Improving land-use modelling within CGE to assess forest-based mitigation potential and costs.

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Summary

We present a computable general equilibrium model properly modified to analyse the potential role of the European forestry sector within climate mitigation. Improvements on database and modelling frameworks allow accounting for land heterogeneity across and within regions and for land transfers between agriculture, grazing, and forestry. The forestry sector has been modified to track carbon mitigation potential from both intensive and extensive forest margins, which have been calibrated according to a forest sectoral model. Two sets of climate policies are simulated. In a first scenario, Europe is assumed to commit unilaterally to reduce CO2 emissions of 20% and 30%, by 2020. In a second scenario, in addition to the emissions quotas, progressively higher forest-sequestration subsidies are paid to European firms to foster the implementation of forestry practices. Results show that including forest carbon in the compliance strategy decreases European policy costs and carbon price, although public spending is redirected towards the financing of the forest sequestration subsidy. Comparing public spending and savings in policy costs a net positive balance is reported for all the European regions. Significant reductions in carbon leakage or pressure on food security and deforestation outside Europe are not acknowledged.

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1. INTRODUCTION AND MOTIVATION

Land-using activities seem to offer significant potential for greenhouse gases (GHGs) mitigation. In particular, forests biomes alone have been recognised as substantial carbon sinks (IPCC, 2007 4AR), to be used as a cost-effective climate mitigation strategy (see, among others, Rose *et al.*, 2008). The role of forestry in climate mitigation has been normally analysed with either of the following approaches: i) bottom-up engineering cost studies (see Moulton-Richards, 1990; van Kooten *et al.*, 2000); ii) econometric studies of foresters' revealed preferences (see Stavins, 1999; Newell-Stavins, 2000; Stavins-Richard, 2005); and iii) sector optimisation models (see Sohngen *et al.*, 1999, Sohngen-Mendelsohn, 2003; Kindermann *et al.*, 2008; and Dixon *et al.*, 2009).[1]

Among these three methodologies, sector-optimisation models have several advantages. First, they endogenously derive agricultural and timber production and prices, as a function of landowners' decisions. Second, their bottom-up structure allows describing land allocation among different forest managements with a good level of detail. However, sectoral models only focus on the forest sector disregarding feedbacks from the rest of the economy. Trade effects on food and timber markets are not fully accounted for (Heistermann, 2006), and opportunity costs of alternative land-use and land-based mitigation strategies, at the economic-system level, are not exhaustively represented (Hertel *et al.*, 2009).

In opposition to sectoral frameworks, computable general equilibrium (CGE) models have the ability of exploring the underlying trade-off mechanisms affecting forestry, other land-using sectors, and the rest of the economy. As for sectoral frameworks, land competition and forest-based carbon sequestration endogenously result from landowners' behavioural decisions on land allocation. Conversely to sectoral models, land distribution across different uses depends not only on factors such as land rents, domestic and foreign product price variations and the existence of specific taxes/subsidies, but also on the interaction with the remainder of the markets in the economy.

The use of CGE models for the specific aim of exploring the role of forests in a climate compliance strategy has been slowed down by the complexity of representing the right timing of forest-carbon flows. It has also been slowed down due to the lack of global databases on land-use and land-based mitigation potential, consistently associated with the underlying economic activity (Hertel *et al.*, 2009).

The recently developed datasets provide the opportunity to progress the discussion on land-use mitigation within CGE frameworks. Today, the research community is able to offer more realistic representations of the dynamics of production and prices, in addition to a more in-depth analysis of the opportunity costs for alternative land-use and land-based mitigation options.

[1] See Richard-Stokes, (2004) and van Kooten (2007) for a useful survey and discussion on the methodologies and cost estimates.

In light of the aforementioned, this paper presents a computable general equilibrium model properly modified to analyse the potential role of the European forestry sector in climate mitigation. The following are the aims of this exercise:

- To use a CGE framework rather than a sectoral-oriented approach to model more realistically land-using activities and their abatement potential;
- To take advantage of the recent progress in global databases to model forest-based mitigation;
- To advance in the understanding of forest management potential in mitigating climate;
- To enrich the scarce number of existing forest-carbon analysis in CGEs, proposing specific climate policy scenarios and/or regional disaggregation;
- To provide support to decision makers about how European forest-based mitigation should be included within climate negotiations.

