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# EU MITIGATION, REDD AND THE CARBON MARKET: A GENERAL EQUILIBRIUM ASSESSMENT

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**SUMMARY** Deforestation is a major source of CO2 emissions, accounting for around 17% of total annual anthropogenic carbon release. While the costs estimates of reducing deforestation rates considerably vary depending on model assumptions, it is widely accepted that emissions reductions from avoided deforestation consist of a relatively low cost mitigation option. Halting deforestation is therefore not only a major ecological challenge, but also a great opportunity to cost effectively reduce climate change negative impacts. In this paper we analyze the impact of introducing avoided deforestation credits into the European carbon market in the context of a EU policy aiming to reducing EU CO2 emissions by 20% wrt 1990 in 2020 using a multiregional Computable General Equilibrium model. Taking into account political concerns over a possible "flooding" of REDD credits, various limits to the number of REDD allowances entering the carbon market are considered. Finally, unlike previous studies, we account for both direct and indirect effects occurring on land, crops' and timber markets resulting from lower deforestation rates. We conclude that allowing REDD credits trade is effective in reducing deforestation activities, has only moderate effects on land and timber markets and negligible effects on food prices. Moreover, it notably reduces climate change policy costs - approximately by 80% with unlimited availbility of REDD credits - and may drastically reduce carbon prices. Policy makers may, however, effectively control for this last effect tuning the supplementarity of avoided deforestation credits use. Finally, avoided deforestation has the additional positive effect of reducing carbon leakage of an unilateral European climate change policy. This is good news for the EU, but not necessarily for REDD regions. Indeed we show that REDD revenues are not sufficient to compensate REDD regions for a less leakage-affected and more competitive EU in international markets. In fact, REDD regions would prefer to free ride on the EU unilateral mitigation policy.

**Keywords:** Human Capital, Education, Health, Root cause of development, 'Quality' dimension in population analysis

**JEL:** I18, I28

# 1 Introduction

Tropical deforestation is a major source of $CO_2$ emissions and the main cause of biodiversity loss. According to the 2007 Fourth IPPC report, deforestation accounts for around 17% of total annual atmospheric carbon release (IPCC 2007). Given the rising concern of potential dangerous risks accruing from high level of atmospheric greenhouse gases (GHGs) concentrations, a large number of economic studies have already analyzed the potential for and costs of emission reduction through avoided deforestation. Estimates vary considerably depending on modelling assumptions, however it is widely accepted that avoided deforestation can offer large mitigation opportunities at a relatively low cost. This result is particularly robust as confirmed by studies conducted with different methodologies.

Thus for instance, Kindermann et al (2008) comparing the results from three different global forestry and land-use models show that a carbon price of 100$ per ton of $CO_2$ could abate 2.8-4.7 of Gt of $CO_2$ from deforestation activities during the period 2005–2030, representing more or less 10% of total 2004 $CO_2$ emissions as reported by IPCC 2007. According to their analysis, the lowest-cost avoided deforestation opportunities are to be found in Africa, Central and South America and Southeast Asia.

Similar findings come from a branch of literature which “couples” forestry models with more economic oriented integrated assessment models in the attempt to nest forestry dynamics into a more realistic representation of the economic system. In this vein Sohngen and Mendelsohn, (2003) linked a global forestry model with the DICE model of Nordhaus and Boyer (2000) and suggest that forestry could cost effectively account for 30% of total carbon abatement across the century. Tavoni et al. (2007) used the World Induced Technological Change Hybrid model (WITCH) to analyse the impacts of introducing forestry mitigation opportunities on the costs of meeting a 550 ppmv $CO_2$ concentration target. According to this last study, forest activities generate policy cost savings of around 40% that could be used to finance an additional 0.25°C less warming by the end of the century. Both studies, however, considered not only opportunities from avoided deforestation but also included afforestation, reforestation and forest management. More recently, Bosetti et al. (2009) analyzed specifically the role of avoided deforestation under a more stringent stabilization target (450 ppmv CO2). This study explicitly models a potential emission trading market based on national emissions reduction commitments and allows for the possibility to "bank" emissions allowances. When REDD generated credits can be sold, forest emissions considerably decrease and total costs of the stabilization policy are lowered by 10-23%. Or alternatively, REDD could enable a additional reduction of 20ppmv of $CO_2$ equivalent concentration without policy costs increase.

The comprehensive Eliasch Review (2008) has investigated the impact of introducing credits from forestry activities and CDM into the European Union emissions trading scheme (EU ETS). The study concludes that a 50% supplementarity[1] would allow a 30% emissions cut at the same cost of a 20% cut with a 30% supplementarity during Phase III of the EU ETS. The role of forest credits is substantial: it could lower the costs of halving global carbon emissions from 1990 levels by up to 50% in 2030 and by up to 40% in 2050.

[1] the proportion of abatement effort that can be met with non-Annex I country credits

Finally, Dixon et al. (2008) using a numerical multi-country, two-sector partial equilibrium model of the global carbon market concluded that international permit price would be reduced by 45% when, in addition to CDM, unlimited carbon credits from avoided deforestation are available. Moreover, policy compliance costs decrease by more than one third. Their analysis assessed the impacts of climate policies in a single period market ending in 2020 considering a post Kyoto 2012-2020 scenario where emission reduction targets were based on public announcements.

