OCEAN CARBON SINKS AND INTERNATIONAL CLIMATE POLICY

Katrin Rehdanz[a]*, Martina Jung*[b,c]*, Richard S.J. Tol*[a,d,e] *and Patrick Wetzel*[f,a]

[a] *Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany*

[b] *International Max Planck Research School of Earth System Modelling, Hamburg*

[c] *Hamburg Institute of International Economics, Germany*

[d] *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*

[e] *Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA, USA*

[f] *Max Planck Institute of Meteorology, Hamburg, Germany*

February 14, 2005

Working Paper FNU-60

Abstract

Terrestrial sinks have entered the Kyoto Protocol as offsets for carbon sequestration, but ocean sinks have escaped attention. Ocean sinks are as unexplored and uncertain as were the terrestrial sinks at the time of negotiation. It is not unlikely that certain countries will advocate the inclusion of ocean carbon sinks to reduce their emission reduction obligations. We use a simple model of the international market for carbon dioxide emissions to evaluate who would gain or loose from allowing for ocean carbon sinks. Our analysis is restricted to information on anthropogenic carbon sequestration within the exclusive economic zone of a country. Like the carbon sequestration of business as usual forest management activities, natural ocean carbon sequestration applies at zero costs. The total amount of anthropogenic ocean carbon sequestration is large, also in the exclusive economic zones. As a consequence, it substantially alters the costs of emission reduction for most countries. Countries such as Australia, Denmark, France, Iceland, New Zealand, Norway and Portugal would gain substantially, and a large number of countries would benefit too. Current net exporters of carbon permits, particularly Russia, would gain less and oppose the inclusion of carbon sinks.

Keywords

carbon dioxide emission reduction, emission permit trade, exclusive economic zones, ocean sinks

JEL Classification

Q540, Q580

1. Introduction

There are two options for limiting the increase of carbon dioxide concentrations in the atmosphere: emission reduction, and sink enhancement. In the Kyoto Protocol, Annex B countries agreed on emission reduction targets. However, terrestrial sinks have entered the Kyoto Protocol as offsets for carbon sequestration. The negotiations on "land use, land use change and forestry" (LULUCF) were among the most complicated and contentious. Some countries have exploited the uncertainties to renegotiate their earlier emission reduction targets through the back door.

Besides terrestrial sinks, there are also ocean sinks.[1] Ocean sinks have escaped attention, although marine carbon flows are large and the science is as uncertain and complex as for terrestrial sinks. One can therefore expect that, sooner or later, a country will claim that the carbon sunk in its part of ocean, is sunk partly by deliberate intervention,[2] and that this should be used as an offset against its emissions targets. This paper explores the implications.

Most of the economic literature on carbon dioxide sinks is placed in the context of the Kyoto Protocol and relates to terrestrial carbon sequestration. Eligible activities under the Protocol are afforestation, reforestation, forest management, cropland management, grassland management and revegetation (UNFCCC, 1997).[3] A number of studies address the potential benefits of carbon sequestration in the land use sector and their related costs.[4] Others deal with the issue of non-permanence of carbon sequestration in the terrestrial biosphere and its environmental, as well as policy and economic implications (e.g. IPCC, 2000; Chomitz, 2000; Dutschke, 2002; Ellis, 2001; Fearnside, 2000; Jung, forthcoming; Kirschbaum, 2003; Missfeldt and Haites, 2001; Moura-Costa and Wilson, 2000; Noble and Scholes, 2001).

Marchetti (1977), Parson and Keith (1998), IEA (2001), and Gielen (2003) study the potential contribution of geological and ocean carbon storage. Technologies for geological storage are available and first projects have been initiated (Gale, 2003; Holloway, forthcoming). For ocean storage, there are two approaches: injecting captured CO_2 into the deep ocean, and fertilizing the ocean with nutrients to increase the draw-down of CO_2 from the atmosphere (IEA, 2002).

Riahi *et al.* (2004) analyze the competitiveness of such technologies relative to other mitigation and abatement options. Ha-Duong and Keith (2003) and Herzog *et al.* (2003) look at the implications of temporary carbon storage. Edenhofer *et al.* (2004) and Reiner and Herzog (2004) study the political and regulatory obstacles.

Proponents of carbon capture and storage technologies claim that it is an option for buying time while preparation for emission reductions are made (IEA, 2002). However, cost estimates vary widely with capture technology, transport distance and medium as well as storage reservoir and depth chosen. There are profitable options as in the case of enhanced oil recovery (EOR) and options costing up to € 100 per tCO2 (see e.g. David and Herzog, 2001; Hendriks *et al.,* 2001 and 2004). Also, carbon storage bears new environmental risks which are currently not well understood. Carbon might not be permanently stored and rapid or slow releases of injected emissions could occur. This might not only have impacts on the environment, ecosystems or human health, but also on the effectiveness of temporary carbon

---

[1] Note that there is carbon capture and storage as well. However, this is to be accounted for as emission reduction and not as removal activities, since the emissions never enter the atmosphere.

[2] Ocean fertilization is the most discussed deliberate intervention. However, in the LULUCF negotiations, the interpretation of deliberate intervention was stretched considerably to include things that were neither deliberate nor interventions, like e.g. most forest management.

[3] See Article 3.3 and 3.4 of the Kyoto Protocol (UNFCCC, 1997). A specification of these articles can be found in the Marrakech Accords (UNFCCC, 2001a and b).

[4] For an overview see e.g. Richards and Stokes (2004).

storage (Baer, 2003; Herzog *et al*., 2003; Wilson *et al*., 2003; Smekens and van der Zwaan, 2004).

