012
Accepted 22 June 2013

JEL classification:
C54
C61
F18
L73
O13
A23
Q41

Keywords:
Carbon markets
International trade
Global Forest Products Model

ABSTRACT

Long-term effects of policies to induce carbon storage in forests were projected with the Global Forest Products Model. Offset payments for carbon sequestered in forest biomass of \$15–\$50/t CO_2e applied in all countries increased CO_2 sequestration in world forests by 5–14 billion tons from 2009 to 2030. Limiting implementation to developed countries exported environmental damage from North to South, as developing countries harvested more, decreasing their stored CO_2e. Substantially more CO_2e was sequestered by allocating a given budget to all countries rather than to developed countries only. As offset payments increased wood prices relatively more than they decreased production, timber revenues generally increased. In the few countries with timber revenues losses they were more than compensated by the offset payments.

Introduction

The last decade has witnessed increasing evidence of global climate change from various observations, ranging from the recession of the snow cap of Kilimanjaro (Thompson et al., 2002) to permafrost and ecosystem changes in the arctic (Hinzman et al., 2005). Furthermore, research suggests a strong causal effect of carbon dioxide (CO_2) concentration in the atmosphere on climate change, marked in particular by a rise in global temperatures (IPCC, 2012; Zickfeld et al., 2012).

* Corresponding author at: Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA. Tel.: +1 608 262 0091; fax: +1 608 262 9922.

E-mail address: jbuongio@wisc.edu (J. Buongiorno).

1104-6899/\$ – see front matter
http://dx.doi.org/10.1016/j.jfe.2013.06.005

Multiple international initiatives have been taken to reduce the amount of CO_2 present in the atmosphere, by lessening CO_2 emissions and stimulating carbon storage in terrestrial ecosystems. These proposals continue to give a central role to economic incentives and to the strengthening of international carbon markets. They also recognize the importance of initiatives at forest sector level, the need to involve developing countries, and to enhance the role of forestry related activities. In particular, the REDD and REDD+ programs, involving several United Nations agencies and numerous countries, is meant to stimulate "all activities that reduce emissions from deforestation and forest degradation and contribute to conservation, sustainable management of forests, and enhancement of forest carbon stocks" (World Bank, 2011). But, more unilateral policies, especially within developed countries, are also being advocated in the hope of achieving significant results quickly. For example, the EU is trying to extend its climate change law to stimulate remedial action within its member countries (Scott and Rajamani, 2012).

Early studies of the economics of carbon sequestration in forests include Parks and Hardie (1995) development of supply schedules for forests plantations to simulate a national carbon sequestration program. They determine that cost-effective actions should focus on softwood forests on pastureland. More recently, Murray et al. (2003) study the amount of carbon sequestration induced by a policy which is undermined by carbon releases elsewhere (a leakage according to which environmental improvements in regions reducing emissions would be offset by an increased in economic activity and attendant pollution in regions maintaining the status quo). Their results with combined econometric and sector models suggest that leakage cannot be ignored in accounting for the effects of CO_2 mitigation activities in forestry. Latta et al. (2011) use an inter temporal optimization model to study voluntary and mandatory carbon offset programs, with results indicating that sequestration costs are substantially higher than previously estimated. Based on simulations of the French forest sector model Lecocq et al. (2011) find that a policy of payments for carbon sequestration *in situ* is the only one that performs better than no intervention, compared to policies that substitute wood products for other energy sources. Among the international studies, Sohngen and Mendelsohn (2005) use an optimal control model of carbon sequestration and energy abatement to determine the potential role of forests in greenhouse gas mitigation. They find that although carbon sequestration is costly, forests can sequester about one-third of total carbon abatement, over two-thirds of which in tropical forests. van Kooten et al. (2004) present a meta analysis of published costs of carbon offsets in forests and conclude that "forest sink projects are competitive with other means of reducing atmospheric CO_2".

The objective of this study was to project the long-term effects of economic policies to induce carbon storage in forests, for the world and for major regions and countries. The projections dealt with the effects on the quantity of carbon dioxide equivalent (CO_2e) sequestered in forests and with the effects on forest product markets. The projections were done for different levels of offset payments, thus yielding supply curves for carbon sequestration, and for policies that applied offset payments in all countries or in developed countries only, with estimates of the attendant leakages and inefficiencies.

Methods

Theoretical framework

Fig. 1 illustrates the principle of the simulations carried out to project the consequences of offset payments for CO_2e sequestered in forests. For simplicity, the figure refers to one single product, wood, supplied and demanded in two world regions. Before any offset payment, the excess supply in region 1, S_1 minus D_1, matches the excess demand in the other region, D_2 minus S_2. The equilibrium price is P (for simplicity we ignore the transport cost which does not affect the argument). The effect of the offset payment for carbon sequestered in forest biomass is to increase the marginal cost of harvesting wood by an amount equal to the offset payment per unit of harvested volume, c, that could be earned by not harvesting. This payment can be envisioned as an annual rent per unit of increase in permanently stored wood, equal to cr, where r is the interest rate.

Consequently, the supply curve with offset payments shifts from A to B. This leads to a new equilibrium indicated by the dashed lines in Fig. 1. The world price increases to P'. However, the price increase is less than the offset payment, c, as the system reacts in a direction that tends to restore

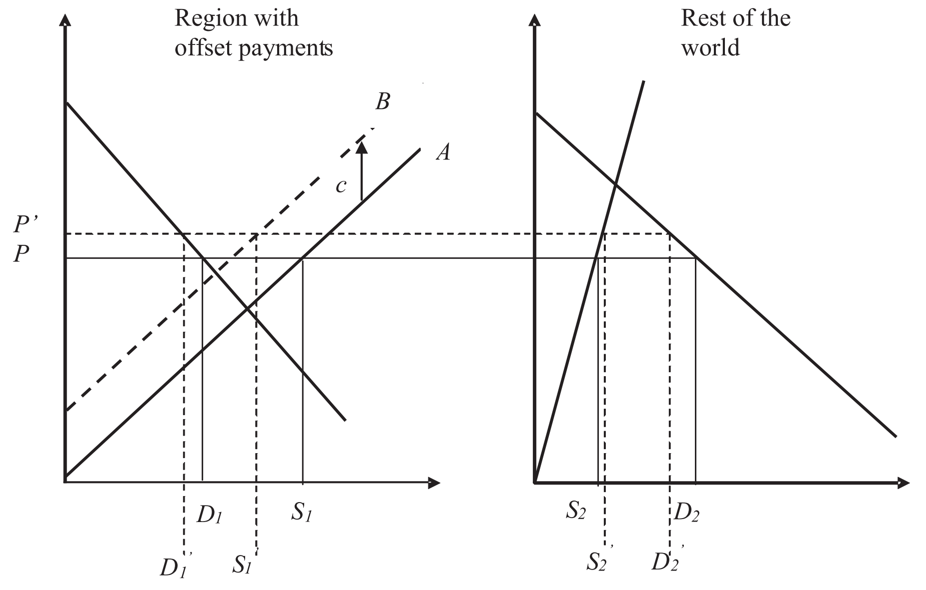

Fig. 1. Wood supply shift due to offset payments for CO_2 sequestration, and effects on world price, production, consumption, and trade. Solid lines refer to the situation before offset payments, and dashed lines after offset payments have shifted the wood supply from *A* to *B*.

the pre-offset payment equilibrium, in accord with the Le Chatelier principle. In the region with the offset payments, the quantity supplied decreases to $S_1{}'$, due to the supply shift compensated in part by the positive movement along the supply curve, while the quantity demanded decreases to $D_1{}'$ along the unchanged demand curve, and net exports decrease to $S_1{}'$ minus $D_1{}'$. In the rest of the world the quantity demanded decreases to $D_2{}'$ and the quantity supplied increases to $S_2{}'$ by movements along the unchanged demand and supply curves, leading to lower net imports equal to the net exports of the region with offset payments.