In this paper we address the role REDD may play in the European carbon market, in the context of a mitigation policy aiming to reduce EU emissions by 20% respect to 1990 in 2020. We use a multiregional Computable General Equilibrium (CGE) model. We not only discuss the likely implications of REDD for carbon market prices and policy costs but also examine carbon leakage, distributional aspects resulting from climate policies or incentives to participate in a carbon trading system when reduction emissions from avoided deforestation are considered. Unlike previous studies addressing the potential introduction of REDD credits in carbon markets we account for direct and indirect effects occurring both on land and timber markets. Reductions in deforestation rates are endogenously calculated using a carbon market price signal, decreasing both the amount of land available to agricultural uses and the flow of wood entering timber markets with respect to what would occur in a business as usual scenario or a policy not accounting for REDD credits. While most studies on carbon markets and avoided deforestation do not take into account this effect, it represents a cost to countries providing REDD credits and may, therefore, influence incentives to participate in a carbon trading system.

The paper is structured as follows. Section 2 presents data and modelling framework. Section 3 discusses results and section 4 concludes.

## 2 The modelling framework

The modelling tool used for the analysis of the implication of REDD in the global economy is provided by the recursive-dynamic ICES CGE model based on the core structure of the Global Trade Analysis Project (GTAP) model and database version 6 (Dimaranan, 2006). Its production side is however that of the GTAP-E model (Burniaux and Truong, 2002). This in order to account for a more satisfactory representation of the energy and emission sides of economic systems. GTAP-E also includes carbon taxes and an Emission Trade (ET) module to simulate international carbon market which are key to our investigation. We updated that, originally restricted to emission reduction from fossil fuel use, to account for emission reduction from avoided deforestation and the trading of carbon credits originated. As said, the model is a dynamic recursive one. However in the present study we use it in a simplified version basically projecting in just one time step all the system from 2001 (the calibration year) to 2020. The regional and sectoral detail of the model, its production tree and baseline assumptions are reported in appendix I.

The role of avoided deforestation has then been introduced through three different channels.

Firstly, a set of equations computing regional emission reductions from avoided deforestation in response to different carbon prices have been added to the model. Parameterization of these equations are derived from the IIASA Cluster model (Gusti et al. 2008) prepared for the Eliasch (2008) report.

Following Kindermann et al. (2008), we assume that avoided deforestation and the associated credits come only from the lowest-cost avoided deforestation opportunities areas: Africa, Central and South America and Southeast Asia. However, according to the deforestation rates obtained trough IIASA Cluster model (Gusti et al. 2008)) more than the 94% of total world deforestation activity took place in these areas (2000 data). We also assume that all these regions have already established institutional and governmental structures that would allow them to immediately enter the European trading scheme. Those reduction are then subtracted from the total emissions originated by the model. The generated credits can be sold in the international carbon market and accrue national income of the sellers and decrease that of the buyers.

Secondly, changes in deforestation patterns fostered by the possibility to sell REDD credits into the carbon market affect agricultural, forestry and pasture land use, i.e. the regional land stocks. Indeed more forest remaining unharvested implies a lower amount of land available to agricultural and pasture activities. This lower availability is defined with respect to a baseline land availability under “business as usual deforestation rates”. Both baseline regional land availability and its mitigation-policy driven change have been estimated starting from the IIASA cluster model. This provides baseline emissions from deforestation that we converted to (lost) forest hectares using UN FAO (2006). To simplify, we assumed that each hectare lost to forest is gained to agriculture/pasture (and vice versa). Then, baseline land availability is endogenously corrected in response to (lower) deforestation under different carbon prices.

Thirdly, reduced deforestation resulting from different carbon prices also decreases the total amount of wood entering timber markets. To account for this fact, we follow a similar approach to the one described above. A business as usual timber supply is then endogenously modified accounting for the lower harvesting induced by the possibility to sell REED credits. The relation between non harvested hectares and timber production from primary forest (cubic meters) has been estimated coupling data from FAO (UN FAO 2006) with Brown (2000) reporting information on timber extraction from primary and forest plantation .

The simulation exercise is performed for year 2020.

Three different scenarios are compared:

The no policy business as usual. This is a 2020 benchmark obtained perturbing the calibration year equilibrium (2001) in order to replicate regional population and GDP growth consistent with the A2 IPCC scenarios.

EU emission reduction policy without REDD: this assumes that the EU implements unilaterally a 20% emission reduction compared to 1990. At this stage we consider only one regional aggregate for the EU, thus this exercise is equivalent to one in which, within the EU, the burden of abatement can be allocated efficiently across sectors and countries through an EU carbon market.

EU emission reduction with REDD. Same as above, but with the additional possibility for Sub Saharan Africa (SSA thereafter), Central and South America (LACA thereafter) and Southeast Asia (EASIA thereafter) to enter the EU ETS selling REDD credits. Note that it is assumed that these regions can participate to the EU carbon market even without accepting binding reduction quota, but only on the basis of proven reduction in "business as usual" deforestation activities. This option has been chosen as it should provide the highest incentive to REED countries to engage in deforestation actions and allows us to isolate its role in the policy context.