Apart from possible CO_2 injection and sequestration by e.g. iron fertilization, the ocean is also a natural sink of atmospheric CO_2. Almost 50% of the anthropogenic emissions are removed by ocean uptake and exchange fluxes with the terrestrial biosphere (Sabine *et al*., 2004). Terrestrial sinks are partly included in the first commitment period of the Kyoto Protocol. Countries can offset emissions by LULUCF activities. Some of the forestry activities, especially parts of forest management, will apply at zero cost, because they can be considered business as usual and will take place anyway.[5] The accounting of forest management was, therefore, limited by a country-specific cap (see Appendix Z of the Marrakech Accords; UNFCCC, 2001a). These caps reflect to a large extent a country's bargaining power during the negotiations.[6] Although the last few years have seen a growing interest in the potential of ocean carbon sinks to limit climate change, they have so far not seriously been considered in climate policy. Neither the natural sink of carbon, nor injection or fertilization are eligible options. A new round of negotiations is supposed to start in 2005. It will have to agree on emission reduction targets and relating rules and modalities for any commitment period beyond the year 2012. Ocean sinks are as unexplored and uncertain as was LULUCF in 1997. It is not unlikely that ocean sinks will be brought up in future negotiations, either as a way to complicate (and hence delay) negotiations, or as a way to offset nominal emission reduction targets.

Regarding ocean sinks and international climate policy, we analyze a counterfactual: What would have happened had the Kyoto Protocol allowed for ocean carbon sinks? The advantage of taking this case is that we do not compare two hypothetical cases (a second commitment period with and without ocean sinks) but rather one hypothetical and one real[7] case. We aim to investigate who would gain most from introducing ocean sinks (and is therefore likely to propose their use), who would gain modestly (and is therefore unlikely to oppose), and who would lose (and is therefore likely to oppose).

We apply data on anthropogenic carbon sequestration within the exclusive economic zone (EEZ) of a country. The EEZ is the maritime zone seawards of the terrestrial sea with an outer boundary to up to 200 nautical miles out of the terrestrial sea's baseline. According to the UN Convention on the Law of the Sea, within this zone the country has the sovereign right to explore and exploit, conserve and manage living and non-living resources in the water column and on the seafloor.[8] However, the overlap of national claims and extended jurisdictions has led to areas with disputed ownership and jurisdiction.

We are aware that it is unlikely that countries will be able to account for the entire natural ocean sink and use the anthropogenic (human-induced) CO_2 uptake within a countries' EEZ instead. Since factoring-out of human-induced uptake from natural uptake will be difficult, countries might try to account for a fraction of the total uptake. Thus, the total uptake serves as a maximum value that a country would want to argue for.

The paper is built up as follows. Section 2 reviews carbon sinks and sources, and maps one particular data set to the exclusive economic zones of countries. Section 3 presents a simple

---

[5] This is due to 'gross-net accounting' which does not consider sinks in the calculation of base year emissions (Article 3.7 Kyoto Protocol).

[6] Russia e.g. was able to double the amount of forest management cap during the negotiations at COP7 (Fry, 2002).

[7] Actually, the first commitment period of the Kyoto Protocol will only start in 2008, but its details are well-established.

[8] See http://www.un.org/Depts/los/index.htm.

model of the costs of emission reduction, with and without trade, and with and without offsets for carbon sinks. Section 4 shows and discusses the results. Section 5 concludes.

2. Ocean carbon sinks

Human activity (e.g. fossil fuel burning and land-use change) has led to higher atmospheric CO_2 concentration and will lead to global warming and other significant climatic changes over the next century and beyond. However, without the exchange fluxes with the terrestrial biosphere and the ocean uptake of anthropogenic emissions, the concentration would have been much higher. Yet, the potential for carbon storage differs widely with respect to place and time. According to Houghton (2002) and Rödenbeck *et al.* (2003) the Northern hemisphere land is mainly a sink, while the Southern hemisphere land regions are neutral with the tropical land regions taking up carbon.

The global sea-to-air fluxes of CO_2 are dominated by outgassing of CO_2 in upwelling regions in such as the equatorial Pacific and Atlantic and the Arabian Sea. High influx of CO_2 in the Southern Ocean and in the Northern high latitudes can be attributed to photosynthetic utilization of CO_2 in summer and, in some areas, to strong cooling and deep water formation (Takahashi *et al*., 2002).

The uptake of anthropogenic CO_2 is different to the actual flux of CO_2, as the preindustrial flux has to be subtracted. The difference is extremely difficult to measure. Therefore we use results from a model simulation by Wetzel *et al.* (forthcoming). In general, the uptake of anthropogenic CO_2 is high where ‘older’ waters, which have not been in contact with the atmosphere for a long time, are brought to the surface; such as in the Northern and Southern high latitudes and in the equatorial upwelling regions. Particularly in the subtropics, the oceanic CO_2 partial pressure follows the partial pressure of the atmosphere almost directly and the uptake is low.

Over the next decades, as CO_2 levels increase, the oceanic buffer capacity will decrease, and the ability of the ocean to absorb more CO_2 diminishes (Revelle and Suess, 1957). Also, because of climate feedbacks, coupled climate-ocean models suggest that the ocean uptake of anthropogenic CO_2 may become less efficient in the future (Matear and Hirst, 1999).

