The additional contribution of non-CO_2 mitigation in climate policy costs and efforts in Europe

Francesco Bosello
FEEM, CMCC and Milan University
Carlo Orecchia
FEEM and CMCC
Ramiro Parrado
FEEM and CMCC

DRAFT VERSION - Please do not CITE

Abstract

The use of CGE models to study the role and costs of mitigation in climate policy has provided a vast literature. However, most of the models used have analyzed mitigation policies considering emission reductions focused only on CO_2 emissions. Although CO_2 emissions stand for most of greenhouse gases (GHG) emissions, the contribution of mitigation efforts based on non-CO_2 emissions is still a field that should be explored. This paper investigates the role of non-CO_2 GHG in climate change mitigation in Europe. We develop a specific modelling framework extending the Intertemporal Computable Equilibrium System (ICES) model with non-CO_2 GHG as an additional mitigation alternative. To model and evaluate the general equilibrium responses to mitigation policies, we tied emissions to explicit endowment, input and output flows. ICES is a recursive-dynamic CGE model based on the Gtap database with detailed sectoral and regional information: on the supply side, the energy production is differentiated to include renewables and nuclear energy sources which offer more flexibility for mitigation policy analysis; the land endowment in each region is split into agro-ecological zones.

These modifications allow us to evaluate the additional contribution for mitigation of multi-gas emissions considering its impact on growth and output sectoral composition. We circumscribe the analysis considering a scenario in which European Union (EU) implements a climate policy until 2020. In particular, two sets of policy scenarios have been developed. In a first scenario, Europe is assumed to reduce only CO_2 emissions by 20% and 30% with respect to 1990 levels. In a second scenario, the same targets are imposed but considering a simultaneous mitigation of CO_2 and non-CO_2 GHG emissions. Results show that multi-gas mitigation options will slightly decrease GDP loss with respect to CO_2 only mitigation options for 2020 climate stabilization.

1 Introduction

Non-CO_2 GHG emissions such as methane and nitrous oxide play an important role in Earth's climate warming: they trap more heat within the atmosphere than CO_2 per unit weight and were responsible of approximately 30% of the anthropogenic greenhouse effect since preindustrial times can be attributed to these non-CO_2 greenhouse gases (Intergovernmental Panel for Climate Change [IPCC], 2001b).

According to latest IEA estimate (IEA 2013), in 2010 non-CO_2 emissions account for 17% of all GHG emissions. Thus, recently, a growing attention has been devoted to these gases. As a matter of fact, these emissions come from sectors not included in the European cap and trade system (the so-called European Trading System ETS). In 2008, the european climate energy package (European Commission, 2008) outlined a differentiated strategy defining commitments for Member States, covering areas like buildings, transport, agriculture, waste and industrial plants falling under the threshold for inclusion in the ETS. In 2009, the so-called Effort Sharing Decision (European Union, 2009) has established binding annual greenhouse gas emission targets for Member States for these emissions/sectors from 2013 untill 2020. Thus, the current situation is the following: on the one hand, GHG emissions from large-scale emitters, mostly in the industry and the energy sectors, are currentlycovered by the ETS. On the other hand, emissions from the transport, residential, and agricultural sectors are subject to national targets. These targets have been set on the basis of Member States relative wealth (measured by Gross Domestic Product per capita). They range from a 20% emissions reduction by 2020 (from 2005 levels) for the richest Member States to a 20% increase for the least wealthy one, Bulgaria. While the ETS received large attention and has been widely studied from an economic standpoint, the implications of the Effort Sharing Decision (ESD) have not been fully explored. An exception are the works of Capros et al. (2011) and Hglund-Isaksson et al. (2010) whose results have been used by the European Commission in the preparatory phase of the ESD.

In general, early economic literature on climate change mainly focused on carbon dioxide from industry and electricity given that it is the largest single source of greenhouse gases. The first analyses on non-CO_2 emissions only appeared at the end of the nineties with quantitative studies on the costs of reducing CH_4 and N_2O emissions (Reilly et al., 1999). Since then, a growing number of studies have focused on multigas mitigation options and costs.

Bosello et al. (2005) carefully reviewed the existing literature on cost efficiency and effectiveness of GHG mitigation policies in the agro-forestry sector, finding an overall number of 77 publications. Povellato et al. (2007) reviewed the methodological issues of relevant literature on cost-effectiveness of climate change policies. In 2006, a large model comparison study was conducted under Stanford University's Energy Modeling Forum (EMF-21; Weyant et al., 2006). The study devoted special attention to non-CO_2 GHGs and their findings showed that a multigas strategy can achieve the same climate goal at considerably lower costs than a CO_2-only strategy.

In the following years, a number of studies (McKinsey 2009, USEPA 2006 and Smith et al. 2007) provided bottom-up engineering-type marginal abatement cost estimates for agricultural and other land use sectors globally. These studies incorporate detailed information on specic abatement technologies but ignore market interactions, including competition for land and international commodity trade.