Implementation in GFPM

The principles outlined above were implemented in the Global Forest Products Model (GFPM). The GFPM is a partial equilibrium model of the forest sector. It assumes that the global forest sector depends on macroeconomic forces such as GDP and population, while the macro economy is unaffected by the forest sector. The model is dynamic as the market equilibrium in a particular year depends in part on the equilibrium in the previous year, with imperfect foresight of future events.

A detailed description of the original model formulation is available in Buongiorno et al. (2003). The most recent version, with the software using the interior point solver BPMPD[1] (Mészáros, 1999), and the documentation are in Buongiorno and Zhu (2012a,b). The essential part of the static phase of the model, which computes the global equilibrium in a given year, can be summarized by the following two equations:

$$\max_{\{D,Y,T\}} \left(\sum_{i,k} \int_0^{D_{ik}} P_{ik}(D_{ik})dD_{ik} - \sum_{i,k} \int_0^{Y_{ik}} m_{ik}(Y_{ik})dY_{ik} - \sum_{i,j,k} c_{ijk}T_{ijk} \right) \tag{1}$$

[1] BPM stands for “belső pontos módszer” or “interior point method” in Hungarian, and PD stands for “primal dual”.

Subject to:

$$\sum_j T_{jik} + Y_{ik} = D_{ik} + \sum_n a_{ikn} Y_{in} + \sum_j T_{ijk} \quad \forall i, k \tag{2}$$

Eq. (1), the objective function, expresses the hypothesis that competitive markets maximize producers and consumers surplus, as in Samuelson (1952), throughout the global forest sector. The first integral is the value of the products to consumers, where:

D_{ik} = quantity of end-product k demanded in country i, and
P_{ik} = inverse demand function expressing price in terms of quantity.

The second integral is the cost of production, where:

Y_{ik} = quantity supplied and
m_{ik} = inverse supply for production modeled with a supply equation, or the marginal manufacturing cost excluding wood and fiber explicit in the model for production modeled with activity analysis (input–output).

The last part of Eq. (1) is the total transportation cost, where T_{ijk} is the shipment from origin i to destination j (in this application, each country exports and imports to and from a single "world market"), and c_{ijk} is the corresponding unit transport cost.

Eq. (2) expresses the equilibrium between demand and supply for each product and country. The left hand side of the equation is the quantity supplied: the sum of imports and of domestic production. The right hand side is the quantity demanded, consisting of the end demand, the demand in the production of other products, where a_{kin} is the amount of product k used in making product n in country i, and of exports. When Eq. (1) is maximized subject to constraints (2), the dual solution or shadow price for each constraint gives the equilibrium price of product k in a particular country, i, in the current year.

The dynamic phase of the GFPM represents the changes in the demand and supply conditions over time. In particular, for this application the upward shift of the linear approximation of the inverse wood supply of a particular country due to the change of offset payments for CO_2e was modeled as follows:

Due to the change in growing stock, the wood production in a year and country, Y^*, given last year's production, Y_{-1}, and at last year's price, P_{-1}, was:

$$Y^* = Y_{-1}(1 + \gamma g) \tag{3}$$

where γ was the partial elasticity of wood supply with respect to growing stock, g was the last year's growth rate of growing stock due to harvest and natural growth, and the natural growth of forest stock in the absence of harvest was inversely related to the density of forest stock per unit area (Turner et al., 2006).

The linear approximation of the inverse supply curve, described by its tangent at point (Y^*, P_{-1}) was then:

$$P = \alpha + \beta Y, \text{ with } \beta = \frac{P_{-1}}{\sigma Y^*} \text{ and } \alpha = P_{-1} - \beta Y^* \tag{4}$$

where σ was the elasticity of supply with respect to price.

An exogenous change in last year's offset payment from C_{-1} to C, in \$/ton of CO_2e, shifted the inverse supply curve further to the position described by:

$$P = \alpha + \beta Y + \omega(C - C_{-1}) \tag{5}$$

where ω was the CO_2e lost from the forest biomass per unit of harvest, in ton/m^3. The equilibrium values of the quantity supplied, Y, and the corresponding price, P, were then determined endogenously by solving the quadratic programming problem described by Eqs. (1) and (2).

For the purpose of this study the GFPM was recalibrated with base year 2009 data, consisting of the average over 2008, 2009 and 2010, for 180 countries. For each country data were obtained from the

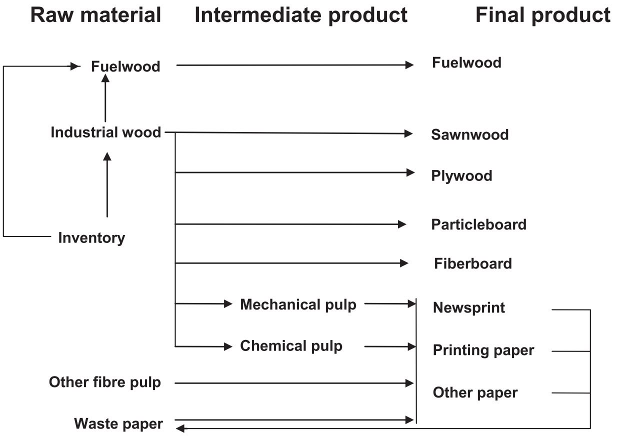

Fig. 2. Within country product flows simulated by the GFPM.

FAOSTAT data base (FAO, 2012) on the production, imports, and exports, of the 14 products shown in Fig. 2. For each product local prices were the unit value of imports for net importers or the unit value of exports for net exporters. The data on forest area and forest stock were from FAO (2010), which served also to establish the initial growth rate of forest stock.

Given these base year data, the GFPM was calibrated for the input–output coefficients, a_{ikn}, in Eq. (2), above, and the manufacturing cost, m_{ik}, in Eq. (1). In each country the calibration finds input–output coefficients that minimize the difference between reported and estimated production, subject to reported imports and exports, and *a priori* bounds on the input–output coefficients (Buongiorno and Zhu, 2012b). The elasticities of demand for end products (fuelwood, sawnwood, panels, paper and paperboard), and the elasticities of supply for raw materials (wood, other fibers), were as in Buongiorno et al. (2012). After calibration the model was validated by checking that the solution of Eqs. (1) and (2) for the base year matched the input data on production, consumption, prices, and net trade (exports–imports).

To make projections to 2030, the exogenous assumptions on the future rate of growth of total and per capita gross domestic product were taken from USDA-ERS (2012). The parameters of the equations predicting forest area change as a function of GDP per capita, and the rate of growth of forest stock as a function of stock density were as in Buongiorno et al. (2012), as were the rates of technical change and the changes of manufacturing cost.