# 3 Results

## *3.1 REDD and overall policy implication*

The EU unilateral mitigation policy imposes the region a reduction of 866 million tons of CO2 originating a price on the carbon market of 46$/t CO2 (Table 1) at a cost for the EU as a whole of roughly 0.9% of its GDP compared to the baseline[2] (Table 2). The unilateral EU effort originates the well known leakage effect. Commodities produced in countries with a less stringent climate policy (in our case without a climate policy indeed) become more competitive as they are not charged with environmental taxes. They are thus increasingly demanded, and increasingly produced. Consequently emissions outside the EU also increase.

[2] These figures are perfectly in line with the existing literature. As a comparison we just quote the 2008 EC staff working documents on the cost of meeting the 20-20-20 EU target which estimate for the EU27 a cost ranging from the 0.54% to the 0.66% of GDP with a price ranging from 30 to 47€/t CO2 (SEC 2008a,b).

The study highlights a quite strong leakage (+1.2 % of emissions in the non EU countries) offsetting roughly 45% of European reductions (see Fig. 1). This however should be interpreted as the most pessimistic possible outcome as it is assumed that no country outside the EU will put in place any emission reduction policy. Interestingly, in this context, it is the USA that contributes more to the world increased emissions, however emerging economies (LACA, FSU, MDE and China) also represent a significant share.

By opening the EU ETS to REDD credits the price of carbon is expected to drop to 8$/t CO2 (a reduction of the 83%). Basically the supply of REED credits, without restriction, could alone meet almost the totality of emission reduction required to the EU. Accordingly, the concern that an unrestricted use of REDD credits could flood the carbon market appears justified in this specific context. The EU would buy 6700 $ million of imported pollution right, but "gaining" a drop of GDP costs from the original 1% to the 0.2% compared to the baseline.

The most interesting effect is probably that on leakage: the possibility for the EU to buy its reduction from REED countries is much less penalizing in term of competitiveness than unilateral reduction. EU commodities "suffer" less in international markets and symmetrically the competitive advantage for non EU countries is reduced. Increase in non EU emissions now offsets just the 12% of EU reduction and GDP gains in the non EU are lower (see table 2).

This trend applies to REDD countries as well.

On the one hand, SSA, EASIA and LACA increase their GDP in the REED compared to the no policy baseline scenario. Thus benefits from selling REDD credits to the EU are larger than their direct and indirect costs. We recall than in our exercise the first are triggered by lower land available to agriculture/pasture and lower raw wood supply to the timber sector (see below). On the other hand, all these regions are unambiguously better off if a carbon market is introduced in Europe without the possibility to use REDD credits (see 8$^{th}$ and 2$^{nd}$ columns in Table 2). While this may seem counter-intuitive, the explanation behind this result is actually straightforward since it is directly related with carbon leakage. For REDD countries, the EU loss of competitiveness in a unilateral mitigation action outweighs gains from selling REED, but to a more competitive EU. This is a typical example of indirect effects - on GDP through competitiveness - being larger than direct effects - on GDP through revenues from sold credits -. This is not uncommon especially when these last, as in our case, are small. They indeed amount just to 0.08%, 0.21% and 0.09% of GDP for EASIA, SSA and LACA respectively.

Thus summarizing: a full opening of the ETS market to REDD credits would be in the EU interest, but not in that of REDD regions. Rephrasing this using the coalition theory jargon: the participation by REDD regions is profitable, but not internally stable. For them it would be better to free ride on the EU agreement. Note also that, in our context, gains from free-riding arise only because of higher competitiveness and not because of an improved environmental quality brought about by EU emission reductions.

It is worth stressing that this result should be interpreted with care: it is driven by the economic leakage which is one of the most difficult aspect to measure.

Firstly, it is determined by the shape of the agreement determining it. Larger participation and the possibility to sell REDD together with other emission reduction credits may lower its size.

Secondly, it depends on the evolution of the import/export composition in the world market on its turn influenced by technological factors which are very difficult to capture.

Thirdly, it depends on the substitution possibility between imported and domestic goods, i.e. Armington elasticities, which can change over time.

### *3.2 Effects on land and timber sectors.*

A critical aspect regarding the use of REDD credits in an international carbon market concerns its eventual impact on land, agricultural goods' and timber prices on regions selling avoided deforestation credits. To show the relevance of this effect, Figures 2, 3 and 4 contrast the change in land, timber and crops' prices estimated by our exercise, i.e. considering impacts on land and timber supply ("modified model" in figures), with those originated by an exercise in which these are not included ("unmodified model" in figures).