Wetzel *et al*. (forthcoming) use a state-of-the-art ocean/sea-ice general circulation model (MPI-OM) coupled on-line to a marine biogeochemistry model (HAMOCC5). The horizontal resolution of the model gradually varies between 20 km in the Arctic and about 350 km in the Tropics. The global anthropogenic air-to-sea CO_2 fluxes from the model were overlaid with the Maritime Claims and Boundaries Database (GMBD) to measure the carbon flux within a countries exclusive economic zone. The GMBD is a GIS based database offering detailed information on agreed, disputed and hypothetical boundaries for every coastal nation in the world. The derived information was then used to calculate the average annual amount of CO_2 flux for each country.[9] Table 1 displays the size of the exclusive economic zones and the amount of carbon dioxide flux (anthropogenic uptake) for all Annex I countries, for two cases: undisputed, disputed and hypothetical ownership, and undisputed only. For countries with disconnected exclusive economic zones, the numbers were added. Note that a negative sign indicates ocean carbon uptake.

---

[9] Information on the average carbon flux is based on monthly data for the period 1990 to 2003.

Table 1: Exclusive economic zones for Annex I countries (area in km^2) and carbon flux (tons CO_2 per year)

Country	Area (km^2)		Anthropogenic Carbon flux (000tons CO_2 per year)[+]	
	disputed*	undisputed**	disputed*	undisputed**
Australia	11,611,965	7,373,998	-344,289	-160,657
Austria	0	0	0	0
Belgium	895	895	-11	-11
Bulgaria	22,919	22,919	-293	-293
Canada	2,652,622	2,652,622	-55,571	-55,571
Croatia	23,853	23,853	-283	-283
Czech Republic	0	0	0	0
Denmark	60,799	60,799	-5	-5
Estonia	11,305	11,305	-1	-1
Finland	24,755	24,755	-8	-8
France	9,278,917	8,238,077	-169,809	-146,404
Germany	32,905	32,905	-92	-92
Greece	368,618	368,618	-5,336	-5,336
Hungary	0	0	0	0
Iceland	685,042	685,042	-43,471	-43,471
Ireland	0	0	0	0
Italy	384,011	383,798	-5,509	-5,506
Japan	3,650,657	3,363,201	-73,548	-66,186
Latvia	17,852	17,852	-2	-2
Lithuania	4,439	4,439	-1	-1
Luxembourg	0	0	0	0
Netherlands	50,268	50,268	-403	-403
New Zealand	9,975,448	6,279,266	-274,911	-140,493
Norway	5,597,875	1,815,290	-218,983	-70,541
Poland	19,434	19,434	10	10
Portugal	1,595,387	1,595,387	-35,676	-35,676
Romania	19,976	16,425	-244	-212
Russia	5,687,163	5,518,204	-57,191	-53,357
Slovakia	0	0	0	0
Slovenia	0	0	0	0
Spain	794,185	754,406	-16,128	-14,907
Sweden	72,492	72,492	21	21
Switzerland	0	0	0	0
Ukraine	97,595	93,900	-748	-716
UK	6,951,912	2,031,477	-174,891	-39,830
USA	10,640,119	10,597,638	-148,114	-147,602

Note: *Exclusive undisputed, disputed and hypothetical ownership; ** exclusive undisputed ownership; [+]Difference in flux between present and preindustrial times.

Source: Own calculation based on GMBD and Wetzel et al. (forthcoming).

If we would have included information on exclusive fishing zones, the areas for some countries would have been larger, with different values for the carbon flux. This applies mainly to the UK (2,526,338 km^2), Denmark (2,247,710 km^2) and Ireland (407,489 km^2).[10] Before the concept of the EEZ was established in the United Nations Convention of the Law of the Sea in 1982, most countries claimed exclusive fishing zones. In contrast to fishing zones, EEZ jurisdiction involves duties as well as rights (UNCLOS Part V). It is straightforward to turn fisheries zones into exclusive economic zones, extending fisheries rights to rights over mineral resources as well as, presumably, carbon dioxide.

3. The market

Above, we considered ocean carbon sinks. These have a value only if they can be used as an offset against emission reduction obligations. In this section, we introduce a simple model of the international market in carbon dioxide emission permits. This model allows to evaluate the implications of the inclusion of ocean carbon sinks on the costs of emission reduction and their distribution. It also allows us to evaluate who would win and loose from including ocean carbon sinks.

Let us consider a market for tradable emission reduction permits with *I* countries. Emission reduction costs *C* are quadratic. Each country solves the problem:

$$\text{(1a)} \quad \min_{R_i,P_i} C_i = \alpha_i R_i^2 Y_i + \pi P_i \text{ s.t. } R_i E_i + P_i \geq E_i - A_i$$

R is proportional emission reduction; *Y* is gross domestic product; *P* denotes the amount of emission permits bought or sold; π is the emission permit price; assuming a perfect market, all companies face the same price; *E* are the emissions; *A* are the allocated emission permits; that is, if a country emits more than has been allocated, $E>A$, it will have to reduce emissions or buy permits on the market; α is a parameter; country are indexed by *i*. If a country's allocation exceeds its emissions, $E<A$, the optimization problem is:

$$\text{(1b)} \quad \min_{R_j,P_j} C_j = \alpha_j R_j^2 Y_j - \pi R_j E_j + \pi P_j \text{ s.t. } P_j \geq E_j - A_j$$

We assume that the country sells its hot air $P=E-A$, and in addition reduces emissions by RE which it sells at the market for πRE. Fixing A, we in fact assume that countries with hot air do not have market power. Countries with hot air are indexed by *j*.

Countries without emission reduction targets are excluded from the market. Although such countries could supply emission permits through the Clean Development Mechanisms of the Kyoto Protocol, the transaction costs of this are high, so that the actual supply is likely to be limited.