The first objective of this paper is to offer insights on the largely unexplored general equilibrium consequences of including forest-based mitigation in the European compliance strategy. In addition, while land use and its changes have been mostly considered a locally restricted environmental matter, this analysis adopts a global perspective and contributes to improving the understanding of the land system in economic theory, which has only recently become a topic of interest.

The second objective of this paper is to better describe the forest-carbon sink potential with our computable general equilibrium model, which has been significantly improved in its database and modelling approach. By adopting the recently structured global GTAP-Agro-Ecological-Zoning database (GTAP-AEZ) of Lee (2005) and Lee *et al.* (2009), our model allows to account for i) land heterogeneity (differences in biophysical characteristics) across and within regions, as well as ii) land switching between agriculture, grazing, and forestry, expressly capturing land competition among different uses. The forestry sector has been modified, according to recent modelling advancements in the forestry and land-use representations in CGE literature.

The third objective is in opposition with most of the existing studies focusing on deforestation and its reduction in old-growth tropical forests (Bosetti *et al.*, 2009; Eliasch, 2008; Kindermann *et al.* 2008). Our application focus, in fact, on afforestation and forest management in temperate regions.

The fourth objective concerns the CGE ability to simulate specific policy exercises and regional disaggregation. Focusing the analysis on the European temperate forests, three sub-regions have been created to account for the differences in socio-economic backgrounds. We foresee two sets of simulations within the policy scenarios. In the first one, Europe is assumed to engage in an independent climate stabilization policy of a 20% and 30% CO_2 emissions reduction below 1990 levels, in 2020.[2] The simulation of both policy scenarios intends to provide support to the policy debate, which has recently focused attention towards a stricter GHG concentration of a 30% emissions reduction (MEF 2009; EU-COM, 2010).[3] In the second set of

[2] By performing a policy exercise centred only on Europe, we follow a standard approach in environmental economics (Lutz-Meyer, 2009; Böhringer *et al*., 2010) which consents to better analyse the role of forestry for European mitigation, leaving out additional uncertainties that would render the analysis futilely more complex.

[3] The reason for applying a unilateral emissions quota on Europe, instead, bases on its frontrunner position in climate policy. Europe is the only regional area with a comprehensive legislation that has been translated into national strategies. Targets on emissions reduction are, in fact, clear and binding. Other countries that are starting, or already pursuing, mitigation actions present commitments that are usually not inclusive: they develop in a fragmented legislation or regional actions and are not translated into an officially approved climate mitigation scheme at the national level.

simulations, in addition to the climate policy, we introduce progressively higher carbon-sequestration subsidies for the European forest sector of 10, 50, 100$/tC. The induced carbon mitigation potential, associated with forest management activity and land-use change, has been calibrated for a 100$/tC price for carbon sequestration, according to the Global Timber Model-GTM (Sohngen *et al.*, 1999; Sohngen-Mendelsohn, 2007).[4] This second set of scenarios allows investigating whether European forests can significantly help in achieving mitigation targets and whether this is a cost-effective solution. Also, simulating the inclusion of different levels of forest-sequestration subsidies allows the investigation of the responsiveness of climate mitigation costs to a progressively greater role envisioned for forest-based abatement.

Finally, it is widely acknowledged that the debate on REDD(+)[5] activities is still underway and a comprehensive formal agreement on forest-carbon mitigation has not been sealed yet. In such a context, and bearing in mind the fifth objective, this research contributes to supporting decision-makers in the process of determining the extent to which forestry activities should be a part of their agenda.

Section 2 briefly frames how land competition and land use have been introduced in CGE contexts, to date, by reviewing some examples offered by the literature. Sections 3 and 4 are devoted to detailing the key methodological processes undertaken to improve the current structure of ICES which is the global CGE framework used in this exercise.[6] These specifically relate to dataset modifications (section 3), and model advancements (section 4). Section 4.1 models land mobility and heterogeneity and section 4.2 models forest-sector mitigation. Section 4.3 describes the process undertaken to calibrate forest-related variables, while concerns connected to carbon reversibility and additionality and to woody biomass production are discussed in sections 4.4 and 4.5. Section 5 presents the business as usual and the climate policy scenarios. Section 6 draws major results and section 7 develops a sensitivity analysis on elasticity parameters. The last section concludes providing policy suggestions.