When direct land use effects resulting from reduced deforestation are not modelled, we observe that land prices are marginally affected when the

European carbon market is opened to this type of credit. In contrast, when these are taken into account and no restrictions are imposed to the used of REDD credits, land prices increase by 1.1% for SSA, 2% for EASIA and 1.4% for LACA with respect to business as usual levels. One could expect to observe a higher increase in land prices especially considering that the current policy would reduce deforestation rates in the year 2020 by 22% compared to business as usual. However in term of agricultural/pasture land this means a lower availability of just the 0.9% compared to BAU. As a consequence also the effects on food prices are negligible (see Figure 4). The highest percent increase is experienced by EASIA where the price of wheat and other cereals reach the 0.35%[3]. A policy requiring more stringent efforts, eventually involving more partners, would likely affect land prices in these regions on a higher scale.

We observe a very similar result regarding changes in timber prices. When timber flows are not directly modelled to take into account land use change impacts, prices remain almost unaffected. However when these are explicitly modelled, timber prices increase by 2.6% in LACA, 3.4% in EASIA and 4.7% in SSA.

An interesting case is that of the LACA region: indeed the EU climate policy (with and without REDD) would *decrease* land and timber prices below business as usual levels when direct effects on land and timber are not considered. This is a typical sectoral recomposition effect: although LACA economies are more competitive when the EU implements its mitigation policy, (indeed LACA GDP increases and its terms of trade improve), these gains are concentrated in the raw material and heavy industry sectors and not in agriculture and forestry whose demand and production fall. When the policy-induced land and timber scarcity are correctly modelled however, their prices increase.

### *3.3 Restrictions and incentives to selling REDD credits*

In this section we analyse the consequences of introducing limits to the use of REDD credits in the European Trading System. Restriction

[3] Note however that in relative terms the increase in crop prices due to the inclusion of land scarcity effect is significant in all the three regions and especially in EASIA where land lost by agriculture is larger.

levels are defined as the maximum amount of total reduction efforts that can be met by Europe using REDD credits. Restrictions can be justified to control the carbon price decrease and maintain a sufficient dynamic stimulus to the development of environmental friendly and energy saving technologies, but also, in the light of what said, as an incentive to REDD countries to sell credits and not free ride on the EU mitigation policy.

Table 1 and 2 present, respectively, the different levels of $CO_2$ prices and policy costs under various restriction levels. As can be expected, under the EU perspective, both carbon prices and policy costs increase with restrictions. Limiting the use of REDD credits therefore consists of an effective option to preventing an eventual flooding of "cheap" credits into the European carbon market and to keeping carbon prices high enough to stimulate investments in greener technologies, however at the expenses of higher policy costs.

A good compromise between these two conflicting instances could be represented by a 30% restriction to REDD credits: the carbon price would be reduced by approximately 32%, against the 83% reduction when no limits to these type of credits are imposed; at the same time the policy cost measured in terms of GDP loss compared to the baseline equals 0.6%, against 1% in the case where no REDD credits are allowed to enter the ETS. The carbon leakage would remain quite high though, still offsetting 35% of European reductions.

Under the point of view of the REDD regions, first of all it can be noticed that revenues from selling credits are not linear with restrictions (Figure 5). They are determined by the elasticity along the supply curves of REDD credits. Thus they typically follow a bell shaped trend. Thus the largest revenues for SSA and LACA are experienced when restrictions approximately reach the 50%, whereas for EASIA when they are no larger than the 10%.

However, it is also clear that, except from the case of SSA when the use of REDD credits is limited to 5-10%, no restriction is able to make REDD regions better off participating to the market, than not participating and having the EU mitigating with unilateral action.

It is thus confirmed that in our specific exercise indirect effects on competitiveness overcompensate direct REDD revenues from selling credits.

Table 1. $CO_2$ Price

| | Access to REDD credits in the ETS market (100% = full) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **5%** | **10%** | **15%** | **20%** | **25%** | **30%** | **50%** | **100%** |
| *$CO_2$ Price $/t* | 46 | 43 | 40 | 38 | 35 | 33 | 31 | 23 | 8 |
| *% reduction wrt full access to REDD credits use* | | -6% | -12% | -17% | -22% | -27% | -32% | -50% | -83% |

Table 2. GDP: % changes w.r.t BAU

| | **ETS w/o REDD** | **ETS REDD 5% Limit** | **ETS REDD 10% Limit** | **ETS REDD 20% Limit** | **ETS REDD 30% Limit** | **ETS REDD 50% Limit** | **ETS unlimited REDD** |
|---|---|---|---|---|---|---|---|
| *USA* | 0,012 | 0,012 | 0,011 | 0,009 | 0,008 | 0,006 | 0,003 |
| *Europe* | -0,952 | -0,895 | -0,839 | -0,733 | -0,635 | -0,463 | -0,160 |
| *FSU* | 0,420 | 0,387 | 0,355 | 0,297 | 0,246 | 0,170 | 0,103 |
| *KOSAU* | 0,079 | 0,075 | 0,071 | 0,064 | 0,056 | 0,044 | 0,023 |
| *CAJANZ* | 0,050 | 0,048 | 0,045 | 0,040 | 0,035 | 0,027 | 0,010 |
| *NAF* | 0,318 | 0,294 | 0,270 | 0,227 | 0,188 | 0,129 | 0,079 |
| *MDE* | 0,184 | 0,171 | 0,158 | 0,134 | 0,112 | 0,078 | 0,039 |
| ***SSA*** | **0,172** | **0,174** | **0,174** | **0,169** | **0,158** | **0,130** | **0,058** |
| *SASIA* | 0,054 | 0,051 | 0,048 | 0,042 | 0,037 | 0,027 | 0,008 |
| *CHINA* | 0,041 | 0,038 | 0,035 | 0,031 | 0,026 | 0,019 | 0,008 |
| ***EASIA*** | **0,047** | **0,044** | **0,041** | **0,035** | **0,030** | **0,021** | **0,006** |
| ***LACA*** | **0,064** | **0,062** | **0,061** | **0,057** | **0,053** | **0,043** | **0,023** |