The first order conditions of (1) are:

$$\text{(2a)} \quad \begin{array}{l} 2\alpha_i R_i Y_i - \lambda_i E_i = 0, i = 1,2,...,I \\ 2\alpha_j R_j Y_j - \pi E_i = 0, j = 1,2,...,J \end{array}$$

$$\text{(2b)} \quad \pi - \lambda_i = 0, i = 1,2,...,I$$

$$\text{(2c)} \quad \begin{array}{l} R_i E_i + P_i - E_i + A_i = 0, i = 1,2,...,I \\ P_j - E_j + A_j = 0, j = 1,2,...,J \end{array}$$

---

[10] The other countries are the Netherlands (66,730 km^2), Australia (30,223 km^2), Norway (2,735 km^2), the Russian Federation (2,735 km^2), France (82 km^2) and Italy (67 km^2).

where λ denotes the Lagrange multiplier. This is a system with 3(*I*+*J*) equations and 3(*I*+*J*)+1 unknowns, but we also have that aggregate supply must equal aggregate supply, that is

$$\text{(2d)} \qquad \sum_{i=1}^{I} P_i + \sum_{j=1}^{J} P_j - \sum_{j=1}^{J} R_j E_j = 0$$

which allows as to solve for the permit price π as well. (2) solves as:

$$\text{(3a)} \qquad \pi = \lambda_i = \frac{\sum_{i=1}^{I}(E_i - A_i) + \sum_{j=1}^{J}(E_j - A_j)}{\sum_{i=1}^{I} E_i^2 \big/ 2\alpha_i Y_i + \sum_{j=1}^{J} E_j^2 \big/ 2\alpha_j Y_j}$$

$$\text{(3b)} \qquad R_i = \frac{\pi E_i}{2\alpha_i Y_i}; R_j = \frac{\pi E_j}{2\alpha_j Y_j}$$

$$\text{(3c)} \qquad P_i = E_i - A_i - \frac{\pi E_i}{2\alpha_i Y_i} E_i; P_j = E_j - A_j$$

So, the permit price goes up if the emission reduction obligation increases or if the costs of emission reduction increase. All companies face the same marginal costs of emission reduction, and the trade-off between reducing emissions in-house and buying or selling permits is driven by the ratio of marginal emission reduction costs and the permit price. The modeled market behaves as expected. Note that the solution without the market in emission permits (P_i=0) is trivial.

Rehdanz and Tol (forthcoming) consider the special case *I*=2. Rehdanz and Tol (2004) expand the model to two periods, including dynamic permit allocation and banking and borrowing.

Following Tol (2003), we specify

$$\text{(4)} \qquad \alpha_i = 1.57 - 0.17\sqrt{\frac{E_i}{Y_i} - \min_i \frac{E_i}{Y_i}}$$

which states that countries that emit a lot of (little) carbon relative to their production, have low (high) emission reduction costs. This specification was calibrated to the literature review of Hourcade *et al.* (1996 and 2001). It gives emission reduction costs for each country in the world for which we have emissions and GDP data.

For the numerical illustration we collected data for the period 1990 to 2010. The year 2010 refers to the middle of the first commitment period. Data on emissions (measured in tons CO_2) and GDP (measured in constant 1995 US $) for 1990, 1995 and 2000 were taken from the World Resources Institute. The data for emissions and GDP were projected to 2005 and 2010 using information on the average annual percent change for the period 2001 to 2025 (IEA, 2004). Data on population was taken from the World Resources Institute for the whole period from 1990 to 2010. Emission reduction targets are those of the Kyoto Protocol.[11] Although ocean sinks are obviously not part of the first commitment period of the Kyoto Protocol, we use this hypothetical case because data are relatively sound and abatement targets known. We multiplied the average annual anthropogenic CO_2 sunk by three to account for the period 2008-2010. Data on allowable terrestrial sinks were taken from the UNFCCC (the so called Appendix Z of the Marrakech Accords; see UNFCCC, 2001a). This data refers

---

[11] See http://unfccc.int/resource/docs/convkp/kpeng.pdf.

to the allowable accounting of forest management towards the reduction targets and is given in tons of carbon per year.[12] To account for the maximum amount of emission reduction in the first commitment period the data was multiplied by three (and converted into tons of CO_2 per year). Both sinks used here are zero cost sinks.

4. Results

Based on the model described above and the emission reduction targets agreed to in the Kyoto Protocol, we calculated the emission reduction obligation for each Annex I country for the year 2010, the middle year of the first commitment period. Table 2 presents the costs of emission reduction for twelve different cases. We distinguish six cases, and analyze each with and without permit trade:

- I: no LULUCF and no ocean sinks
- II: no ocean sinks but LULUCF (country-caps under forest management)
- III: no LULUCF but ocean sinks for exclusive economic zones with undisputed ownership (ocean sinks are restricted to 10% of the anthropogenic uptake for the first commitment period)
- IV: no LULUCF but ocean sinks for exclusive economic zones with undisputed, disputed and hypothetical ownership (ocean sinks are restricted to 10% of the anthropogenic uptake for the first commitment period)
- V: no LULUCF but ocean sinks for exclusive economic and fishing zones with undisputed ownership (ocean sinks are restricted to 10% of the anthropogenic uptake for the first commitment period)
- VI: LULUCF and ocean sinks for exclusive economic zones with undisputed ownership (ocean sinks are restricted to 10% of the anthropogenic uptake for the first commitment period)

Without international permit trade, ocean carbon sinks would reduce costs, particularly in Australia, France, Iceland, New Zealand, Norway, and Portugal. This is true even if only 10% of all "anthropogenic" carbon is counted (scenario III). Australia and the UK sink substantial carbon in the disputed parts of their exclusive economic zone (scenario IV). Denmark and Ireland would benefit if fishing zones are included (scenario V). See Table 2.