2. MODELLING LAND COMPETITION AND LAND USE CHANGE IN A GENERAL EQUILIBRIUM FRAMEWORK

By representing the overall economic system, accounting for trade across all the regions of the world, and modelling a good number of market sectors, the general equilibrium framework is able to draw a comprehensive and micro founded analysis of prices and production dynamics and of feedback mechanisms between all markets. For these reasons it represents a valid, flexible, and powerful framework to assess policy impacts on both developing and developed economies, and to compare implications and competitiveness of different mitigation options.

CGEs also offer a valuable structure to investigate the opportunity costs of a set of land-uses and land-based mitigation alternatives. Such an analysis, however, requires relaxing the conventional assumption that land is perfectly substitutable among different uses and sectors, and that agriculture, livestock production, and forestry compete for the same land (Heistermann *et al.*, 2006). Indeed, showing different biophysical characteristics in different regions of the world the land-system representation calls for the modelling of land heterogeneity across regions and land transfers across different uses.

[4] The calibration of forest-related variables has been pursued in the baseline as well as in the subsidy scenario. For a detailed description of the scenarios developed see section 5.

[5] Within the REDD+ activities, in addition to reducing emissions from deforestation and degradation, the following are acknowledged: actions of conservation, forests sustainable management, and forest carbon stocks enhancement in developing countries (UNFCCC COP-13, Bali).

[6] The detailed description of the original ICES specification is described in Appendix A

Unfortunately, CGE analysis developed thus far have mostly modelled the economics of land-based mitigation by considering the land endowment as homogeneous across sectors and regions (see Hsin *et al.*, 2004; Brooks-Dewbre, 2006; Keeney-Hertel, 2005). In addition, these studies also tend to disregard or exogenously model forestry mitigation potential (see Hertel, 1997; McKibbin-Wang, 1998; Hsin *et al.*, 2004; Brooks-Dewbre, 2006; Keeney-Hertel, 2005; Ronneberg *et al.*, 2008).

Efforts to develop new global datasets with a more extensive representation of land-based emissions and forest-carbon sequestration have provided a concrete possibility to progress economic land modelling in CGEs (see the USEPA 2005 and 2006 for non-CO2 emissions; Lee 2004 and Lee *et al.* 2009 for the GTAP-AEZ database; Rose *et al.* 2007 for the forestry database). As a result, some analyses focusing precisely on land-based mitigation potential have been already developed.

For example, with GTAPE-L Burniaux (2002) and Burniaux-Lee (2003), model land-use allocation between agriculture and forestry by using a land transition matrix derived from IMAGE (IMAGE, 2001). Hertel *et al.* (2008) and Golub *et al.* (2009) introduce land heterogeneity and competition in their CGE model by changing functional forms of production and demand for land-using sectors. They distinguish between carbon sequestration resulting from forest intensification (timber management) and that derived from forest extensification (land use change), both calibrated according to the GTM sectoral forestry model (Sohngen-Mendelsohn, 2003). Their analysis of a 3-region world is extended in Golub *et al.* (2010), which provide results for 19 regions. Sands-Kim (2008), focusing only on the US, create a forward market for forestry in CGE, by intersecting existing wood supply and demand. They derive the steady-state equilibrium values for the rotation period and forest carbon for different carbon price levels. In Golub *et al.* (2009) an interesting attempt to model the dynamics of forest-carbon flows within a recursive-dynamic CGE model is provided. However, a number of complications lead them to couple their CGE with the GTM model of Sohngen-Mendelsohn (2007). They also attempt to represent investment decisions on unmanaged lands as described in Gouel-Hertel (2006), by incorporating access-cost functions in the CGE model. Ahamad-Mi (2005), propose an enhanced CGE model where the introduction of forestry vintages allows to better model forest-carbon sequestration. A more refined approach with the same recursive-dynamic CGE model has been recently provided by Pant (2010). Agriculture is assumed to compete with commercial, naturally native, and environmentally valuable forests, while forest activities are distinguished by plantation, holding, and harvesting. Also, cost functions to access new forestlands are derived as specified by Golub-Hertel-Sohngen (2007).

Despite these attempts, currently there are still very few CGE models which assess the role of forestry at the global level. Now that new inclusive databases allow a more in-depth analysis, researchers are called to provide a correct assessment of land competition among different uses to derive reliable results on alternative mitigation opportunities. In light of this, our exercise aims at improving the modelling of the existing ICES framework to include an appropriate forest sector and account for its mitigation potential under specific climate policy scenarios. The contribution of this paper therefore lies in providing the existing literature with an additional global, multi-sectoral, CGE model with an enhanced forest-sector representation. This objective is achieved, as described below, by taking advantage of the advancements in global databases for the land-use system and by notably modifying the original structure of the ICES modelling framework.