The assumptions regarding the future evolution of offset payments for CO_2 sequestration were guided by existing projections of market prices for CO_2e, three of which appear in Fig. 3. The highest, IEA (2009), projects that the price reaches \$50/t of CO_2e in 2020 and increases to \$110/t in 2030 according to the “450 scenario” (IEA, 2010). Synapse (2011) highest forecasts are more modest, going from \$15/t of CO_2e in 2015 to \$80/t in 2030, while their lowest forecast goes from \$50/t in 2018 to \$50/t in 2030. The shorter projections of CEC (2011) reach even lower at about \$24/t of CO_2e in 2020. Given this wide range of possible future prices, and based on judgment, the GFPM simulations assumed three scenarios for offset payments. They all started at 0 \$/t in the base year of 2009, increased to \$15/t, \$30/t, or \$50/t[2] by 2015 and then stayed at those levels until 2030 (Fig. 3). As indicated above, the opportunity cost in Eq. (5) was the payment lost by the owner for the carbon in the biomass of the forest per m^3 of harvested wood. We estimated the amount of biomass on which payments are foregone, per unit of harvested wood, as 0.55 t/m^3 based on data in FAO (2010) [3].

[2] All values are in dollars of the United States in 2009.

[3] The global forest resources assessment (FAO, 2010) reports a world growing stock in 2010 of 527.2 billion m^3 (Table 2.13, p. 38), and a carbon stock in forest biomass (excluding dead wood, litter, and soil) of 288.8 billion t (Table 2.21, p. 45). The carbon lost for offset payments per unit of harvest was then set equal the average ratio of carbon in biomass to stock of 0.55 t/m^3.

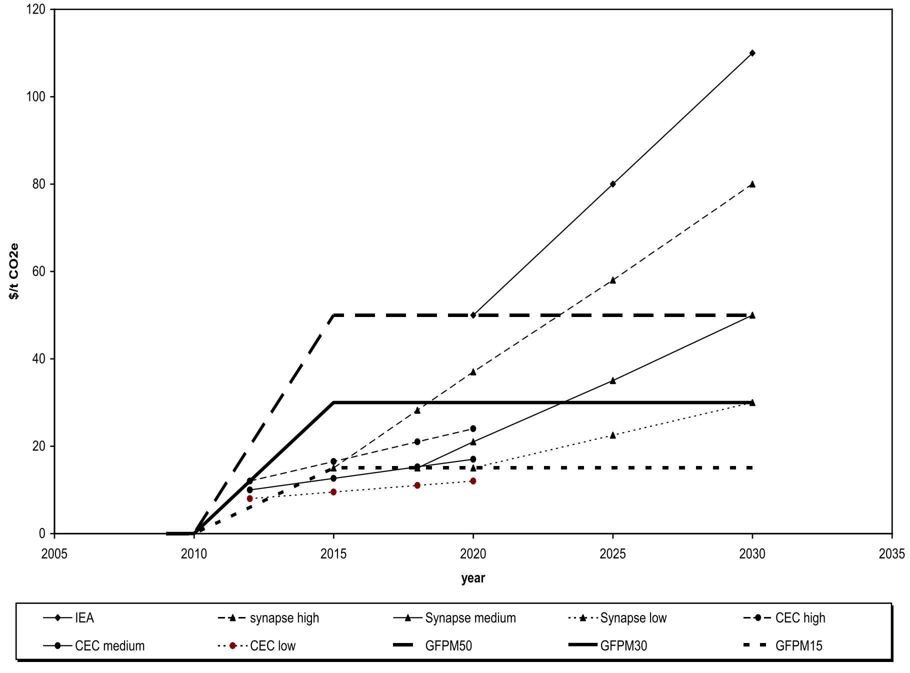

Fig. 3. Projections of the price of CO_2e by IEA (2009), Synapse (2011), CEC (2011), and projections adopted in the GFPM.

Results

Consequences for CO_2e stored in forests

Fig. 4 shows the trends of carbon dioxide equivalent (CO_2e) stored in forest stock projected by the GFPM according to the base scenario which assumed no carbon offset payment. The amount of CO_2e stored in world forests from 2009 to 2030 increased by approximately 159 billion tons or 15% of the 2009 level, of which 60% in developed countries and 40% in developing countries. This implies an average yearly accumulation of 2.1 billion tons of carbon in world forests, slightly below Pan et al. (2011) estimate of 2.3 (±0.5) billion tons per year from 2000 to 2007. The largest GFPM projected increase of stored CO_2e from 2009 to 2030 was in North/Central America, 45 billion t, followed by Europe, 37 billion t, Africa, 35 billion t, and South America, 22 billion t. Asia and Oceania together added 21 billion t. It can be noted that, according to this base scenario, the total amount of CO_2e added in all the forests of the world in 21 years was only five years of the annual global CO_2 emissions estimated at 32 billion tons in 2008 (Boden et al., 2011).

Table 1 shows the predicted changes in CO_2e stored by main region, compared to the base scenario, due to offset payments for stored CO_2e of $30/t beginning in 2015 (the hypothesis described by the line "GFPM30" in Fig. 3). With offset payments in all countries, compared to the base scenario, the amount of CO_2e stored globally in forests increased by 9.1 billion tons by 2030, or 6 percent more than what was stored from 2009 to 2030 in the base scenario, of which 5.1 billion tons more in developed countries and 4 billion tons more in developing countries. The increase occurred in all regions and mostly in Europe (3.2 billion tons), followed by Asia and North America at (about 1.6 billion tons each), and South America (1.1 billion tons).

Offset payments of $30/t of CO_2e applied in developed countries only led as expected to less global carbon stored, 5.0 billion t, or 3 percent more stored CO_2e by 2030 compared to no offset payments. Although the developed countries stored more, 5.0 billion t in Europe and 3.6 billion t in North America, the CO_2e stored in developing countries decreased by 1.9 billion t in Asia and 1.1 billion t in South

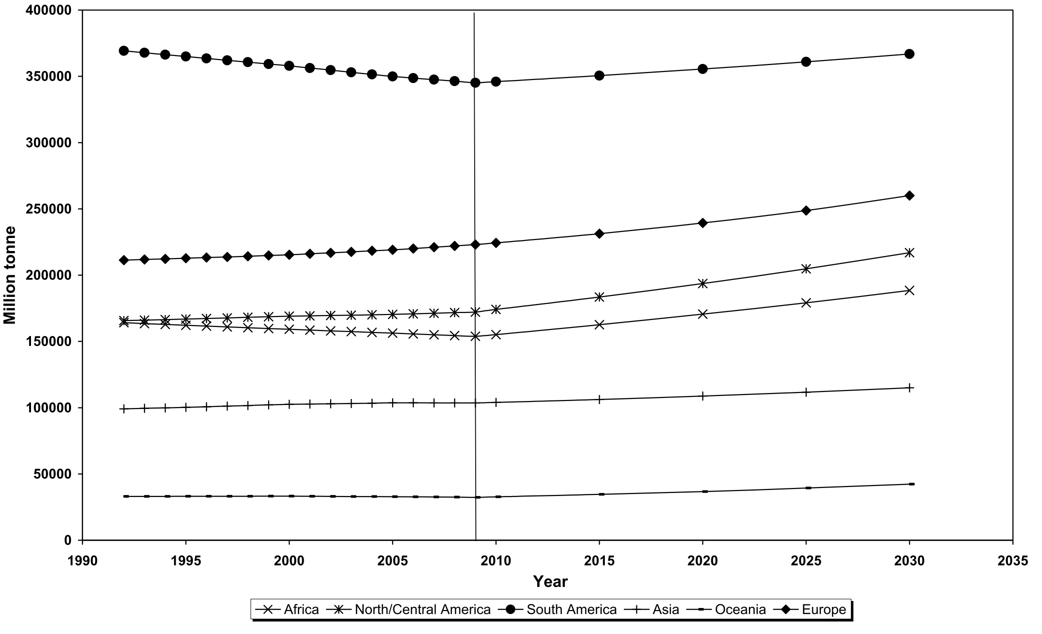

Fig. 4. Historical and GFPM projections of the CO_2e in forest stock from 2009 to 2030 according to the base scenario with no offset payment.