Note: in bold REDD regions

Figure 1. Carbon Leakage (in % of European emission reductions)

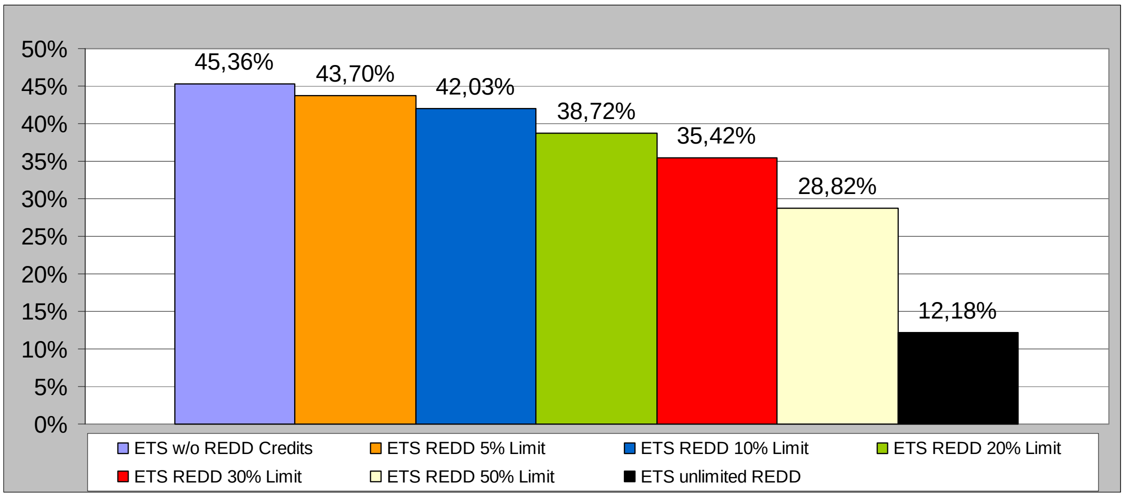



Figure 2. Land Price: % Changes w.r.t BAU

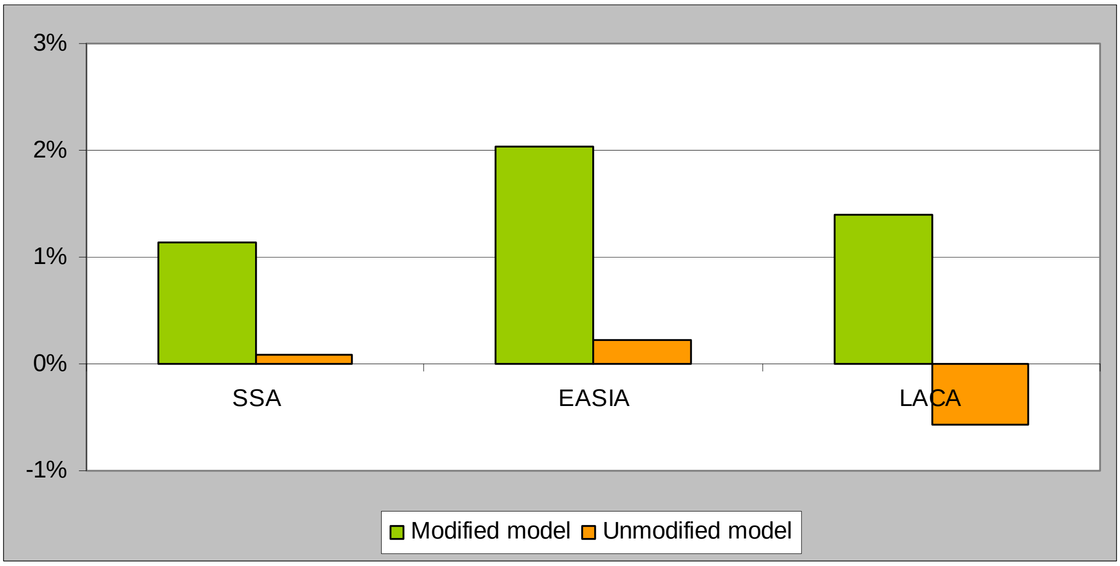