3. IMPROVING INFORMATION ON LAND-USING ACTIVITIES

We improved information on land-using activities and related carbon flows by using the GTAP-AEZ land-use database (GTAP6-Release 2.1, 2009) and the non-CO_2 emissions database (GTAP6-Release 2.0, 2009).[7] These datasets, whose combination will be referred to as "AGRI-FOR-AEZ" from this point on, provide information for the year of 2001 on land-use, land-cover data, and land rents distinguished into 18 Agro-Ecological-Zones (AEZs).

The AEZ is a zone characterized by a specific Length of Growing Period (LGP) and specific climatic attributes. Specifically, 6 LGPs are defined at global level according to humidity gradients across the world. They are derived as the number of days with adequate temperature and precipitation or soil moisture for growing both crops and tree species. In addition, the different LGPs are spread over 3 climatic zones (tropical, temperate, boreal), depending on temperatures and growing degree days.[8] By matching these categories the following land distribution is recognized for all AEZs:

Table 1: Definition of global agro-ecological zones used in GTAP

LGP in days	Moisture Regime	Climate zone	GTAP class
0-59	Arid	Tropical	AEZ1
		Temperature	AEZ7
		Boreal	AEZ13
60-119	Dry semi-arid	Tropical	AEZ2
		Temperature	AEZ8
		Boreal	AEZ14
120-179	Moist semi-arid	Tropical	AEZ3
		Temperature	AEZ9
		Boreal	AEZ15
180-239	Sub-humid	Tropical	AEZ4
		Temperature	AEZ10
		Boreal	AEZ16
240-299	Humid	Tropical	AEZ5
		Temperature	AEZ11
		Boreal	AEZ17
>300 days	Humid; year-round growing season	Tropical	AEZ6
		Temperature	AEZ12
		Boreal	AEZ18

Source: Monfreda *et al.* (2008)

The land-using activities considered within the AEZ land-types are crop production, livestock raising, and forestry. Cropland data for 87 regions accounts for 175 crops aggregated into 8 macro categories by 18 AEZs (Monfreda *et al.*, 2008). Forest data for 226 countries report forest-carbon stock, timberland area and forest-land rent data (Sohngen *et al.* 2008; Rose *et al.*, 2008). Forest land is allocated among the 18 different AEZs, 14 tree-managements types, and 3 tree species (Coniferous, Broadleaf, and Mixed). The same distribution is used for forest-carbon stock. Finally, data regarding non-CO_2 emissions (Rose *et al.*, 2008) were also included to account for emissions from agricultural sectors, associated with the use of intermediate inputs (N_2O from fertilizer use in crops), primary factors (CH_4 from paddy rice), and emissions related to sector output (CH_4 from agricultural residue burning).

[7] We refer readers interested in this issue to the documentation on non-CO_2 emissions available on the GTAP website (https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2604).
[8] See Monfreda et al. (2008) for a detailed description of agro-ecological zoning.

The level of regional disaggregation between the different sources was first harmonized by grouping forest data from 226 countries to 87 world regions of the GTAP6 database. The new database is then aggregated to 14 macro regions (See Appendix B for final regional aggregation). The final distribution of timberland and forest-carbon stock across regions and AEZs is reported in Tables 2 and 3 respectively for the base year of 2001:

Table 2: Timberland Distribution by Region and AEZ in 2001, 1000ha

	USA	Med_Eu	North_Eu	East_Eu	FSU	KOSAU	CAJANZ	NAF	MDE	SSA	SASIA	CHINA	EASIA	LACA	Total
AEZ1	0	0	0	0	0	58	0	0	0	0	0	514	0	378	*950*
AEZ2	1	70	2	185	1	0	542	0	0	0	0	21	95	2	*28*
AEZ3	421	192	30	224	67	0	17	0	124	0	0	14	910	3	*134*
AEZ4	2	3	9	0	100	0	8	0	440	0	65	5	3	8	*137*
AEZ5	2	0	0	0	4	0	290	0	0	0	65	3	0	252	*9*
AEZ6	69	1	549	0	410	4	5	0	0	35	549	13	5	21	*120*
AEZ7	22	20	2	1	535	8	7	0	67	200	1	17	9	2	*90*
AEZ8	36	23	15	22	23	7	47	3	2	6	1	22	4	9	*222*
AEZ9	3	4	3	1	5	117	36	3	6	6	246	17	705	12	*99*
AEZ10	5	0	0	0	3	0	3	980	6	13	119	11	0	8	*50*
AEZ11	1	0	0	0	2	0	0	770	5	3	65	3	0	6	*20*
AEZ12	0	0	0	0	0	1	0	0	0	98	1	698	42	200	*343*
AEZ13	0	0	0	0	0	117	0	0	0	54	2	514	28	55	*140*
AEZ14	0	0	0	0	0	2	0	0	0	90	7	0	7	9	*116*
AEZ15	0	0	0	0	0	0	0	0	21	13	3	0	0	5	*21*
AEZ16	0	0	0	0	0	0	0	47	0	6	137	0	0	2	*8*
AEZ17	0	0	0	0	0	0	0	479	1	5	0	0	0	233	*7*
AEZ18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*0*

Source: Own Elaboration

Table 3: Forest carbon stock by Region and AEZ in 2001, MtC

	USA	Med_Eu	North_Eu	East_Eu	FSU	KOSAU	CAJANZ	NAF	MDE	SSA	SASIA	CHINA	EASIA	LACA	Total
AEZ1	0	0	0	0	0	1	0	0	0	0	0	114	0	147	*262*
AEZ2	211	15	425	55	546	0	83	0	0	0	0	5	33	715	*7*
AEZ3	60	59	7	55	4	0	2	0	37	0	0	3	130	1	*17*
AEZ4	272	231	2	0	6	0	825	0	132	0	0	882	623	2	*14*
AEZ5	272	0	0	0	307	0	38	0	0	0	0	612	0	77	*1*
AEZ6	12	293	33	0	114	262	803	0	0	0	100	1	2	145	*161*
AEZ7	4	4	634	227	79	1	1	0	18	18	589	3	3	521	*20*
AEZ8	7	4	5	12	19	2	5	400	546	2	502	3	634	2	*63*
AEZ9	483	458	587	367	708	13	4	499	2	803	33	2	101	2	*14*
AEZ10	725	0	0	0	65	0	243	150	968	1	10	2	0	2	*7*
AEZ11	181	0	0	0	44	0	0	55	429	231	0	495	0	2	*3*
AEZ12	0	0	0	0	0	298	0	0	0	58	152	57	14	97	*169*
AEZ13	0	0	0	0	0	3	0	0	0	20	251	114	10	18	*49*
AEZ14	0	0	0	0	0	413	0	0	0	19	922	0	2	2	*24*
AEZ15	0	0	0	0	0	0	0	0	0	2	584	0	0	425	*3*
AEZ16	0	0	0	0	0	0	0	4	0	825	20	0	0	110	*958*
AEZ17	0	0	0	0	0	0	0	44	81	631	0	0	0	176	*931*
AEZ18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*0*

Source: Own Elaboration

The following reasons justify our choice of converting the standard GTAP database structure (Hertel *et al*., 1997) into the AGRI-FOR-AEZ database:

- The traditional information on the land included in the GTAP database simply accounts for one broad class of land, which is equal across sectors and regions. This endowment is uniquely used for growing crops and grazing, while it is assumed that there is no land-use for the production and expansion of the forest-sector. As a result, land competition is only made possible between cropland and pastureland. Conversely, in the AGRI-FOR-AEZ database the land endowment is distinguished among agricultural crops, grazing, and forestry for each of the 18 AEZs.

- Information on land in GTAP is expressed in terms of land rents for agricultural crops and graze production rather than in physical units. This implies that hectares of land transfers between these two categories cannot be directly derived. On the contrary, AGRI-FOR-AEZ land transfers across different uses, including forestry, can be derived explicitly and can be expressed in physical units. The use of the AGRI-FOR-AEZ database, along with a properly modified model structure allows a more precise consideration of land-based mitigation opportunities and costs, where changes in land distribution within and across AEZs can be directly linked to emissions variation. In other words, compared with the traditional version, it directly offers the possibility to account for emissions and mitigation opportunities from land-using sectors in addition to those resulting from energy-intensive ones.

- As regional land endowment is composed of several AEZs, using AGRI-FOR-AEZ provides the opportunity of assessing changes in agriculture and forest areas at a level which is smaller than the single region. This represents an interesting opportunity, given that most models assessing land movements produce results only at the country level (see KLUM by Ronneberger *et al*. 2005; AgLU by Sands-Leimbach, 2003).