The results confirm that international trade reduces the costs of emission reduction. If countries would be allowed to account for ocean carbon sinks, this would reduce total costs further. The effect of a 10% use of ocean carbon sinks within a country's undisputed exclusive economic zone (scenario III) is marked. Most permit selling countries would loose, while most buyers show significant gains. Gains are particularly pronounced for countries such as France, Iceland, New Zealand, Norway and Portugal, who become net exporters of carbon permits. If its disputed EEZ is counted, Australia would also become a carbon exporter. An increase in the percentage use of ocean carbon sinks (not displayed) would be especially beneficial for Australia, Canada, France, Japan, New Zealand, the UK and the US.

Most permit sellers would prefer to exclude ocean sinks, as they would sell less permits on the market and would gain less from emission permit trade. These losses are substantial, ranging from 18% (Latvia) to 43% (Hungary) in scenario III; Russia loses 21% of its revenues. As disputed EEZs and fishing zones are included, losses increase further. However, these

---

[12] LULUCF in Annex I countries is considered by deducing the country specific forest management caps from the respective emission reduction targets.

countries would still gain from exporting permits; ocean carbon sinks would make them gain less, but would not lead to net costs of greenhouse gas emission reduction.

Comparing scenario III to scenario II (ocean carbon sinks versus forest management under LULUCF), most permit buying countries are better off under the scenario II. Only Australia, France, Iceland, New Zealand, Norway and Portugal would prefer ocean sinks to terrestrial sinks. Compared to the LULUCF scenario with a total allowable reduction under forest management of 767 000 tCO_2 for Annex I countries, scenario III allows for a total maximum reduction of 296 000 tCO_2 only. Setting the percentage use of ocean carbon sinks to allow for a total reduction of 767 000 tCO_2 in scenario II, Canada, Greece, Italy and Spain would join the above group preferring ocean carbon sinks. Even if the anthropogenic carbon flux for all exclusive economic zones including zones with undisputed, disputed and hypothetical ownership (scenario IV) is used to reduce emission reduction obligations, the effect is the same. Cost savings are again large for example for Australia, Norway and New Zealand. If fisheries zones are included (scenario V), Denmark would also gain considerably from the inclusion of ocean sinks.

In scenario VI, we compare the hypothetical case where both terrestrial sinks (country-caps under forest management) and ocean carbon sinks (for exclusive economic zones with undisputed ownership, restricted to 10% of the anthropogenic uptake for the first commitment period) are allowed. The total allowable reduction for Annex I countries is further decreased to 1 073 000 tCO_2.The positive and negative effects for most countries would be more pronounced compared to scenarios II and III. Only a few countries would gain less (Iceland, New Zealand, Norway, Sweden and Switzerland).

Table 2: Emission reduction targets and costs of emission reduction for Annex I countries for different cases (in million US$)[13].
Countries with numbers in **bold** gain from the inclusion of (ocean) sinks, countries in italics *lose*.

Country	Reduction target (%) rel. to 1990	No Trade						Trade					
		No sinks and no LULUCF	LULUCF	Sinks (un-disputed, 10%)	Sinks (10%)	Sinks (undisp. EEZ and FZ, 10%)	LULUCF and sinks (undisp., 10%)	No sinks and no LULUCF	LULUCF	Sinks (un-disputed, 10%)	Sinks (10%)	Sinks (undisp. EEZ and FZ, 10%)	LULUCF and sinks (undisp., 10%)
		I	II	III	IV	V	VI	I	II	III	IV	V	VI
Australia	108	602	602	**165**	**0**	**164**	**165**	292	**167**	**114**	**-29**	**111**	**57**
Austria	87	358	**136**	358	358	358	**136**	58	**19**	**48**	**42**	**47**	**13**
Belgium	93	242	**235**	242	242	242	**235**	71	**38**	**59**	**51**	**57**	**26**
Bulgaria	92	0	0	0	0	0	0	-101	*-55*	*-80*	*-66*	*-77*	*-35*
Canada	94	616	**601**	**438**	**438**	**438**	**425**	306	**173**	**213**	**187**	**207**	**98**
Croatia	95	0	0	0	0	0	0	-5	*-2*	*-4*	*-3*	*-4*	*-1*
Czech Rep.	92	0	0	0	0	0	0	-108	*-52*	*-82*	*-66*	*-78*	*-32*
Denmark	79	136	**121**	136	136	**0**	**121**	29	**15**	**24**	**21**	**-37**	**10**
Estonia	92	0	0	0	0	0	0	-65	*-35*	*-52*	*-44*	*-50*	*-23*
Finland	100	56	**34**	56	56	56	**34**	24	**10**	**20**	**17**	**19**	**7**
France	100	452	**284**	**2**	**0**	**2**	**0**	144	**63**	**-1**	**-16**	**-1**	**-10**
Germany	79	272	**171**	**271**	**271**	**271**	**170**	176	**81**	**151**	**134**	**147**	**56**
Greece	125	20	**16**	**14**	**14**	**14**	**10**	19	**11**	**13**	**12**	**12**	**6**
Hungary	94	0	0	0	0	0	0	-7	-7	*-4*	*-3*	*-4*	*-4*
Iceland	110	1	1	**0**	**0**	**0**	**0**	0	0	**-36**	**-31**	**-35**	**-15**
Ireland	113	148	**135**	148	148	**47**	**135**	40	**21**	**33**	**29**	**17**	**14**
Italy	94	1,082	**1,041**	**1,048**	**1,048**	**1,048**	**1,008**	324	**176**	**265**	**230**	**257**	**116**
Japan	94	5,813	**1,738**	**5,105**	**5,029**	**5,105**	**1,361**	1,014	**295**	**785**	**673**	**761**	**175**
Latvia	92	0	0	0	0	0	0	-51	*-34*	*-42*	*-36*	*-41*	*-22*
Lithuania	92	0	0	0	0	0	0	-81	*-48*	*-66*	*-56*	*-64*	*-31*
Luxembourg	72	32	**29**	32	32	32	**29**	8	**4**	**6**	**6**	**6**	**3**
Netherlands	94	980	**976**	**976**	**976**	**964**	**972**	207	**113**	**171**	**148**	**165**	**75**
New Zealand	100	156	**106**	**0**	**0**	**0**	**0**	39	**17**	**-84**	**-168**	**-82**	**-38**

---

[13] Sinks are referring to ocean sinks only.