Figure 3. Timber Price: % Changes w.r.t BAU

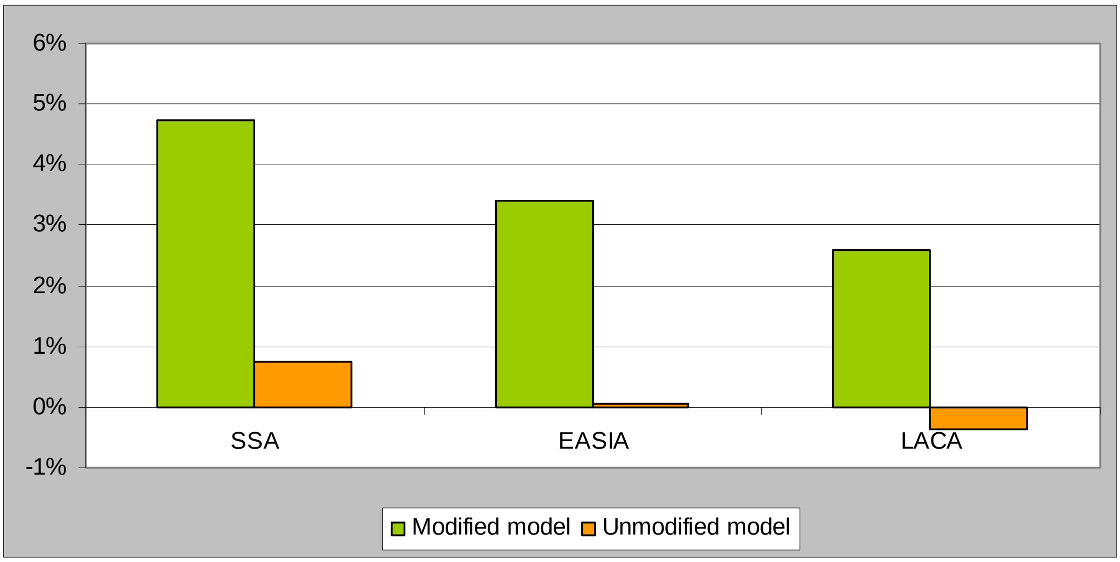


Figure 4. Crop prices: % Changes w.r.t. BAU

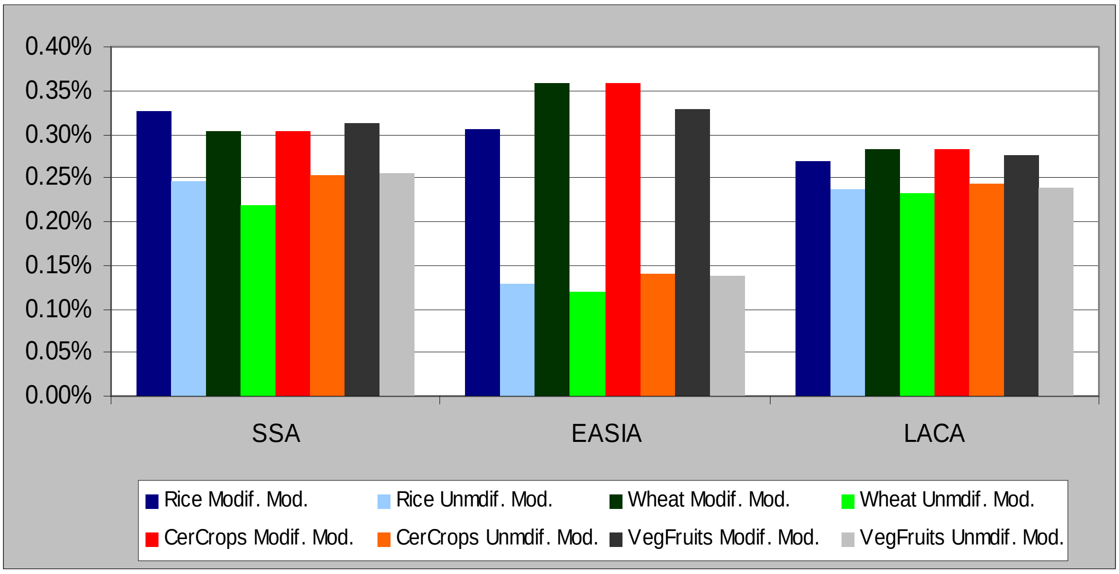
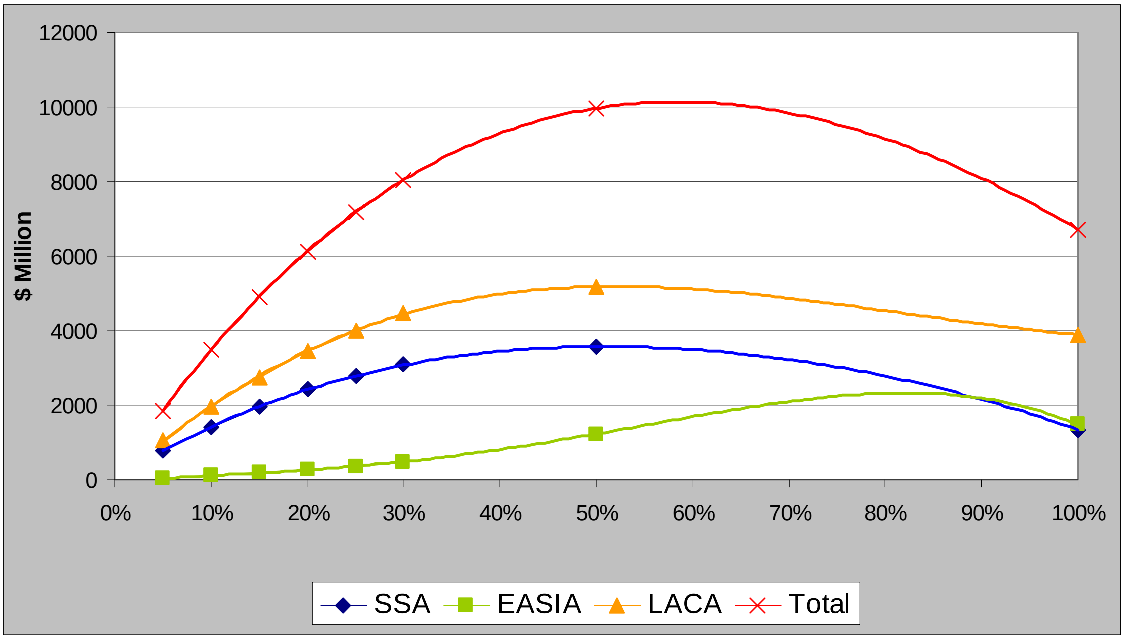