- While existing literature has been generally opposing land-use economic models to geographical land and land-use representation, and has often disregarded biophysical aspects (Heistermann *et al.*, 2006), the information contained in AGRI-FOR-AEZ integrates land-use economics with biophysics. Production diversification as a function of land heterogeneity is therefore replicated by the existence of different land types. Indeed, dissimilar land qualities in terms of climatic, physical, and economical factors make it more valuable to grow different crops or different tree types in different areas of the world.

4. IMPROVING THE MODELLING STRUCTURE

The key changes brought to the original ICES aim to:[9]

- Explicitly capture land competition among different use,
- Endogenize the landowners' decisions on land transfers between forestland, grazing, and cropland,
- Better represent the forest sector and related mitigation strategies.

The improved ICES used in the context of this exercise, which will be referred to as ICES-AEZ from this point on, accounts for a 17-sector and 14-region economy. Europe, the region of interest in this analysis, has been separated into 3 sub-regions to better account for cost and price differentials. The model involves 22 primary factors of production (capital, labour, fishing and fossil fuels natural resources, and land split in 18 AEZs) while land-using sectors can be broken down into agriculture (rice, wheat, other cereal crops, and vegetable and fruits), grazing, and forestry. Production functions for forestry and non-forestry sectors have been improved following Hertel *et al*. (2008), as explained in Sections 4.1 and 4.2.

CO_2 emissions are connected with i) the use of domestic or imported fossil fuels (coal, oil, oil products and gas) associated with all productive sectors, and ii) the forest-carbon sinks or sources driven by forest management and land-use change activities in the forest sector. Non-CO_2 emissions are included and modelled depending on their source. They can be linked to the use of primary factors (CH_4 from land-use for rice production), intermediates goods (N_2O as in the case of fertiliser use), or directly to final production (CH_4 from agricultural residue burning).

ICES-AEZ maintains the climate policy module included in the previous model versions, which replicates a carbon market, or Emission Trading Scheme (ETS). It allows i) imposing quotas on CO_2 emissions released from fossil fuels use and ii) trading emissions permits among those countries participating in a climate policy.

For the purpose of this exercise, the static-core version of our model is used, projecting the economy in one-time step from 2001 (calibration year) to 2020. After obtaining a reference scenario in 2020 (baseline), we can include additional exogenous shocks to generate counterfactual scenarios and run conventional comparative static exercises.

[9] See Appendix A for a description of the standard version of the model.

4.1. *Land Allocation and mobility across different commercial uses*

Accounting for the switching of land across different uses requires a consistent modification of the original ICES structure that was performed by mainly following the approach presented in Hertel *et al*., (2008). Land demand and supply for land-using sectors have been modified in the following manner.

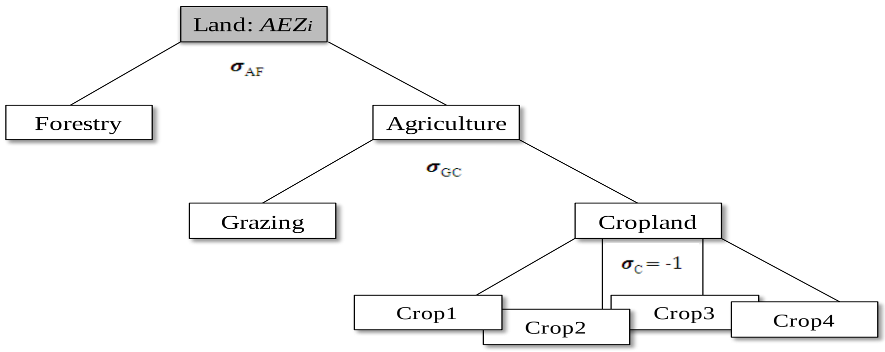
4.1.1.Allocation in households' land supply

A supply function for land derives, from each AEZ input of land, multiple land-cover outputs (cropland, grazing, and forestry land covers). Within every region *r*, a representative landowner faces the problem of providing land to firms, either for crop growing, timber production, or graze raising. Within each AEZ the land tenant behaves as a profit-maximising agent allocating land between the different land covers as to maximise the total value of land rents.[10] Given that i) p_{AEZir} is the price paid by firms for AEZ_{ir}; ii) AEZ_{ir} is the amount of land *i* (with *i* =1,..., 18) owned by the representative land tenant, and that iii) $Land_r$ is the total land supply at regional level, we can formulate the following landowner' maximisation problem:

$$\begin{aligned} &\underset{AEZ_i}{Max} \sum_i p_{AEZ_{ir}} AEZ_{ir} \\ &s.t. \sum_i AEZ_{ir} = Land_r \end{aligned} \qquad \text{(E1)}$$