Recently, attention has been devoted to assess the linkages between land-based climate policies, development, and food security, with a particular emphasis on abatement opportunities and impacts in the agricultural sectors. Golub et al. (2010) analysed the effects of GHG policy mitigation on the livestock sector using the Gtap-AEZ-GHG model; they show that given higher emission intensities of livestock industries in many developing compared to developed countries and of ruminant meat compared to other livestock sectors, and given large differences in abatement costs across livestock sectors and regions, a global carbon tax, together with a sequestration subsidy in forestry, would hurt livestock production in developing countries particularly strongly, resulting in increased net imports to Sub-Saharan Africa and reduced exports from South America. Such a scenario, however, may not be very likely, given food security considerations in developing countries. Sparing developing (non-Annex 1) countries from the carbon tax would reduce those pressures, even though much of the reduced crop and livestock output in South America is found to be linked to reduced deforestation and increased re-forestation due to the sequestration subsidy. In another paper Golub et al. (2012) also evaluate the impacts of climate policies on livelihoods and food consumption in developing countries: they find out that due to the strong rise in farm prices a multigas mitigation policy determines a fall in food consumption among unskilled labor and on the contrast,a sharp rise in real incomes of representative farm households.

Many different methodological approaches are available and have been used to study the costs of climate policy mitigation. A possible way to synthesize this heterogeneity is provided by Vermont and De Cara (2010). They reviewed the existing literature on the costs of mitigation in agriculture and identified three modelling approaches: first, studies on the supply side using microeconomic models (De Cara et al., 2005; Hediger, 2006); they incorporate a detailed description of the technical and economic constraints that define the feasible production at farm level. Second, studies based on partial or general equilibrium models (Golub et al, 2012) represent the influence of market responses (changes in input and output prices) on the marginal abatement costs; here the geographical coverage is usually wider, and the resolution is generally lower in these studies than in those models based on the supply side. Third, studies that use an engineering approach (Beach et al, 2008;. Hglund-Isaksson et al, 2010) provide detailed, bottom-up assessments of the carbon price needed to ignite the adoption of (a set of) available technologies, and the mitigation potential associated. These studies are able to better capture the impacts of the adoption of new technologies and / or investment in equipment eco-friendly. However, they ignore important market interactions such as competition compitition for land and international trade that are better treated in a macroeconomic framework.

The approach followed in this work pertains to the second category proposed by Vermont and De Cara. The adoption of a computable general equilibrium model with both built-in CO_2 and non-CO_2 endogenous dynamics to assess the costs of a multigas mitigation policy is quite new to the literature. This enables us to have a comprehensive and realistic analysis of multigas mitigation policy costs and opportunities and also provides additional information on potential distributional effects in terms of changes in the distribution of production, trade and consumption. Non-CO_2 emissions accounted in the present work include methane (CH_4), nitrous oxide (N_2O) and fourteen fluorinated gases (F-gases). While it is true that CO_2 is quantitatively the most important gas, non-CO_2 emissions still represent a significant share of global greenhouse gases emissions, namely 27% in 2010. Furthermore, focusing only on non-CO_2 GHG, large differences exist between developed and developing countries. While they constitute 17% and 20% of all greenhouse gases in the United States and in Europe, this share increases dramatically in Africa and in South East Asia regions where they represent 85% and 60% respectively. Additionally, the largest non-CO_2 emitting economic activities are the production of ruminant livestock (which generates enteric methane emissions as well as manure methane and nitrous oxide emissions) and fertilizers usage in the agricultural sectors (which generates nitrous oxide emissions). This does not consider indirect emissions due to the significant role of these sectors in deforestation related carbon emissions.

In fact, future climate policy implementation could produce important effects at different levels. For example, the imposition of a carbon tax in agriculture might have impacts on food consumption and on food security given that global demand for meat and dairy products is forecasted to increase by 30% in 2020 with respect to 2000 levels. Another crucial issue to be considered is the geographical distribution of non-CO_2 emissions. Large differences exist in terms of emissions per unit of output (emission intensity) between regions and sectors (Avetisyan, 2010). As we will explain later in the paper, emission intensities play a crucial role in defining the impact of a carbon tax in a given economy and its sectors. These considerations suggest that a multigas approach can, in principle, improve societal welfare by better internalizing the costs of climate change but that it can also have important distributional consequences that need to be addressed in advance.

Combining some of the issues raised above, this paper aims at a quantitative assessment of the extension of the European ETS to the non-CO_2 GHG, examining emission reduction efforts in line with the post Doha commitments. In particular, we want to answer the following questions: what happens in terms of social welfare if the European Union include non-co_2 emissions in the emission trading system (ETS)? How, a multi-gas ETS might impact the sectoral composition of output? We restrict our analysis to the EU running two sets of policy scenarios where Europe is assumed to reduce only CO_2 emissions and a multigas mitigation by 20% and 30% with respect to 1990 emissions levels. The rest of the paper is organized as follows. Section 2 presents the ICES model and most notable features of this updated version. Section 3 explains the modelization of non-CO_2 GHG. Policy scenarios and results are detailed in section 4. Section 5 concludes.