Figure 5. REDD credits revenues




Note: 100% means no restriction to REDD credits use, 0% means no possibility to use REDD credits

## 4 Conclusions

In this paper we addressed the role REDD may play in the European carbon market assuming that the EU reduces its CO2 emissions by 20% with respect to 1990 levels in year 2020. We used a multiregional Computable General Equilibrium (CGE) model and, differently from previous studies, we account for both direct and indirect effects occurring on land and timber markets resulting from lower deforestation rates. These, endogenously driven by carbon price signals, then trigger changes in land available to agricultural/pasture activities and in raw timber supply to the wood industry according to estimated functions which are implemented into the model.

Consistently with previous works, we observed that including emissions reductions from avoided deforestation generates considerable policy cost savings peaking up to 80% when no restriction to REDD credit use is imposed. We also confirmed that an unlimited availability of REDD credits could "flood" the market, drastically reduce carbon prices (by 83%), and therefore possibly lower the incentive to develop energy and carbon saving technologies. This can be, however, effectively controlled limiting the access to avoided deforestation permits. For instance, a 30% restriction to REDD credit use would anyway reduce the policy cost by 34%, but keeping carbon price at the acceptably high level of 31$/t CO2.

Interestingly enough, REDD has the additional benefit of reducing carbon leakage effects resulting from the introduction of the EU climate change policy. While leakage amounts for almost 45% of european reductions under a European trading system excluding REDD, this number decreases to 12% when unlimited access to REDD credit is allowed. The trend in carbon leakage is "mirrored" by that of the economic leakage. Each reduction in the first is coupled with a lower decrease in the competitiveness of EU commodities in international markets. This has important policy implications. Allowing REDD surely entails gain for the EU. This is not necesarily so for REDD regions though. They benefit from the inflow of REDD revenues, but they also face a more competitive EU in the trade arena. Indeed, we showed that the second effect prevails on the first. In particular, GDP in REDD regions is higher when they sell avoided deforestation credits to the EU compared with a no EU policy scenario. Thus benefits from avoided deforestation are higher than the opportunity costs represented by a lower land available to agriculture and pasture activities and by a lower timber supply to the wood industry. Nonetheless, when EASIA, SSA and LACA sell credits to the EU their GDP is lower compared to the case in which the EU implements unilaterally its mitigation policy. In other words, REDD regions would find it preferable to free ride on the EU mitigation policy. Note that in this analysis we are not taking into account the environmentl benefits triggered by EU emission reductions, but just those arising from international trade effects. If those were included, the free riding incentive would be even stronger. We also showed that, by and large, no restriction to REDD credit use can revert this outcome.

Finally, the use of REDD credits can effectively reduce de-forestation activities (by 22% in 2020 without restriction) and induce only moderate increases on land, food and timber prices in REDD regions (in a range of the 1%-2% the first, of the 0.3%-0.35% the second and of the 2.6%-4.7% the third).

At least two developments are foreseen for the present work.

Firstly, due to the crucial role played by the leakage effect, we would like to test the robustness of our results either to different parameterization of the Armington elasticities which drives the substitutability between domestic and imported commodities (even though a plausible trend is that of an increase in this substitutability and accordingly that of a stronger leakage) or to a different design of the mitigation agreement. In this last respect an enlarged participation - for instance including all developed regions – will decrease the leakage and possibly reduce the incentive to free ride.

Secondly we would like to improve the dynamic nature of the whole exercise. At present we are using a recursive-dynamic model just projecting the whole system in one jump to 2020. In a next work we would use one year time-steps to implement more detailed time specific curves for de-forestation activities.

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## *Annex I: ICES technical appendix*

ICES is a recursive-dynamic CGE model for the world economy.

The regional and sectoral detail of the model used for this study are represented in Table A1.