America. Thus, the effect of a unilateral policy concentrating on developed countries only was in large part to export an environmental problem from north to south.

Table 1 also shows what happened in selected countries under the two scenarios. With offset payments in all countries, the amount of stored CO_2e increased almost everywhere, but especially in forest rich countries, such as Russia, the United States, and Brazil. With offset payments in developed countries only, stored CO_2e rose further in the United States, Russia and other European countries, but declined in Brazil, China, and Indonesia.

Supply curves for carbon storage

Fig. 5 summarizes the effects of the level of carbon offset payments, in $/ton of CO_2e, on the amount of CO_2e stored in forests. The data came from GFPM simulations from 2009 to 2030 assuming offset payments of $0, $15, $30, or $50 per ton of CO_2e sequestered in forests, according to the schedule in Fig. 3, with the policy applied throughout the world or in developed countries only. The horizontal axis refers to the additional CO_2e stored from 2009 to 2030 at various prices and for each policy, other things being equal, and taking into account the opportunity cost of not using the wood sequestered to produce other commodities.

When offset payments were applied to all the countries, the increment of carbon storage increased almost linearly with the price paid per unit of CO_2e. However, when offset payments occurred in developed countries only, an increase of the price of CO_2e decreased the amount of CO_2e stored in the forests of Asia (almost linearly) and of South America (at a decreasing rate with rising prices), while the price had practically no effect on the CO_2e stored in African forests. The net result was a supply curve for the world which was much steeper with offset payments in developed countries only than with offset payments in all countries.

Fig. 6 shows the global total cost of offset payments, computed as the area under the world supply curves in Fig. 5, for different levels of stored CO_2e. It underlines the inefficiency of a unilateral policy concentrating on developed countries only. For example, a global budget of $100 billion for offset payments spread over all countries increased the amount of CO_2e stored in forests by 7.7 billion tons

Table 1
Change of CO_2e stored in living forest biomass from 2015 to 2030 due to offset payments of \$30/t CO_2e applied in all countries or in developed countries only.

	Offset payment applied in:	
	All countries (million t)	Developed countries only (million t)
Africa	1159	71
Egypt	2	−1
Nigeria	157	−4
South Africa	122	219
North/Central America	1642	2649
Canada	561	1185
Mexico	61	−85
United States of America	928	1563
South America	1132	−1114
Argentina	56	−53
Brazil	701	−587
Chile	243	−365
Asia	1680	−1914
China	305	−859
India	497	−102
Indonesia	292	−324
Japan	8	93
Korea, Republic of	21	−68
Malaysia	104	−274
Oceania	260	344
Australia	151	282
New Zealand	76	122
Europe	3243	4984
EU-27	1957	3127
Austria	61	114
Finland	226	394
France	231	392
Germany	115	317
Italy	25	36
Russian Federation	919	1308
Spain	115	147
Sweden	519	718
United Kingdom	−3	22
Developed	5095	8455
Developing	4021	−3433
World	9116	5022

with a marginal cost of \$16/t while the \$100 billion limited to developed countries achieved only 5.8 billion tons with a marginal cost of \$20/t.

Consequences for wood and product prices

In accord with the theory outlined above, the effect of payments for CO_2e stored in forests was to decrease the wood production while increasing the price of wood. Fig. 7(a) shows past and projected real world prices of fuelwood, industrial roundwood, and sawnwood, measured by the unit value of world exports, in constant United-States dollars of 2009 per cubic meter. The figure shows projections according to the base scenario with no offset payment, the scenario with offset payments at \$30/t of CO_2e applied in all countries, and the scenario with offset payments of \$30/t of CO_2e applied in developed countries only. Fig. 7(b) shows similar data for wood pulp and other fibers.

Without offset payment, the real price of fuelwood, industrial roundwood, and sawnwood decreased by 9%, 11%, and 14%, respectively from 2009 to 2030. During the same period, the real

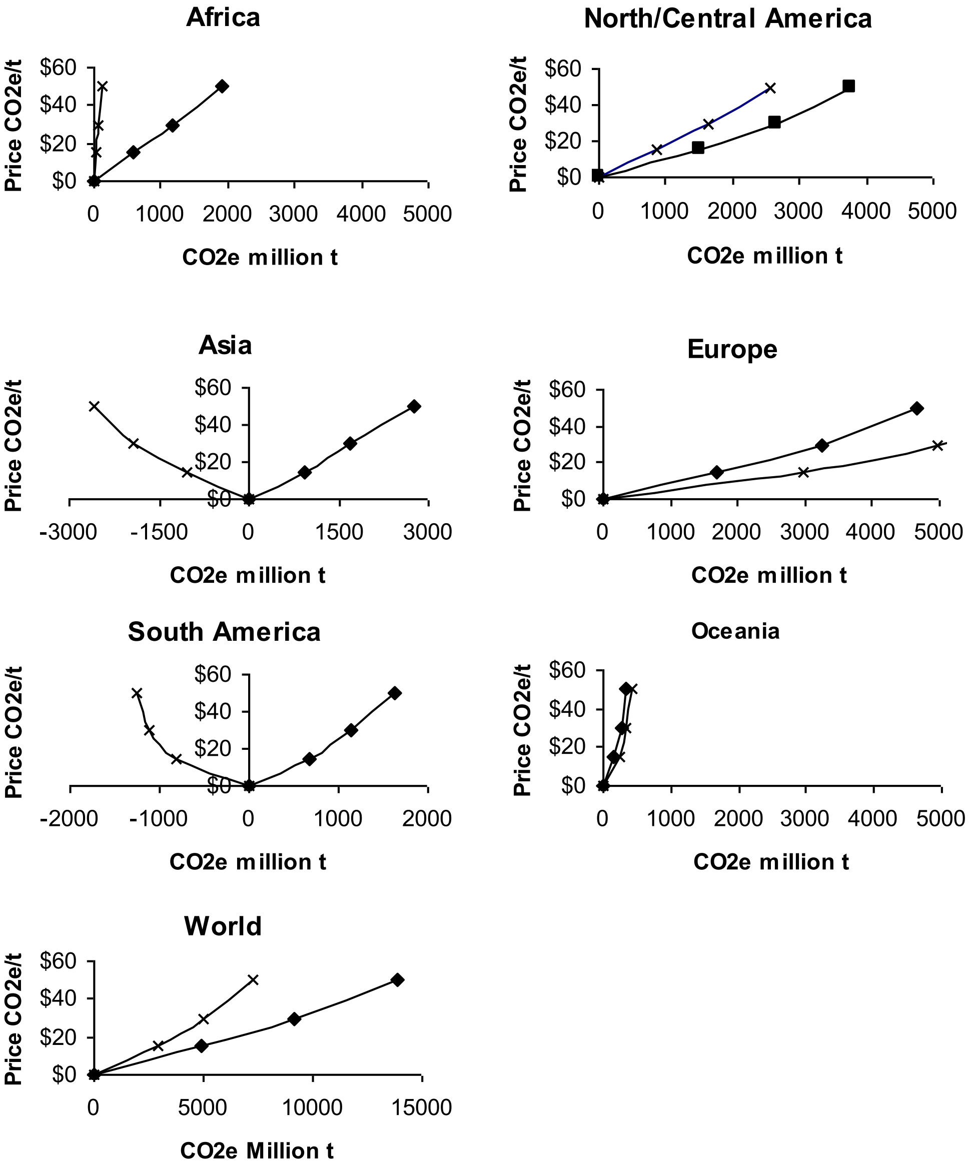

Fig. 5. Additional CO_2e stored in forests from 2009 to 2030 at varying prices of CO_2e paid in all countries (—♦—) or in developed countries only (—×—).

price of wood-based panels, wood pulp, and paper and paperboard decreased by 11%, 13% and 5%. Offset payments of \$30/t of CO_2e increase the real price of fuelwood in 2030 by 94% and that of industrial roundwood by 52% relative to the base scenario. Meanwhile, the real price of sawnwood and wood-based panels increased by 31% and 15%, respectively, while the price of wood pulp and paper and of paperboard increased by 19% and 5%.