2 The updated ICES model

The analysis throughout the paper is carried out with the Intertemporal Computable Equilibrium System (ICES) model. Originally developed to study the effects of international trade policies and, to a lesser extent, public policies, computable general equilibrium (CGE) models are increasingly used to assess costs and benefits associated with climate change impacts. The appeal of such tools is the explicit modeling of market interactions between sectors and regions (inter industry and international trade flows are accounted for by databases relying upon input output Social Accounting Matrices). This allows tracing adjustment mechanisms in the whole economic system triggered by a shock concerning initially just one part of it (region or sector).

The base model is a recursive-dynamic CGE based on the Gtap 7 database, and incorporates several model and database improvements. The model solves recursively a sequence of static equilibria linked by endogenous investment determining the growth of capital stock from 2010 to 2050. Standard Gtap7 base year is 2004. In order to replicate exact historical trends, we calibrate the model to 2010 which becomes the reference starting point for the simulations. Variables used for re-calibration to 2010 were GDP and GHG emissions . The world is divided in 13 regions (see Table 1). Each region distinguishes 18 sectors with production of goods and services (see Table 2).

As in all CGE models, ICES makes use of the Walrasian perfect competition paradigm to simulate adjustment processes, although the inclusion of some elements of imperfect competition is also possible. Industries are modeled through a representative firm, minimizing costs while taking prices as given. In turn, output prices are given by average production costs. The production functions are specified via a series of nested CES functions. Domestic and foreign inputs are not perfect substitutes, according to the so-called Armington assumption.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labor, capital). Capital and labor are perfectly mobile domestically but immobile internationally. Land and natural resources, on the other hand, are industry-specific. This income is used to finance three classes of expenditure: aggregate household consumption, public consumption and savings. The expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification. Public consumption is split in a series of alternative consumption items, again according to a Cobb-Douglas specification. However, almost all expenditure is actually concentrated in one specific industry: non-market services. Private consumption is analogously split in a series of alternative composite Armington aggregates. However, the functional specification used at this level is the Constant Difference in Elasticities form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. Investment is internationally mobile: savings from all regions are pooled and then investment is allocated so as to achieve equality of expected rates of return to capital. In this way, savings and investments are equalized at the world, but not at the regional level. Because of accounting identities, any financial imbalance mirrors a trade deficit or surplus in each region.

Renewable energy sources (Hydro, Solar, Wind) are disentangled from the original all-inclusive Electricity sector, relying upon data from IEA, (2010) for energy volumes. Various other sources are used to calibrate production costs for each technology. For completeness sake Nuclear Energy production is also modelled. Renewable Energy Sources (Hydro, Solar, Wind) are stand-alone sectors providing electricity to the rest of the economic system. The intermittency of solar and wind is accounted for by a low substitution with other energy sources which limit their penetration over time in the energy mix. Biofuels are transformation sectors processing the output of the agricultural Other Crops sector and selling their output (biofuels) to the Services sector that includes retail sale of automotive fuels. Nuclear Energy is an alternative option for base-load energy, along with coal but with lower substitution between coal and other fossil fuels (oil, gas).

Moreover, following FAO and IIASA methodology, the world land endowment is split into 18 different agro ecological zones (AEZ). The AEZ database (Avetisyan et al. 2011) identifies crop, forest extent and production for each region by AEZ. The original data contains detailed information for 175 crops that were aggregated into the 8 GTAP crops definition. By embedding the AEZs approach in ICES, land is now assumed to be suitable to different uses within, but not between AEZ. This for instance implies that in a country crop switching is possible only across crops existing in each AEZ and that land elasticity of transformation in principle could differ across AEZ (Hertel et al. 2008, Michetti et al. 2012).

3 Modeling non-CO_2 GHG emissions and their mitigation potential

The model is updated with sectoral emissions from CO_2, CH4, N2O, PFCs, HFCs, and SF6 derived by Rose et al. (2010). This version updates to 2004 (Gtap7 base year) the original database developed for Gtap6 (Rose et al. 2007). Identifying emissions drivers as precisely as possible enables us to better evaluate the effects of multigas mitigation policies. To include non-CO_2 emissions in ICES we used the existing satellite GTAP dataset derived by Rose et al. (2010). This database distinguishes between three sources of non-CO_2 emissions: those related to input consumption (e.g. fertilizers usage in agriculture), those related to endowment consumption (e.g. land in rice cultivation) and those related to output production (e.g. wastewater treatment).

Consequently, in ICES the evolution of non-CO_2 emissions is modeled keeping the linkage of non-CO_2 emissions to these three sources: emissions coming from inputs usage evolve proportionally to the demand for this inputs; emissions coming from endowment or primary factor usage are linked to the evolution of consumption of these inputs; finally, emissions related to output are linked to output production.