Norway	101	51	**7**	**0**	**0**	**0**	**0**	21	**4**	**-41**	**-141**	**-40**	**-22**
Poland	94	3	**0**	3	3	3	**0**	-65	*-26*	*-39*	*-26*	*-36*	*-11*
Portugal	127	75	**47**	**0**	**0**	**0**	**0**	34	**15**	**-1**	**0**	**-1**	**-2**
Romania	92	0	0	0	0	0	0	-197	*-116*	*-156*	*-131*	*-150*	*-74*
Russia	100	0	0	0	0	0	0	-3,692	*-2,036*	*-2,916*	*-2,419*	*-2,799*	*-1,301*
Slovakia	92	0	0	0	0	0	0	-61	*-40*	*-49*	*-41*	*-47*	*-26*
Slovenia	92	23	**0**	23	23	23	**0**	10	**-1**	**9**	**7**	**8**	**-1**
Spain	115	656	**523**	**574**	**567**	**574**	**450**	212	**105**	**165**	**143**	**160**	**66**
Sweden	104	4	**0**	4	4	4	**0**	3	**-9**	3	3	3	**-6**
Switzerland	92	53	**0**	53	53	53	**0**	12	**-3**	**10**	**9**	**10**	**-2**
Ukraine	100	0	0	0	0	0	0	-1,555	*-730*	*-1,208*	*-1,000*	*-1,159*	*-455*
UK	88	1,154	**1,087**	**964**	**446**	**749**	**903**	420	**227**	**318**	**181**	**269**	**140**
USA	93	14,165	**9,649**	**13,462**	**13,460**	**13,462**	**9,071**	5,316	**2,428**	**4,335**	**3,775**	**4,208**	**1,598**
Total	95	27,148	17,538	24,072	23,302	23,607	15,225	2,790	787	1,882	1,390	1,762	347

5. Discussion and conclusion

We analyze the implications of ocean carbon sinks on international climate policy. A number of conclusions emerge. First, anthropogenic ocean carbon sinks (rather, the difference between current and pre-industrial ocean carbon sinks) are significant, also in the exclusive economic zones, compared to the terrestrial carbon sinks claimed in the Marrakech Accords. Second, although global emission reduction costs of all countries are affected by the inclusion of ocean carbon sinks (a corollary of the first conclusion), a few countries would face considerably lower costs for meeting their emission reduction obligations. These countries are Australia, France, Iceland, New Zealand, Norway, Portugal and, perhaps, Denmark (if it were to claim its fisheries zone as an exclusive economic zone). These countries have large ocean areas. Third, these countries would gain more under a system of international trade in emission permits. Fourth, the losses for big carbon permit exporters (e.g. Russia) would be substantial (again, a corollary of the first conclusion).

Therefore, it seems fair to predict that, at some time during the international negotiations on the second, perhaps third commitment period, its rule and emission reduction obligations, one or more of the above-mentioned countries will propose that ocean carbon sinks can be used as an off-set against emission abatement obligations. A few countries would gain substantially, and a larger number of countries would gain less. Of course, there would be opposition to this proposal, coming from two sides. Net exporters of carbon permits in the situation without ocean carbon sinks would gain less, but they would still gain and their opposition to ocean carbon sinks would easily be classified as “the pot calling the kettle black”. Environmentalists would also protest. However, ocean carbon sinks are small compared to the terrestrial sinks included in the Marrakech Accords.

The analysis above is in many ways rudimentary, but the conclusions are robust nonetheless. The amount of carbon sunk in the ocean is uncertain, and so is the difference between the amount sunk at present and the amount sunk in pre-industrial times. However, we widely varied the ocean carbon sink in our scenarios, and the basic structure of the conclusions did not change. The details of the spatial distribution of ocean carbon sinks are very uncertain, too. We did not vary this, but most studies would agree with the basic spatial pattern used here. The costs of emission reductions are uncertain, but this uncertainty makes ocean carbon sinks more or less relevant. It changes the intensity with which countries would argue for inclusion of ocean carbon sinks, not the argument itself. Finally, we used the first commitment period to study the implications of ocean carbon sinks, rather than the second commitment period in which they may surface. However, countries’ roles are unlikely to change in the near future. The countries of the OECD are likely to remain the drivers behind emission reduction, the countries of Eastern Europe and the former Soviet Union are likely to continue to supply cheap emission reduction, and the countries with large swathes of ocean would continue to benefit from the inclusion of ocean carbon sinks. The political dynamics would change, if ocean carbon *sources* would count as well. Countries with substantial net outgassing of carbon dioxide in their exclusive economic zones, however, are in the tropics. These countries are unlikely to accept emission reduction obligations any time soon.

Therefore, we are reasonably confident in our prediction that ocean carbon sinks will be tabled at the international climate negotiations in the foreseeable future. Although it is certainly possible that there would be technical negotiations as contracted as those on LULUCF, ocean carbon sinks are much smaller and therefore less damaging to global emission abatement efforts.