When the same offset payments of \$30/t of CO_2e were applied in developed countries only, the price increases relative to the base scenario were more moderate. The price of fuelwood and industrial roundwood was 88% and 36% higher in 2030. The price of sawnwood and wood-based panels

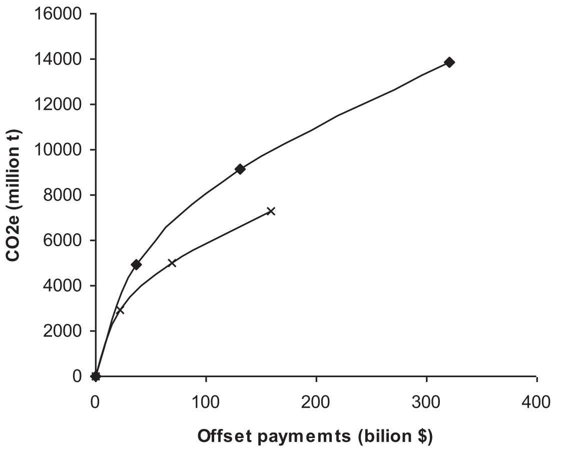

Fig. 6. Offset payment cost of CO_2e stored in world forests from 2015 to 2030 with offset payments paid in all countries (—♦—) or in developed countries only (—×—).

was 22% and 11% higher, and the price of wood pulp and of paper and paperboard was 13% and 4% higher.

Consequences for wood production and revenues

When offset payments of $30/t of CO_2e were applied to all countries, the world production of total roundwood (fuelwood and industrial roundwood) in 2030 was 308 million ton (9%) lower than production without offset payments (Table 2, column 2). Production decreased in almost all developed and developing countries, and approximately 20% more in developing countries than in developed. The largest decrease of production occurred in Russia, Brazil, the United States, India, and China.

With offset payments of $30/t confined to developed countries (Table 2, column 3) production in 2030 decreased further in all developed countries, especially the United States, Russia, Canada, and numerous countries of the European Union. However, this decrease was compensated in part by higher production in developing countries, especially Brazil, China, and Indonesia, leading to a net world decrease of production of 138 million tons, or 4% compared to the 2030 production without offset payments.

The changes in the revenues of wood producers, measured by the value of fuelwood and industrial roundwood production at prevailing real prices are in the second and third column of Table 3. When offset payments of $30/t of CO_2e were applied in all countries world timber revenues increased by 54% relative to the base scenario because the increases in prices of fuelwood and industrial roundwood largely exceeded decreases in production. Two thirds of the timber revenue increase occurred in developing countries, with high gains in India, China, and Brazil. The United States and Canada also experienced large increases in timber revenues. With offset payments of $30/t of CO_2e in developed countries only, the world timber revenues still increased by 51%, and 87% of the increase was in developing countries, especially in China and Brazil.

In addition to increased timber revenues, producers could also benefit from direct offset payments for carbon storage in forests. The last two columns of Table 3 show the average yearly offset payments received by producers in 2030 at $30/t of CO_2e. The global offset payments were nearly the same when applied to all countries or to developed countries only, 17–18% of the change in global timber revenue. However, with payments to all countries, nearly 700 million tons per year of CO_2e were stored globally in 2030, of which 400 million tons in developed countries and 300 million tons in developing countries. With payments limited to developed countries, only 400 million tons per year of CO_2e were stored globally in 2030, with an addition of 700 million tons per year in developed countries countered by a reduction of 300 million tons per year in developing countries.

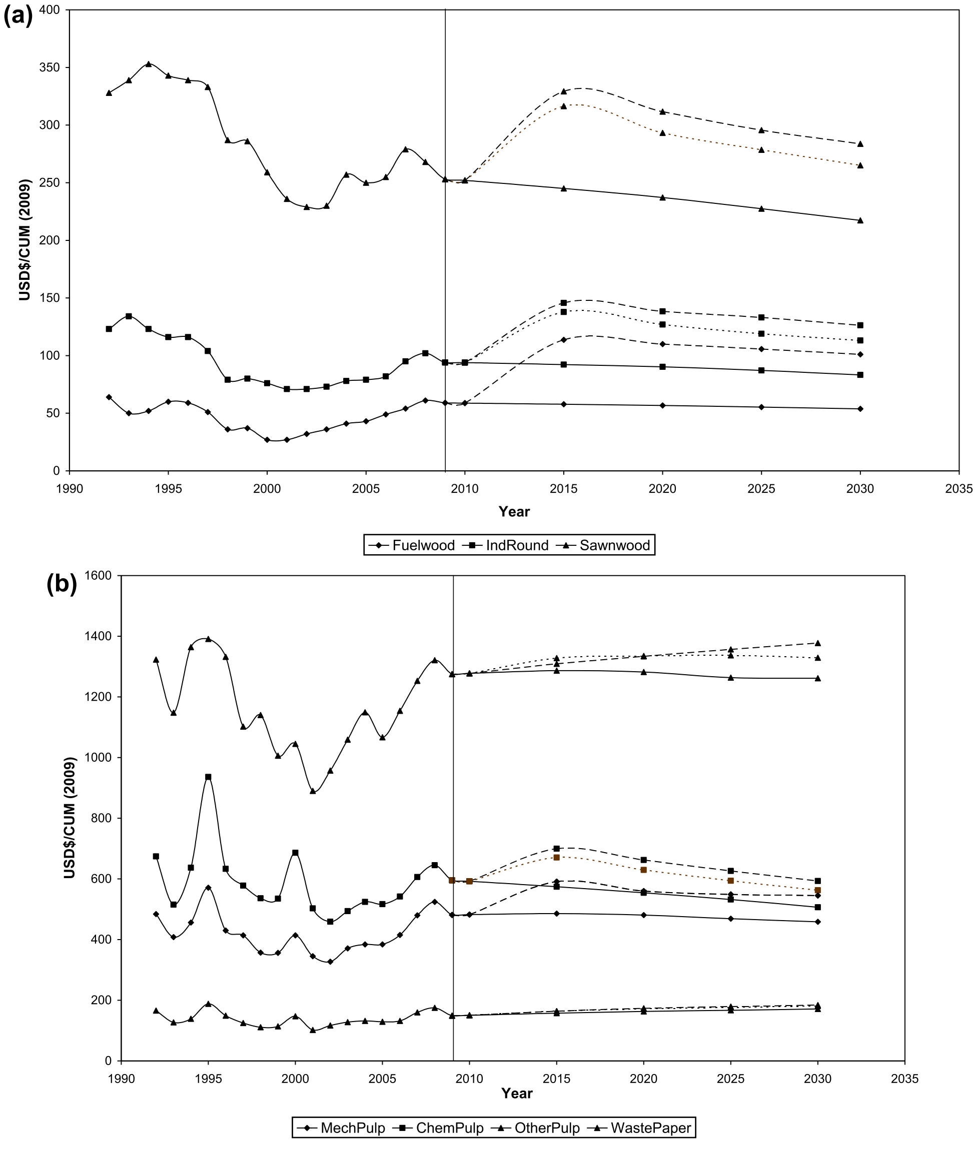

Fig. 7. Projected prices of solid wood products (a) and fiber products (b) in the base scenario with no offset payment (___), and with offset payments of \$30/t of CO_2e in all countries (—) or in developed countries only (. . .).