As an example, nitrous oxide emissions from fertilizers use depend on the demand made by the agricultural sectors (i.e. Rice, Other Crops and Vegetables and fruits) for the sector that produce fertilizers (i.e. chemicals sector). Methane emissions that arise from the rice cultivation are tied to the demand for the land endowment. If the demand for these inputs/endowments increases the related nitrous oxide and methane emissions will increase as well.

In addition, as mentioned in the previous paragraph, we also used the AEZ database (Avetisyan et al. 2011) to allow for land heterogeneity: through this database we can divide the endowment land into different AEZ land types. Thus, along with the AEZ database, we are able to disaggregate non-co_2 emissions to a very detailed level in terms of sectors and endowments: 18 sectors and 10 land types. This modelization is quite unique and enables us to precisely relate the evolution of emissions to economic activities.

Data on emissions are presented in Table 2 and Table 3. Among regions, China accounts for the highest share of total non-CO_2 emissions (16.7%) in 2004, followed by Latin America (14.1%), USA (11.5%), Transitional Economies (11.0%) and Sub-saharan Africa (9.5%). Things change if we look only at CO_2: the biggest emitter is USA (22.3%) followed by China (19.4 %) and Western Europe (13.9%).

Finally, we complemented the analysis on non-CO_2 emissions introducing into the model the possibility of include non-CO_2 gases, along with the CO_2 energy related gases, in the mitigation policies. We applied the same methodology used in GTAP-E (Burniaux and Truong. 2002) for the taxation of energy inputs related emissions: in GTAP-E, carbon tax was calculated for each input as the ratio between tax revenues (i.e. nominal value of the carbon tax times the amount of the emission coming from the input usage) and the total tax base (i.e. the total value of the energy purchases).

For non-CO_2 emissions, however, we distinguish between three different sources of emissions. Thus, to better evaluate the effects of mitigation policies on economic activities, we introduce three different types of carbon tax: one for the use of inputs, one for the use of endowments and one for the output emissions.

Thus, carbon tax rates were calculated for each emitting input/endowment/output as the corresponding ratio between tax revenues and the total tax base. Then, this ad valorem tax was added up to the supply price and determined the market price that households and firms faced in the market. The tax revenues accrued to the representative consumer of each region and increased his income. The carbon tax formulation was extended to model an alternative Emission Trading Scheme (ETS), which allows the exchange of emissions permits among selected countries which choose to participate to a coordinated mitigation effort. For this case it is possible to set the regional quotas as well as the total ETS market quota to establish the carbon price of the traded emission permits.

Such modelization of the carbon tax implied that a change in the ad valorem tax rate could depend not only on the change in the size of the tax levied on associated emissions but also on the emissions intensity of the input/endowment/output used (i.e. total emissions from the use of the input in production divided by the amount of input used).

4 Policy scenarios and results

We developed a business as usual scenario (BAU) and four sets of policy scenarios (see Table 4). The policy results presented are calculated as difference with respect to the business as usual scenario. In particular, the bau scenario in 2020 is the result of the evolution of both endogenous and exogenous variables. Among the latter, we have: 1) Population (UNPD, 2010), 2) Energy efficiency (Bosetti et al. 2006), 3) Land productivity and 4) Labor productivity. The rest of the variables are endogenous; some of theme were calibrated to reproduce expected future trends on key variables: GDP growth rates and fossil fuels price trends are calibrated to the Witch model (Bosetti et al. 2006); these trends are constructed following a methodology developed in the Ampere project, a multi-model ensemble experiment involving the participation of four global integrated assessment models. Main variables of the bau scenario are reported in table 6.

In addition, we also developed a set of four policy scenarios. In all scenarios we assume that EU commits independently from other countries to reduce emissions. This is done considering a single cap on all greenhouse gases. We define two caps, a reduction of 20% and of 30% with respect to 1990 values. Within the same reduction cap (either -20% or -30%), we distinguish two abatement opportunities: CO_2 gases only and both CO_2 and non-CO_2 gases. In both cases, we limit the emissions imposing quotas within an ETS (Emission trading system). These quotas increase the price of polluting intermediate energy inputs (CO_2) and the price of polluting inputs/endowment/output goods (non-CO_2) purchased by firms, households and the government.

Results show that in terms of GDP, the cost of mitigation is slightly lower when we consider all greenhouse gas emissions: in the case of CO_2 only mitigation and for the -20% reduction target, the two European regions, Western Europe (WEURO) and Eastern Europe (EEURO), reduce GDP with respect to the baseline scenario by -0.28% and -0.88% respectively; in the case of all greenhouse gas emissions the indirect cost of the policy in terms of GDP loss is -0.25% and -0.87%. The price of carbon is lower when all greenhouse gas emissions are considered reducing the overall burden of the mitigation policy from \$ 18.8 per ton. of CO_2 to \$ 16.3 per ton. of CO_2.