Acknowledgements

We would like to thank General Dynamics Advanced Information Systems (Herndon, USA) and in particular Lorin Pruett for making their Global Marine Boundaries Database available to us. Martin Pratt directed us to this database. Jenny Behm, Heiko Hansen and André Krebber provided welcome help arranging the dataset. The CEC-DG Research's Fifth Framework Programme through the ORFOIS project (EVK3-CT-2001-20001) and the NOCES project (EVK2-CT-2001-00134), the International Max Planck Research School of Earth System Modelling, and the Michael Otto Foundation provided welcome financial support. All errors and opinions are ours.

References

Baer, P. (2003) An Issue of Scenarios: Carbon Sequestration as Investment and the Distribution of Risk, *Climatic Change* **59** 283-291.

Chomitz, K.M. (2000) Evaluating Carbon Offsets from Forestry and Energy Projects: How do they Compare? World Bank Working Paper 2357, June 2000, Washington D.C.

David, J. and Herzog, H. (2001) The cost of carbon capture. In: Williams, D.; Durie, B.; McMullan, P.; Paulson, C. and Smith, A. (Eds), GHGT-5: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies, 13-16 August 2000, Cairns, Australia.

Dutschke, M. (2002) Fractions of permanence – Squaring the cycle of sink carbon accounting. *Mitigation and Adaptation Strategies for Global Change* **7** (4) 381-402.

Edenhofer, O., Held, H. and Bauer, N. (2004) A Regulatory Framework for Carbon Capturing and Sequestration within the Post-Kyoto Process, Paper presented at the 7th International Conference on Greenhouse Gas Control Technologies, Vancouver BC, Canada, 5-9 September 2004.

Ellis, J. (2001) Forestry Projects: Permanence, Credit Accounting and Lifetime, IEA/OECD Information Paper COM/ENV/EPOC/IEA/SLT(2001)11.

Fearnside, Ph. M. (2000) Accounting for Time in Mitigating Global Warming through Land-use Change and Forestry, *Mitigation and Adaptation Strategies for Global Change* **5** (3) 239-270.

Fry, I. (2002) Twists and Turns in the Jungle: Exploring the Evolution of Land use, Land-use change and Forestry Decisions within the Kyoto Protocol, *RECIEL* **11** (2) 159-168.

Gale, J. (2003) Geological Storage of CO_2: What's Known, Where are the Gaps and What more Needs to be Done, Gale, J. and Kaya, Y. (Eds.), Greenhouse Gas Control Technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1-4 October 2002, Kyoto, Japan, Vol. 1, pp. 207-212.

Gielen, D. (2003) The Future Role of CO2 Capture and Storage: Results of the IEA-ETP Model, IEA/EET Working Paper EET/2003/04, Paris.

Ha-Duong, M. and Keith, D.W. (2003) Carbon Storage: The Economic Efficiency of Storing CO_2 in Leaky Reservoirs, *Clean Technologies and Environmental Policy* **5** 181-189.

Hendriks, C., Wildenborg, A.F.B., Blok, K., Floris, F. and Van Wees, J.D. (2001) Costs of Carbon Dioxide Removal by Underground Storage, in: Williams, D., Durie, B., McMullan, P., Paulson, C. and Smith, A. (Eds) GHGT-5: Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies, 13-16 August 2000, Cairns, Australia.

Hendriks, C., Graus, W. and Bergen, F. van (2004) Global carbon dioxide storage potential and costs, EEP-02001, Ecofys, Utrecht.

Herzog, H., Caldeira, K. and Reilly, J. (2003) An Issue of Performance: Assessing the Effectiveness of Temporary Carbon Storage, *Climatic Change* **59** 293-310.

Holloway, S. (forthcoming) Underground Sequestration of Carbon Dioxide – A Viable Greenhouse Gas Mitigation Option, *Energy*.

Houghton, R.A. (2002) Magnitude, distribution and causes of terrestrial carbon sinks and some implications for policy, *Climate Policy* **2** 71–88.

Hourcade, J.-C., Halsneas, K., Jaccard, M., Montgomery, W.D., Richels, R., Robinson, J., Shukla, P.R. and Sturm, P. (1996) A review of mitigation cost studies. In Bruce, J. Lee, H. and Haites, E. (Eds.) *Climate Change 1995: Economic and Social Dimensions of Climate Change – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, pp.297-366. Cambridge University Press, Cambridge.

Hourcade, J.-C., Shukla, P., Cifuentes, L., Davis, D., Edmonds, J., Fisher, B., Fortin, E., Golub, A., Hohmeyer, O., Krupnick, A., Kverndokk, S., Loulou, R., Richels, R., Segenovic, H., Yamaji, K. (2001) Global, regional, and national costs and ancillary benefits of mitigation. In Metz, B., Davidson, O., Swart, R. and Pan, J. (Eds.) *Climate Change 2001: Mitigation – Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* pp 499-559. Cambridge University Press, Cambridge.

IEA (2001) Putting Carbon back into the Ground, IEA Greenhouse Gas R&D Programme.

IEA (2002) Ocean Storage of CO_2, IEA Greenhouse Gas R&D Programme, 2^{nd} revised edition.

IEA (2004) International Energy Outlook 2004, Energy Information Administration, Washington, DC.

IPCC (2000) Land Use, Land-Use Change, and Forestry, Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken D.J. (Eds.), Special Report of the Intergovernmental Panel on Climate Change, Cambridge, UK.

Jung, M. (forthcoming) The Role of Forestry Projects in the Clean Development Mechanism, *Environmental Science & Policy.*

Kirschbaum, M.U.F. (2003) Can Trees buy Time? An Assessment of the Role of Vegetation Sinks as Part of the Global Carbon Cycle, *Climatic Change* **58** 47-71.