Consequences for forest industries

The consequences of carbon offset payments for the consumption, production, and trade of forest products tend to vary according to the share of wood cost in the total cost of the manufactured product. For example, Table 4 shows the impact of global or partial offset payment policies on sawnwood consumption and production in 2030 for world regions and selected countries. With offset payments in all countries sawnwood consumption decreased everywhere due to the higher prices noted above, and total world consumption was about 3% lower in 2030 than without offset payments. Meanwhile, production decreased by 5% in developed countries but increased by 2% in developing countries, and

Table 2
Change of annual total roundwood (fuelwood and industrial roundwood) production in 2030 due to offset payments of $30/t CO_2e applied in all countries or in developed countries only from 2015 to 2030.

	Offset payment in:	
	All countries (million m^3)	Developed countries only (million m^3)
Africa	−40	−1
Egypt	−1	0
Nigeria	−7	0
South Africa	−3	−5
North/Central America	−48	−77
Canada	−16	−36
Mexico	−3	2
United States of America	−24	−44
South America	−46	44
Argentina	−2	2
Brazil	−29	34
Chile	−9	8
Asia	−75	55
China	−21	16
India	−23	4
Indonesia	−11	13
Japan	2	−1
Korea, Republic of	0	2
Malaysia	−3	9
Oceania	−8	−11
Australia	−5	−9
New Zealand	−2	−4
Europe	−91	−148
EU-27	−46	−88
Austria	−2	−3
Finland	−4	−10
France	−6	−11
Germany	−5	−14
Italy	0	−1
Russian Federation	−34	−42
Spain	−3	−4
Sweden	−10	−19
United Kingdom	1	0
Developed	−139	−248
Developing	−169	110
World	−308	−138

the impact on production across countries was much more varied than on consumption, reflecting the competitive advantage of countries, and their different sensitivity to wood costs due to differences in their techniques of production.

With offset payments in developed countries only the world sawnwood consumption decreased less than with a global policy in conjunction with the lower price increase, by about 2% both in developed and developing countries (Table 4). But while production was 9% lower in developed countries than without offset payments, it was 13% higher in developing countries. In this scenario and in the scenario with offset payments in all countries the annual production decreased most in Russia, Sweden, and the United States, while it increased most in Japan, Canada, and Germany.

These substantial effects of offset payments on consumption and production led to large variations on international trade. For example, Fig. 8 shows projections of sawnwood net trade (export minus imports) by world region for different scenarios. The base scenario, which assumed no offset payments, led to increasing net exports from Europe, matched by increasing net imports in Asia, while there was little change in Africa, North and South America, and Oceania. With the scenario of offset payments

Table 3
Change in timber harvest revenues and offset payments in year 2030 with offset payments of \$30/t CO_2e applied in all countries or in developed countries only from 2015 to 2030.

Region	Change in timber harvest revenues with:		Offset payments with:	
	Offset payments in all countries (million \$)	Offset payments in developed countries only (million \$)	Offset payments in all countries (million \$)	Offset payments in developed countries only (million \$)
Africa	25,304	27,004	2424	142
Egypt	696	94	5	0
Nigeria	3148	25	336	0
South Africa	1256	686	287	558
North/Central America	20,071	10,839	3864	6416
Canada	4979	440	1408	2899
Mexico	2322	530	126	0
United States of America	11,677	5937	2122	3725
South America	12,629	20,015	2543	0
Argentina	261	349	130	0
Brazil	9870	6001	1490	0
Chile	1066	1779	619	0
Asia	42,141	50,380	3811	0
China	13,716	6159	850	0
India	19,758	1982	1082	0
Indonesia	3784	2262	659	0
Japan	1104	484	0	149
Korea, Republic of	378	412	43	0
Malaysia	689	1533	239	0
Oceania	2114	1034	619	900
Australia	1039	188	365	722
New Zealand	748	351	179	341
Europe	20,453	7436	7730	12,377
EU-27	13,698	4553	4458	7783
Austria	481	173	128	251
Finland	1538	233	479	931
France	1918	883	541	952
Germany	2655	751	234	902
Italy	427	328	50	79
Russian Federation	3355	1822	2346	3150
Spain	202	−23	289	374
Sweden	1978	−94	1148	1770
United Kingdom	619	329	0	53
Developed	40,789	15,278	12,031	20,783
Developing	81,923	101,430	8960	0
World	122,712	116,708	20,992	20,783

for CO_2 sequestration applied in all countries, net exports from Europe were 26% lower in 2030 than without offset payments, and net imports of Asia were 50% lower. A policy of offset payments restricted to developed countries further reduced the trade imbalance between Europe and Asia, leading to European net exports 48% less than in the base scenario in 2030, while Asian net imports were 54% lower.

Table 5 summarizes the consequences of offset payments of \$30/t on the value added of all forest industries, in world regions and major countries in 2030. As computed in the GFPM, the value added is the difference between the value of the output and the cost of wood and fiber inputs, at local prices. The impact of offset payments on the world value added was less than 0.5%, both with offset payments in all countries, or in developed countries. However, with both policies, the effect was positive in developing countries, and negative by an almost equal amount in developed countries. With offset payments in all countries, value added was 6% higher in developing countries in 2030, and 5% lower

Table 4
Change in sawnwood consumption and production in selected countries in 2030 with offset payments of \$30/t CO_2e applied in all countries or in developed countries only from 2015 to 2030.

	Offset payments in:			
	All countries		Developed countries only	
	Consumption (1000 m^3)	Production (1000 m^3)	Consumption (1000 m^3)	Production (1000 m^3)
Africa	−564	−1932	−307	400
Egypt	−137	0	−103	0
Nigeria	−115	−126	−4	−3
South Africa	−136	−475	−104	−442
North/Central America	−3068	−4253	−2279	−4
Canada	−570	5525	−427	7886
Mexico	−207	981	−140	2025
United States of America	−2227	−10,737	−1688	−10,214
South America	−1633	−10,921	−652	−3490
Argentina	−32	−36	−14	412
Brazil	−1297	−4935	−533	−942
Chile	−183	−5534	−88	−3249
Asia	−3020	23,206	−1897	26,301
China	−1072	9492	−791	10,348
India	−388	−324	−136	−29
Indonesia	−281	−602	−139	−13
Japan	−390	9465	−297	8431
Korea, Republic of	−121	1608	−83	1324
Malaysia	−52	2076	−30	2423
Oceania	−261	902	−194	640
Australia	−212	−923	−160	−511
New Zealand	−41	1893	−31	1132
Europe	−3069	−18,617	−2316	−31,492
EU-27	−2401	2386	−1767	−9641
Austria	−143	247	−104	−104
Finland	−182	−3015	−132	−2835
France	−311	−311	−204	−205
Germany	−360	12,225	−248	4783
Italy	−189	3042	−143	2403
Russian Federation	−361	−21,728	−309	−20,554
Spain	−118	−2155	−93	−1672
Sweden	−213	−14,463	−154	−14,833
United Kingdom	−225	4066	−174	3140
Developed	−6708	−13,841	−5069	−25,206
Developing	−4907	2227	−2575	17,561
World	−11,615	−11,615	−7644	−7645

in developed countries. With offset payments in developed countries only the value added increased by 11% in developing countries, while it decreased by 9% in developed countries. Under both policies, the largest gains of value added were in China and Indonesia, and the largest losses in Finland and the United States. Brazil's value added turned from medium loss to the second largest gain when offset payments were in developed countries only.