Turning to the -30% reduction cap, in the case of CO_2 only mitigation, the two European regions, Western Europe (WEURO) and Eastern Europe (EEURO), reduce GDP with respect to the baseline scenario by -0.71% and -2.07% respectively; in the case of all greenhouse gas emissions the indirect cost of the policy in terms of GDP loss is -0.62% and -2.05%. The price of carbon is lower when all greenhouse gas emissions are considered reducing the overall burden of the mitigation policy from \$ 49.1 per ton. of CO_2 to \$ 41.4 per ton. of CO_2.

For what regards changes of emissions, we can capture two important effects. First, there is some reduction also in the agricultural and livestock sector also in the case of CO_2 only taxation. Spillover effects between gases are very important as they show that the actual reduction in GHG is not just the one achieved with the set cut in the GHG targeted but that there are synergies between the gases that need to be taken into account when designing policies.

A second important aspect that we are able to see in our results, is that of gases substitution: taxing all greenhouse gases induce both regions to substitute CO_2 with non-CO_2 emissions (see Table 6).

Finally, important differences there are also in terms of sectoral output composition. For ease of interpration we now consider only the cap of -30% reduction with respect to 1990 values. In both regions the mitigation policies penalize the sector responsible of emissions, i.e. the energy sectors. However, the sectors responsible of non-CO_2 emissions reduce their output more than in the scenario with CO_2 only. Focusing on the results for the -30% reduction cap, we see that 'Other crops' goes from -0.6% to -0.8% in WEURO and from -1.6% to -2.1% in EEURO in 2020. This acts in favor of the CO_2 polluting energy sectors where the multigas mitigation scenario offers lower reductions with respect to baseline; output loss in the coal, oil and Gas sectors in WEURO goes from 40.8% to 42.1%, from 8% to 7% and from 27.1% to 26.3% respectively.

At the same time, under the scenario that tax all greenhouse gases the positive effect on the renewable energy sectors (Solar and Wind in particular) is weaker than in the scenario where only the CO_2 emissions are taxed: in the solar energy the increase with respect to the baseline scenario goes from 23.1% to 20.8% while in the wind sector it goes down from 13.0% to 11.0% in WEURO.

5 Conclusions

We modified the ICES model framework to include multigas emissions of GHG using the existing satellite GTAP dataset derived by Rose et al. (2010). This database distinguishes between three sources of non-CO_2 emissions: those related to input consumption (e.g. fertilizers usage in agriculture), those related to endowment consumption (e.g. land in rice cultivation) and those related to output production (e.g. wastewater treatment). In this new setting different simulations address the problem of climate policies.

Results show that policies targeting CO_2 also lead to a reduction in the other GHG included in the model. However, multigas policies show that when obtaining reduction in GHG by cutting non-CO2 emissions, it is possible to reduce the GDP loss and therefore to achieve emission targets in a less costly manner.

References

[1] Avetisyan, M., A. Golub, T. Hertel and S. Rose. (2010), ""Why a Global Carbon Policy could have a dramatic impact on the pattern of worldwide livestock productio". Draft manuscript, Center for Global Trade Analysis. Purdue University, West Lafayette, IN.

[2] Böhringer, C., Fisher, C. and K.E. Rosendahl (2010), The global effects of subglobal climate policies, Resources for the Future Discussion Paper 10-48.

[3] Böhringer C., Rutherford T. and Tol R., (2009), The EU 20/20/20 targets: an Overview of the EMF22 Bosello, F., Lazzarin, M., Roson, R. and R.S.J. Tol (2007), Economy-wide estimates of climate change implications: sea-level rise, Environment and Development Economics, 37:549571.

[4] Bosello, F., Roson, R. and R.S.J. Tol (2006), Economy wide estimates of the implications of climate change: human health Ecological Economics, 58, 579-591.

[5] Bosello, F., Buchner, B., Crimi J., Giupponi C., Piovesan F. and Povellato A. (2005), Cost efficiency and effectiveness of GHG mitigation policies and measures in the agro-forestry sector: a survey of the economic literature MEACAP WP2 D6. Feem, Milan, Italy.

[6] Burniaux, J.-M., Truong, T.P., (2002), GTAP-E - an energy-environmental version of the GTAP model. GTAP Technical Papers, No. 16. Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana, USA 47907-1145.

[7] Calzadilla, A., Rehdanz, K., Tol, R. (2008), The Economic Impact of More Sustainable Water Use in Agriculture: A CGE Analysis. Research Unit Sustainability and Global Change, FNU-169. Hamburg University.

[8] Capros, P., Mantzos, L., Parousos, L., Tasios, N., Klaassen, G., Van Ierland, T., (2011), Analysis of the EU policy package on climate change and renewables. Energy Policy 39 (3), 14761485.

[9] Ciscar, J.-., A. Iglesias, L. Feyen, L. Szab, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, R. Dankers, L. Garrote, C.M. Goodess, A. Hunt, A. Moreno, J. Richards, and A. Soria, (2011), Physical and economic consequences of climate change in europe. Proceedings of the National Academy of Sciences of the United States of America, 108(7), 2678-2683.