Marchetti, C. (1977) On Geoengineering and the CO_2 Problem, *Climatic Change* **1** 55-68.

Matear, R.J. and Hirst, A.C. (1999) Climate Change Feedbacks on Future Oceanic CO_2 Uptake, *Tellus* **51b** 722-733.

Missfeldt, F. and Haites, E. (2001) The Potential Contribution of Sinks to Meeting the Kyoto Protocol Commitments, *Environmental Science & Policy* **4** 269-292.

Moura-Costa, P.H. and Wilson, C. (2000) An Equivalence Factor between CO_2 avoided Emissions and Sequestration – Description and Applications in Forestry, *Mitigation and Adaptation Strategies for Global Change* **5** (1) 51-60.

Noble, I. and Scholes, R.J. (2001) Sinks and the Kyoto Protocol, *Climate Policy* **1** 5-25.

Parson, E.A. and Keith, D.W. (1998) Fossil Fuels Without CO_2 Emissions, *Science* **282** (November) 1053-1054.

Rehdanz, K. and Tol, R.S.J (forthcoming) Unilateral Regulation of Bilateral Trade in Greenhouse Gas Emission Permits, *Ecological Economics*.

Rehdanz, K. and Tol. R.S.J. (2004) On Multi-Period Allocation of Tradable Emission Permits, FNU-43, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Reiner, D.M. and Herzog, H.J. (2004) Developing a Set of Regulatory Analogs for Carbon Sequestration, *Energy* **29** 1561-1570.

Revelle, R. and Suess, H.E. (1957) Carbon Dioxide Exchange between Atmosphere and Ocean and the Question of an Increase of Atmospheric Carbon Dioxide During the Past Decades, *Tellus* **9** 18-27.

Riahi, K., Rubin, E.S., Taylor, M.R., Schrattenholzer, L. and Hounsell, D. (2004) Technological Learning for Carbon Capture and Sequestration Technologies, *Energy Economics* **26** 539-564.

Richards, K.R. and Stokes, C. (2004) A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research, *Climatic Change* **63** 1-48

Rödenbeck, C., Houweling, S., Gloor, M. and Heimann, M. (2003) CO_2 fluxes history 1982-2001 inferred from atmospheric data using a global inversion of atmospheric transport, *Atmospheric Chemistry and Physics* **3** 1919-1964.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.-H., Kozyr, A., Ono, T. and Rios, A.F. (2004) The Oceanic Sink for Antropogenic CO2, *Science* **305** (July) 367-371.

Smekens, K. and van der Zwaan, B. (2004) Environmental Externalities of Geological Sequestration Effects on Energy Scenarios, Nota die Lavoro 58, Fondazione Eni Enrico Mattei, Milano.

Takahashi, T., Sutherland, S.C., Sweeney, C., Poisson, A., Metzl, N., Tilbrook, B., Bates, N., Wanninkhof, R., Feely, R.A., Sabine, C., Olafsson, J. and Nojiri, Y (2002), Global Sea-air CO2 Flux based on Climatological Surface Ocean pCO_2, and Seasonal Biological and Temperature Effects, *Deep-Sea Research II* **49** 1601-1622.

UNFCCC (1997) Kyoto Protocol to the United Nations Framework Convention on Climate Change.

UNFCCC (2001a) Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001, FCCC/CP/2001/13/Add.1.

UNFCCC (2001b) Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001, FCCC/CP/2001/13/Add.2.

Wetzel, P., Winguth, A. and Maier-Reimer, E. (forthcoming) Sea-to-Air CO2 Flux from 1948 to 2003 - a Model Study, *Global Biogeochemical Cycles*.

Wilson, E.J., Johnson, T.L. and Keith, D.W. (2003) Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage, *Environmental Science and Technology* **37** (16) 3476-3483.

Working Papers
Research Unit Sustainability and Global Change
Hamburg University and Centre for Marine and Atmospheric Science

Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60** (submitted)

Schwoon, M. (2005), *Simulating The Adoption of Fuel Cell Vehicles*, **FNU-59**

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (submitted)

Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57** (submitted)

Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making,* **FNU-56** (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (submitted)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54** (submitted)

Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (submitted)

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50** (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (submitted)

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48** (submitted to *Mitigation and Adaptation Strategies for Global Change*)

Erdil, Erkan and Yetkiner, I. Hakan (2004), *A Panel Data Approach for Income-Health Causality,* **FNU-47**

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46** (submitted)

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND*,* **FNU-45** (submitted)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport,* **FNU-41** (forthcoming in *Water Resources Research*)

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg,***FNU-40** (submitted to *Coastline Reports*)

Rehdanz, K. and Maddison, D. (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (submitted)

Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO_2-abatement with socio-economic inertia and induced technological change*, **FNU-37** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism,* **FNU-36** (submitted to *Journal of Sustainable Tourism*)

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)

Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach,* **FNU-34** (submitted to *Climate Research*)

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods,* **FNU-33** (submitted to *Environmental Science and Policy*)

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study,* **FNU-31** (submitted to *Global Environmental Change*)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (submitted)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (submitted)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series,* Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (forthcoming in *Integrated Assessment*)

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)

Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, FNU-22 (*Desalination*, **163** (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**

Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics,* **52** 111-125)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (forthcoming in *Energy Policy*).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (submitted to *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists,* **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (forthcoming in *Climate Policy*).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (forthcoming in *Climatic Change*).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (submitted to *Environment and Development Economics*).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (forthcoming in *Ecological Economics*).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (forthcoming in *Resource and Energy Economics*).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted to *International Environmental Agreements*).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics,* **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).