Summary and conclusion

The objective of this study was to predict some of the effects of offset payments on the global forest sector. The projections were done with the GFPM model from 2009 to 2030, for offset payments ranging from \$15 to \$50 per ton of CO_2e applied from 2015 to 2030. Two types of policies were examined; one applying offset payments in all countries, and another applying them in developed countries only.

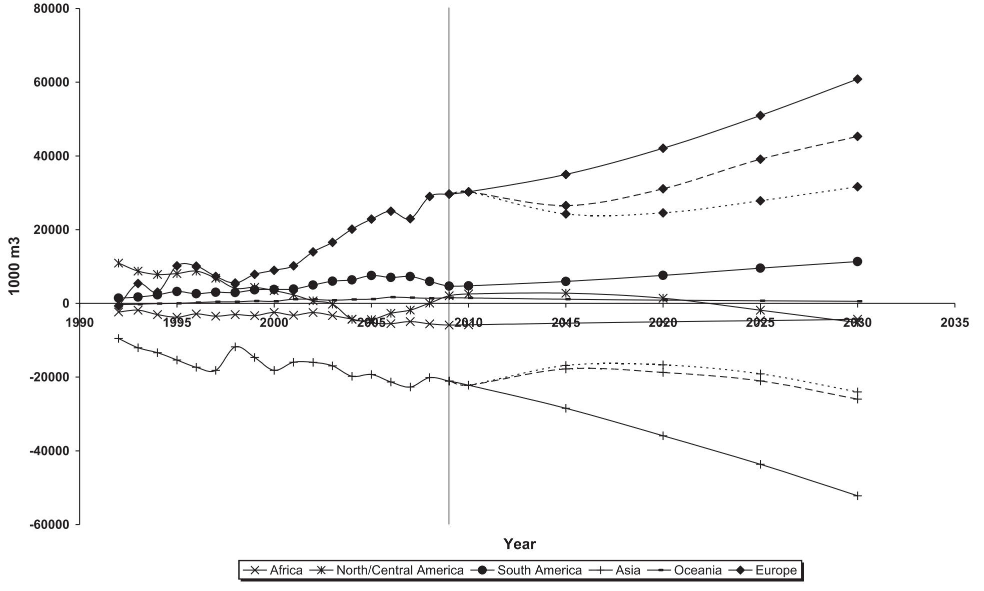

Fig. 8. Projected regional net trade (export minus import) of sawwood in the base scenario with no offset payment (___), and with offset payments of \$30/t of CO_2e in all countries (—) or in developed countries only (. . .).

In the scenario with the highest sequestration level, brought about by offset payments of \$50/t applied in all countries, the amount of CO_2e sequestered in world forests increased by 14 billion tons, or 9%, relative to the sequestration obtained without offset payment from 2009 to 2030. This was a modest amount compared to the current world CO_2 emissions of approximately 32 billion tons per year (Boden et al., 2011).

The study indicated that partial policies, concentrated in rich countries, would lead to a classical export of environmental damage from North to South. As producers in developed countries would reduce harvests in response to offset payments for CO_2e sequestration, the world price of wood and products would rise, and more harvesting would occur in developing countries, decreasing the forest stock and partially offsetting the gains in CO_2e sequestration obtained elsewhere.

The results also show that a unilateral policy of offset payments in developed countries only was economically inefficient. Almost twice as much CO_2e could be sequestered world wide by allocating a given budget for offset payments to all countries than by spending it in developed countries only. These two findings underline the importance of policies that apply to developing as well as developed countries. Although international programs such as REDD and REDD+ and bilateral agreements are funding projects in developing countries (Anonymous, 2011), they are still modest in scope and face many implementation difficulties (Creed and Nakhooda, 2012).

There were few countries that lost timber production revenues due to offset payments for CO_2 sequestration, with either a global or a partial policy, because the relative change in production was less than the relative change in price. Where losses did occur they were more than compensated by the receipts for sequestered CO_2e. However, one must acknowledge the stylized nature of the policies investigated here. In practice, the policies are likely to be more targeted, for example toward forest owners rather than forest enterprises, and to specific countries through bilateral aid.

In the markets for wood products, sawnwood, panels, pulp, and paper and paperboard, the reduction of wood supply due to the opportunity cost of offset payments led to higher product prices and diminished consumption for all products, implying lower consumer welfare in all markets. While the decrease in consumption was uniform across countries, there were large differences between countries in the changes of production, international trade, and value added due to offset payments, reflecting the differences in resource endowment, production techniques and cost between countries.

Table 5
Change in value added in wood industries of different world regions in 2030, with offset payments of \$30/t CO_2e applied from 2015 to 2030 in all countries or in developed countries only.

	Offset payment in:	
	All countries (million \$)	Developed countries only (million \$)
Africa	−1047	−550
Egypt	−61	−32
Nigeria	−34	11
South Africa	−918	−796
North/Central America	−8149	−12,399
Canada	−3567	−5840
Mexico	1042	1181
United States of America	−5699	−7860
South America	−1252	7812
Argentina	−367	58
Brazil	−679	5931
Chile	−196	1421
ASIA	15,123	15,044
China	7376	5350
India	191	724
Indonesia	4166	6807
Japan	670	−106
Korea, Republic of	1076	599
Malaysia	363	1515
Oceania	222	−147
Australia	−193	−193
New Zealand	424	51
Europe	−3044	−8858
EU-27	−1552	−6532
Austria	2407	1635
Finland	−9233	−9126
France	2303	1866
Germany	2440	1137
Italy	1251	1159
Russian Federation	−2682	−2661
Spain	231	−40
Sweden	−797	−1945
United Kingdom	1115	719
Developed	−12,213	−23,515
Developing	14,065	24,417
World	1852	902

These results are necessarily incomplete. For example, they ignore the still imperfectly known connection between forest carbon sequestration and forest biodiversity (Phelpsi et al., 2012). Furthermore, one should not underestimate the difficulty of implementing the policies. Creed and Nakhooda (2012) note that delivering REDD+ finance is proving difficult. Financing is still done through bilateral channels, with little transparency around these arrangements and major coordination challenges. Implementing REDD+ requires credible commitments of long-term finance from both developed and developing countries. It also requires the implementation of monitoring systems to estimate carbon stock changes with sufficient accuracy (Plugge et al., 2012).