[10] Darwin, R. F. and Tol, R. S. J. (2001), Estimates of the Economic Effects of Sea Level Rise, Environmental and Resource Economics, 19, 113-129.

[11] De Cara, S., Houz, M., Jayet, P.-A., (2005), Methane and nitrous oxide emissions from agriculture in the EU: a spatial assessment of sources and abatement costs. Environmental and Resource Economics 32 (4), 551583.

[12] Deke, O., Hooss, K. G., Kasten, C., Klepper, G., Springer, K. (2002) Economic Impact of Climate Change: Simulations with a Regionalized Climate-Economy Model. Kiel Institute of World Economics, Kiel, 1065.

[13] Eboli, F., Parrado, R. and R. Roson (2009), Climate Change Feedback on Economic Growth: Explorations with a Dynamic General Equilibrium Model. FEEM Note di Lavoro 2009.043.

[14] European Commission, (2008) 20 20 by 2020: Europe's climate change opportunity. Communication COM(2008) 30 nal. Commission of the European Communities, Brussels, Belgium.

[15] European Union, (2009), Decision on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Decision of the European Parliament and the Council of the European Union 406/2009/EC, Ofcial Journal of the European Union, Brussels, Belgium, L140, pp. 136138.

[16] Golub, Alla., Thomas Hertel, Huey-Lin Lee, Steven Rose, Brent Sohngen (2009), The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry, Resource and Energy Economics 31 pp 299-319.

[17] Golub, Alla., B. Henderson, T. Hertel, S. Rose, M. Avetisyan, B. Sohngen (2010), Effects of GHG Mitigation Policies on Livestock Sectors, GTAP Working Paper No.62.

[18] Golub A A, Henderson B B, Hertel T W, Gerber P J, Rose S K and Sohngen B (2012), Global climate policy impacts on livestock, land use, livelihoods, and food security Proc. Natl Acad. Sci. at press (doi:10.1073/pnas.1108772109).

[19] Höglund-Isaksson, L., Winiwarter, W., Wagner, F., Klimont, Z., Amann, M., (2010), Potentials and costs for mitigation of non-CO_2 greenhouse gas emissions in the European Union until 2030. Results. Report to the European Commission, DG Climate Action Contract No. 537 07.030700/2009/545854/SER/C5. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

[20] Hediger, W., (2006), Modeling GHG emissions and carbon sequestration in Swiss agriculture: an integrated economic approach. Greenhouse Gases and Animal Agriculture: An Update. Proceedings of the 2nd International Conference on Greenhouse Gases and Animal Agriculture (Zurich, Switzerland): International Congress Series, 1293, pp. 8695.

[21] Hertel T.W., Lee H., Rose S., Sohngen B., Hertel T.W.,Rose S.,Tol R. (2008), Economic Analysis of Land Use in Global Climate Change Policy, Modeling Land-use Related Greenhouse Gas Sources and Sinks and their Mitigation Potential (Oxford University Press, UK) Forthcoming, Chapter 6 In, eds.

[22] Michetti M., Parrado R. (2012), ”Improving Land-use modelling within CGE to assess Forest-based Mitigation Potential and Costs. Feem Note di Lavoro 2012.019.

[23] Narayanan, G.B. and T.L. Walmsley, Eds. 2008. Global Trade, Assistance, and Production: The GTAP 7 Data Base, Center for Global Trade Analysis, Purdue University.

[24] Povellato A., Bosello F. and Giupponi C. (2007) Cost-effectiveness of GHG mitigation measures in the european agro-forestry sector: a literature survey. Environmental Science & Policy 10 (5), 474-490.

[25] Ronneberger, K., Berrittella, M., Bosello, F. and R.S.J. Tol (2009), KLUM@GTAP: introducing biophysical aspects of land use decisions into a general equilibrium model. A coupling experiment, Environmental Modelling and Assessment, Vol. 14, n. 2.

[26] Rose, S., Finn, S., Scheele, E., Mangino, J., Delhotal, K., (2007), Detailed greenhouse gas emissions data for global economic modeling. US Environmental Protection Agency, Washington, DC.

[27] Rose, S.K., Avetisyan, M., and Hertel, T. W (2010), Development of the Preliminary Version 7 Non-CO_2 GHG Emissions Dataset, GTAP Research Memorandum No. 17.