*Table A1. Regional and sectoral disaggregation of the ICES model*

| *Regions* | | *Sectors* | |
|---|---|---|---|
| USA: | United States | Rice | Water |
| EUX | EU including | Wheat | Energy Intensive industries |
| FSU: | Former Soviet Union | Other Cereal | Other industries |
| KOSAU: | Korea, S. Africa, Australia | Vegetable Fruits | Market Services |
| CAJANZ: | Canada, Japan, New Zealand | Animals | Non-Market Services |
| NAF: | North Africa | Forestry | |
| MDE: | Middle East | Fishing | |
| SSA: | Sub Saharan Africa | Coal | |
| SASIA: | India and South Asia | Oil | |
| CHINA: | China | Gas | |
| EASIA: | East Asia | Oil Products | |
| LACA: | Latin and Central America | Electricity | |

ICES solves recursively a sequence of static equilibria linked by endogenous investment determining the growth of capital stock from 2001 to 2050. For the present study the model is run in a simplified version where endogenous investment decision drives 2001-2020 growth in just one time leap.

GDP growth rates for the region modelled replicate those of the IPCC A2 scenario and are reported in table A2.

*Table A2. GDP growth rates for the BAU (% 2001-2020)*

| *Region* | *GDP growth* |
|---|---:|
| USA | 52.7 |
| Med_Europe | 35.3 |
| North_Europe | 33.3 |
| East_Europe | 103.0 |
| FSU | 157.6 |
| KOSAU | 47.5 |
| CAJANZ | 33.2 |
| NAF | 165.0 |
| MDE | 146.2 |
| SSA | 199.6 |
| SASIA | 225.4 |
| CHINA | 275.6 |
| EASIA | 172.3 |
| LACA | 106.9 |

Assumptions on the evolution of population (taken from UNPD, 2008), energy efficiency (taken from Bosetti et. al., 2006), GHG emission and of major fossil fuel prices (based on EIA, 2007 and EIA, 2009) are also incorporated and reported in Table A3.

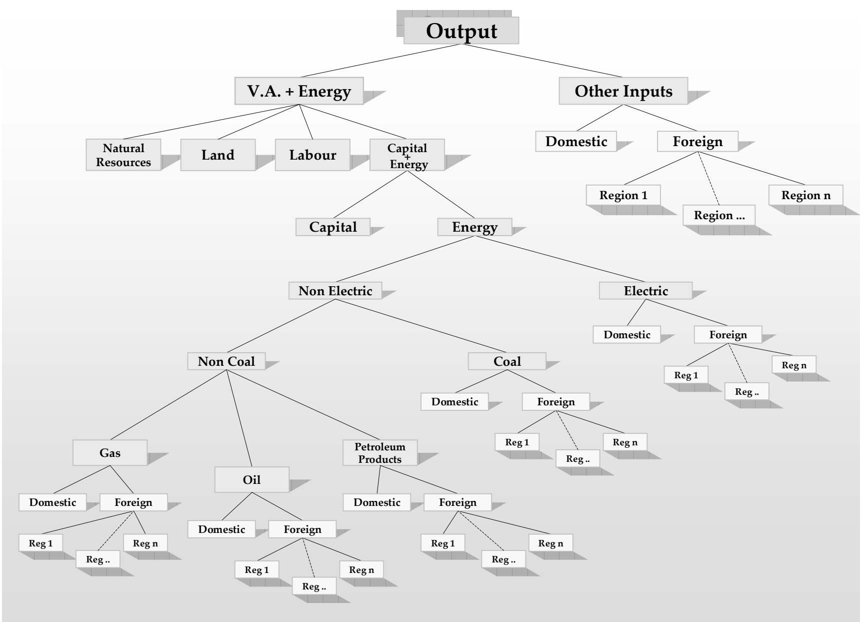
*Table A3. Major exogenous variables growth rates for the BAU (% 2001-2020)*

| *Region* | *Population* | *Energy efficiency* | *CO2* |
|---|---|---|---|
| USA | 15.6 | 12.8 | 21.6 |
| Med_Europe | 0.5 | 17.1 | 1.7 |
| North_Europe | 0.1 | 17.1 | 1.8 |
| East_Europe | -4.6 | 40.4 | 28.6 |
| FSU | -3.2 | 36.6 | 74.0 |
| KOSAU | 9.4 | 27.5 | 10.1 |
| CAJANZ | -0.4 | 17.3 | 2.2 |
| NAF | 31.7 | 26.8 | 65.5 |
| MDE | 37.6 | 26.8 | 72.8 |
| SSA | 46.9 | 22.0 | 129.2 |
| SASIA | 29.9 | 44.7 | 115.5 |
| CHINA | 12.3 | 47.5 | 145.7 |
| EASIA | 24.3 | 43.5 | 75.3 |
| LACA | 26.4 | 23.5 | 36.4 |

| *Fuel* | *Price* |
|---|---|
| Coal | 16 |
| Oil | 74 |
| Gas | 28 |
| Oil Products | 40 |

Industries are modelled 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. The production tree is reported in Figure A1.

*Figure A1. Nested tree structure for industrial production processes of the ICES model*



A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labour, capital, see Figure A2). Capital and labour 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.

*Figure A2. Nested tree structure for final demand of the ICES model*