It must also be kept in mind that the results presented here were obtained with a model, the GFPM, with all its merits and limitations. The merits include a comprehensive representation of the sector, allowing an assessment of the multiple impacts in individual countries, at levels ranging from the stock of CO_2e in forest live biomass to the production, consumption, international trade, and prices of products of forest industries. The limitations lie in the poor quality of some of the data, limited knowledge of the parameters such as the demand and supply elasticities, and the imperfect fit of the competitive equilibrium theory with reality. All of this leads only to a rough fit of the model predictions with actual (imperfect) observations. As documented in Buongiorno et al. (2003), the model mimics reasonably well the general trends by major regions, but not the year to year variations, and the forecast errors can be large for individual countries, especially the smallest. As result, and in consideration of differences in assumptions and methods, comparisons are difficult with other national studies (*e.g.* Lecocq et al., 2011).

Despite these limitations we trust that the results and methods presented here will provide some guidelines regarding the potential effects of international offset payments for carbon sequestration in forests, and the possible courses of further studies.

Acknowledgments

The work leading to this paper was supported in parts by the USFS Southern Research Station through a cooperative research agreement directed by Jeff Prestemon. The research was stimulated by comments and discussions during the Workshop in Forest Sector modeling held in Nancy, France, May 31 to June 1, 2012, and by the helpful suggestions of two anonymous reviewers.

References

http://www.environment.gov.ki/CC/Brief%20on%20CC%20and%20Finance.pdf

Boden, T., Marland, G., Andres, B., 2011. Global CO_2 emissions from fossil-fuel burning cement manufacture, and gas flaring: 1751–2008. In: Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, Oak Ridge, Tennessee, Available at: http://cdiac.ornl.gov/ftp/ndp030/global.1751_2008.ems (last accessed 25.07.12).

Buongiorno, J., Zhu, S., Zhang, D., Turner, J.A., Tomberlin, D., 2003. The Global Forest Products Model: Structure, Estimation and Applications. Academic Press, San Diego, pp. 301.

Buongiorno, J., Zhu, S., 2012a. Using the Global Forest Products Model (GFPM version 2012 with BPMPD). In: Staff Paper Series # 76. Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, pp. 37, Available at: http://forest.wisc.edu/staticsites/buongiorno/index.htm (last accessed 21.08.12).

Buongiorno, J., Zhu, S., 2012b. Calibrating and updating the Global Forest Products Model (GFPM version 2012 with BPMPD). In: Staff Paper Series # 77. Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, pp. 30, Available at: http://forest.wisc.edu/staticsites/buongiorno/index.htm (last accessed 21.08.12).

Buongiorno, J., Zhu, S., Raunikar, R., Prestemon, J., 2012. Outlook to 2060 for world forests and forest industries. A technical document supporting the Forest Service 2010 RPA assessment. In: Gen. Tech. Rep. SRS-151. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, pp. 119.

CEC, 2011. European CO_2 emission trading system, publication of CO_2 price forecast (ZEPHYR-Flex model) Climate Economics Chair. Press Release-December 19th 2011. Available at: http://climateeconomicsblog.blogspot.com/2011/12/eu-ets-publication-of-cecs-co2-price.html (last accessed 21.08.12).

Creed, A., Nakhooda, S., 2012. REDD+ finance delivery: lessons from early experience. Overseas Development Institute, Available at http://www.forestcarbonportal.com/resource/redd-finance-delivery-lessons-early-experience (last accessed 20.08.12).

FAO, 2010. Global forest resources assessment 2010. In: FAO Forestry Paper 163. Food and Agriculture Organization of the United Nations, Rome, pp. 340.

FAO, 2012. Food and Agriculture Organization FAOSTAT data base. Available at: http://faostat.fao.org/site/626/default.aspx#ancor (last accessed 05.04.12).

Hinzman, L., Bettez, N., Bolton, W., Chapin, F., Dyurgerov, M.<Et-AL>, 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. Climatic Change 72 (3), 251–298.

IEA, 2009. How the energy sector can deliver on a climate agreement in Copenhagen. In: Special early excerpt of the World Energy Outlook 2009 for the Bangkok UNFCCC Meeting. International Energy Agency, Paris, pp. 56.

IEA, 2010. 450 Scenario: Methodology and Policy Framework. International Energy Agency, Paris, Available at: http://www.iea.org/weo/docs/weo2010/Methodology_450_Scenario.pdf (last accessed May 2012).

IPCC, 2012. Meeting report of the Intergovernmental Panel on Climate Change expert meeting on economic analysis, costing methods, and ethics. In: Field, C.B., Barros, V., Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Mastrandrea, M.D., Mach, K.J., von Stechow, C. (Eds.), IPCC Working Group II Technical Support Unit. Carnegie Institution, Stanford, CA, USA, p. 75.

Latta, G., Adams, D.M., Alig, R.J., White, E., 2011. Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. Journal of Forest Economics 17, 127–141.

Lecocq, F., Caurla, S., Delacote, P., Barkaoui, A., Sauquet, A., 2011. Paying for carbon or stimulating fuelwood demand? Insights from the French forest sector model. Journal of Forest Economics 17, 157–168.

Murray, B.C., McCarl, B.A., Lee, H.C., 2003. Estimating leakage from forest carbon sequestration programs. Available at: http://economics.uwo.ca/econref/WorkingPapers/researchreports/wp2004/wp2004_3.pdf (last accessed 20.04.12).

Mészáros, C., 1999. The BPMPD interior point solver for convex quadratic problems. Optimization Methods and Software 11 & 12, 431–449.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.

Parks, J., Hardie, I.W., 1995. Least-cost forest carbon reserves: cost-effective subsidies to convert marginal agricultural land to forests. Land Economics 71 (1), 122–136.
Phelpsi, J., Webbi, E.L., Adams, W.M., 2012. Biodiversity co-benefits of policies to reduce forest-carbon emissions. Nature Climate Change 2, 497–503.
Plugge, D., Baldauf, T., Köhl, M., 2012. The global climate change mitigation strategy REDD: monitoring costs and uncertainties jeopardize economic benefits. Climate Change, http://dx.doi.org/10.1007/s10584-012-0524-3.
Samuelson, P.A., 1952. Spatial price equilibrium and linear programming. American Economic Review 42 (3), 283–303.
Scott, J., Rajamani, L., 2012. Eu climate change unilateralism. European Journal of International Law 23 (2), 469–494.
Sohngen, B., Mendelsohn, R., 2005. An optimal control model of forest carbon sequestration. American Journal of Agricultural Economics 85 (2), 448–457.
Synapse, 2011. 2011 Carbon Dioxide Price Forecast. Synapse Energy Economics, Inc., Cambridge, MA, pp. 28, February 11, 2011 (amended August 10, 2011).
Thompson, L., Mosley-Thompson, E., Davis, M., Henderson, K., et al., 2002. Kilimanjaro ice core records: Evidence of holocene climate change in tropical Africa. Science 298 (5593), 589–593.
Turner, J.A., Buongiorno, J., Zhu, S., 2006. An economic model of international wood supply, forest stock, and forest area change. Scandinavian Journal of Forest Research 21, 73–86.
USDA-ERS, 2012. Real Projected Gross Domestic Product (GDP) Per Capita and Growth Rates of GDP Per Cap for Baseline Countries/Regions (in 2005 dollars) 2000–2030. Available at: http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx (last accessed 13.04.12).
van Kooten, G.C., Eagle, A.J., Manley, J., Smolak, T., 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environmental Science & Policy 7 (4), 239–251.
World Bank, 2011. State and Trends of the Carbon Market 2011. Environment Department, World Bank, Washington, DC, pp. 78.
Zickfeld, K., Arora, V.K., Gillett, N.P., 2012. Is the climate response to CO_2 emissions path dependent? Geophysical Research Letters 39, L05703.