[28] Rose SK, et al. (2012), Land-based mitigation in climate stabilization. Energy Econ 34: 365380

Appendix

Code	Region in the model	GTAP regions	Group
USA	United States of America	United States Rest of North America,	Annex I and II
WEURO	Western Europe	Austria, Belgium, Denmark, Greece, Ireland Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom	Annex I and II
EEURO	Eastern Europe	Bulgaria, Cyprus, Czech Republic, Estonia, Lithuania, Poland, Malta, Hungary, Latvia, Romania, Slovakia, Slovenia	Annex I and II
KOSAU	Korea, South Africa Australia	Korea, South Africa, Australia	Non-Annex I
CAJANZ	Canada, Japan New Zeland	Canada, Japan New Zeland	Annex I and II
CHINA	China	China	Non-Annex I
INDIA	India	India	Non-Annex I
EASIA	Rest of South East Asia	Cambodia, Indonesia, Singapore, Thailand, VietNam, Philippines, Lao, Rest of Southeast Asia, Rest of Oceania, Rest of East Asia,	Non-Annex I

LACA	Latin America	Mexico, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay Perú, Uruguay Venezuela, Costa rica, Guatemala, Nicaragua, Panama Rest of Central America, Caribbean, Rest of South America	Non-Annex I
TE	Transitional Economies	Albania, Belarus, Croatia, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Turkey	Non-Annex I
MENA	Meaddle East and North Africa	Iran, Egypt, Rest of Western Asia Morocco, Tunisia, Rest of North Africa	Non-Annex I
SSA	Sub-saharan Africa	Nigeria, Senegal Rest of Western Africa Rest of Central Africa Rest of South Central Africa Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe Rest of Eastern Africa, Botswana, Rest of South African Customs Union	Non-Annex I
SASIA	South Asia	Bangladesh, Pakistan Sri Lanka, Rest of South Asia	Non-Annex I

Table 1: Regional detail of the ICES model.

Table 2: Sectoral aggregation

Sectors		
Agriculture/Land Use	***Energy***	***Others***
Rice	Coal	Heavy Industry
Other Crops	Crude Oil	Light Industry
Vegetables & Fruits	Natural Gas	Services
Livestock	Petroleum Products	
Timber	Nuclear	
	Hydro	
	Solar	
	Wind	
	Other Electricity	
	Biofuels	

Table 3: Regional emissions in 2004, MtC

	CO2	%	N2O	%	CH4	%	Fgas	%	Non CO2	%	All GHG	%
USA	1744.1	22.3	106.4	13.1	146.7	9.1	42.4	29.8	295.4	11.5	2039.5	19.6
WEURO	1085.9	13.9	95.2	11.7	93.1	5.8	22.1	15.5	210.4	8.2	1296.3	12.5
EEURO	171.7	2.2	15.4	1.9	20.6	1.3	1.4	1.0	37.4	1.5	209.2	2.0
KOSAU	378.0	4.8	18.7	2.3	55.2	3.4	10.2	7.2	84.2	3.3	462.2	4.4
CAJANZ	584.1	7.5	25.8	3.2	39.4	2.4	16.6	11.7	81.8	3.2	665.9	6.4
TE	785.4	10.0	53.8	6.6	218.5	13.5	9.1	6.4	281.4	11.0	1066.8	10.3
MENA	471.5	6.0	34.4	4.2	95.7	5.9	2.7	1.9	132.8	5.2	604.3	5.8
SSA	46.9	0.6	85.9	10.6	156.6	9.7	0.7	0.5	243.3	9.5	290.2	2.8
SASIA	47.0	0.6	23.9	2.9	49.6	3.1	0.3	0.2	73.7	2.9	120.8	1.2
CHINA	1516.1	19.4	184.3	22.7	219.7	13.6	25.8	18.1	429.8	16.7	1945.9	18.7
INDIA	317.5	4.1	18.4	2.3	135.6	8.4	2.7	1.9	156.7	6.1	474.2	4.6
EASIA	283.7	3.6	32.1	3.9	145.7	9.0	2.2	1.5	180.0	7.0	463.7	4.5
LACA	402.7	5.1	118.5	14.6	237.7	14.7	6.1	4.3	362.3	14.1	765.0	7.4
Total	7834.7	100.0	813.0	100.0	1614.0	100.0	142.4	100.0	2569.3	100.0	10404.0	100.0

Table 4: The definition of the scenarios.

Name	**Description**
BL	Baseline
$20CO_2$	All GHG emissions reduction of 20% wrt 1990 values $\rightarrow$ Tax only on CO_2 emissions
$20all$	All GHG emissions reduction of 20% wrt 1990 values $\rightarrow$ Tax on all GHG emissions
$30CO_2$	All GHG emissions reduction of 30% wrt 1990 values $\rightarrow$ Tax only on CO_2 emissions
$30all$	All GHG emissions reduction of 30% wrt 1990 values $\rightarrow$ Tax on all GHG emissions

Table 5: Policy costs in 2020 (GDP loss wrt BAU)

	20co2	**20all**	**30co2**	**30all**
USA	0.0	0.0	0.1	0.1
WEURO	**-0.28**	**-0.25**	**-0.71**	**-0.62**
EEURO	**-0.88**	**-0.87**	**-2.07**	**-2.05**
KOSAU	0.0	0.0	0.1	0.1
CAJANZ	0.0	0.0	0.1	0.1
TE	-0.2	-0.2	-0.4	-0.3
MENA	0.0	0.0	-0.1	0.0
SSA	0.0	0.0	0.0	0.0
SASIA	0.0	0.0	0.1	0.1
CHINA	0.0	0.0	0.1	0.1
INDIA	0.1	0.1	0.1	0.1
EASIA	0.0	0.1	0.1	0.1
LACA	0.0	0.0	0.1	0.1

Table 6: Carbon price: \$ per tCO_2

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
20co2	1.1	2.2	3.6	5.1	6.9	8.8	11.0	13.3	16.0	18.8
20all	1.0	2.0	3.2	4.6	6.1	7.8	9.7	11.7	13.9	16.3
30co2	2.3	5.0	8.1	11.8	16.1	21.0	26.7	33.2	40.6	49.1
30all	2.1	4.5	7.3	10.5	14.2	18.4	23.1	28.5	34.6	41.4

Table 7: CO_2 emissions reductions wrt BAU in 2020

	20co2	**20all**	**30co2**	**30all**
USA	0.1	0.1	0.2	0.2
WEURO	**-9.8**	**-9.0**	**-19.7**	**-17.9**
EEURO	**-21.1**	**-20.1**	**-35.9**	**-34.3**
KOSAU	0.2	0.2	0.4	0.4
CAJANZ	0.1	0.1	0.3	0.3
TE	0.2	0.2	0.4	0.4
MENA	0.1	0.1	0.2	0.2
SSA	0.1	0.1	0.1	0.1
SASIA	0.1	0.1	0.2	0.2
CHINA	0.1	0.1	0.3	0.3
INDIA	0.1	0.1	0.3	0.3
EASIA	0.1	0.1	0.2	0.3
LACA	0.1	0.1	0.3	0.3

Table 8: Non-CO_2 emissions reductions wrt BAU in 2020

	20co2	**20all**	**30co2**	**30all**
USA	0.0	0.1	0.0	0.1
WEURO	**-1.1**	**-3.8**	**-2.2**	**-7.8**
EEURO	**-4.7**	**-9.3**	**-8.2**	**-16.2**
KOSAU	-0.2	0.0	-0.4	0.2
CAJANZ	0.0	0.1	0.1	0.2
TE	-0.3	-0.2	-0.5	-0.3
MENA	0.0	0.1	-0.1	0.1
SSA	0.0	0.1	0.0	0.2
SASIA	0.0	0.1	0.1	0.2
CHINA	0.0	0.1	0.1	0.2
INDIA	0.1	0.1	0.1	0.2
EASIA	0.0	0.1	0.1	0.2
LACA	0.0	0.1	0.0	0.2

Table 9: WEURO sectoral output: % differences wrt BAU in 2020

Sector	**20co2**	**20all**	**30co2**	**30all**
Rice	-0.3	-0.2	-0.7	-0.5
Other Crops	-0.2	-0.2	-0.5	-0.6
Vegetable & Fruits	-0.1	0.0	-0.1	-0.1
Livestock	-0.2	-1.2	-0.4	-2.8
Timber	-0.1	0.0	-0.2	-0.1
Coal	-24.5	-24.0	-42.0	-42.3
Crude Oil	-3.1	-2.7	-7.7	-6.6
Natural Gas	-12.2	-12.0	-26.0	-25.5
Petr. Prod.	-3.8	-3.3	-9.4	-8.1
Biofuels	-0.6	-0.5	-1.6	-1.4
Nuclear	2.1	2.1	4.5	4.4
Solar	10.1	9.3	23.4	21.1
Wind	5.7	5.2	13.5	12.1
Hydro	5.1	5.1	8.5	8.4
Other Electricity	-2.1	-1.9	-4.5	-4.0
Heavy Industry	-0.4	-0.3	-0.8	-0.7
Light Industry	-0.2	-0.3	-0.4	-0.8
Services	-0.2	-0.1	-0.4	-0.3

Table 10: EEURO sectoral output: % differences wrt BAU in 2020

Sector	**20co2**	**20all**	**30co2**	**30all**
Rice	-1.3	-1.3	-3.1	-3.1
Other Crops	-0.4	-0.5	-0.8	-1.1
Vegetable & Fruits	-0.5	-0.5	-1.3	-1.3
Livestock	-0.5	-1.1	-1.0	-2.3
Timber	-0.5	-0.4	-1.3	-1.1
Coal	-30.7	-32.3	-49.2	-52.6
Crude Oil	-10.0	-9.3	-22.8	-21.2
Natural Gas	-18.5	-23.8	-37.6	-46.5
Petr. Prod.	-8.6	-7.8	-19.6	-17.6
Biofuels	-0.9	-1.0	-2.6	-2.6
Nuclear	2.1	2.1	4.5	4.4
Solar	17.7	17.1	37.9	36.3
Wind	15.6	14.9	33.7	31.9
Hydro	4.1	4.1	6.5	6.4
Other Electricity	-7.4	-7.0	-14.0	-13.2
Heavy Industry	-1.8	-1.6	-4.7	-4.3
Light Industry	-0.3	-0.4	-0.6	-0.8
Services	-0.5	-0.4	-0.8	-0.8