Land-cover outputs for each AEZ are derived from landowners' choices according to a nested land supply structure included by means of a Constant Elasticity of Transformation function (CET), which captures land competition, separability, and mobility between different uses.[11] We assume that within each AEZ, first the landowners allocate land between crops and second, crops as a whole compete with grazing land. Finally, the composite of grazing and cropland (say agricultural land) competes with forestry in the upper level of the land-supply function (see Figure 1).

Figure 1: Land supply tree



Source: Authors' elaboration from Hertel *et al.* (2008)

[10] In our model, the landowner agent coincides with the representative household who will maximise his utility also counting on the received rents from providing firms with land.

[11] In modelling land heterogeneity, the desirable properties of the CET function have made it a widely used approach within CGE frameworks (Hertel-Tsigas 1988; Hertel 1997; Eickhout *et al.* 2008; and Golub *et al.* 2008). It provides, for instance, the necessary convexity condition for revenue maximisation, implying non -increasing returns to scale. Nevertheless, given that its tractability "covers a multitude of sins", "a more explicit approach to handling land heterogeneity" has been recently claimed by Hertel (2012).

Assuming that $\boldsymbol{\alpha}$ is a share parameter, $\boldsymbol{\nu}$ is the factor productivity varying across regions (with $\boldsymbol{\nu}>0$), and that *FOR*, *AGR*, *GRZ*, *CRP* respectively correspond to the forestry, agriculture, grazing, and cropland cover type, we can write the following CET functions for each region, leading the process of land allocation in each of the AEZ_i:

$$AEZ_{ir} = \upsilon \left[\alpha_{for} FOR_{ir}^{\frac{\sigma_{AF}-1}{\sigma_{AF}}} + \alpha_{agr} AGR_{ir}^{\frac{\sigma_{AF}-1}{\sigma_{AF}}} \right]^{\frac{\sigma_{AF}}{\sigma_{AF}-1}} \quad \text{(E2)}$$

$$AGR_{ir} = \left[\alpha_{grz} GRZ_{ir}^{\frac{\sigma_{GC}-1}{\sigma_{GC}}} + \alpha_{c} CRP_{ir}^{\frac{\sigma_{GC}-1}{\sigma_{GC}}} \right]^{\frac{\sigma_{GC}}{\sigma_{GC}-1}} \quad \text{(E3)}$$

$$CRP_{ir} = \left[\sum_{c} \alpha_{c} CROP_{c,ir}^{\frac{\sigma_{C}-1}{\sigma_{C}}} \right]^{\frac{\sigma_{C}}{\sigma_{C}-1}} \quad \text{(E4)}$$

The CET function, which reproduces the nested representation in Figure 1, expresses land opportunity costs across different uses by means of elasticities of transformation, governing the sensitivity of the land supply reaction to changes in relative yields. The equilibrium elasticities, which are strictly negative ($\frac{\sigma-1}{\sigma}>1$), define the extent to which the land supply changes as a result of a shock to the model, once the economic system has adjusted to a given perturbation (a tax on carbon emissions or output tax). For equations E2-4 we adopt the values derived by elaborating on the recent work of Bouet *et al*., (2010), and reported in Table 4, which are maintained constant across sectors but differ across regions. It is assumed that crops, *c*, can be more easily substituted among themselves ($\boldsymbol{\sigma}_C$), than the overall cropland is with grazing ($\boldsymbol{\sigma}_{GC}$), and the composite agricultural land with forestry ($\boldsymbol{\sigma}_{AF}$).

Table 4: Elasticities of transformation in land supply tree

Regions	$\boldsymbol{\sigma}_C$	$\boldsymbol{\sigma}_{GC}$	$\boldsymbol{\sigma}_{AF}$
1 USA	-1	-0.15	-0.1
2 Med_Europe	-1	-0.21	-0.05
3 North_Europe	-1	-0.21	-0.05
4 East_Europe	-1	-0.21	-0.05
5 FSU	-1	-0.21	-0.05
6 KOSAU	-1	-0.13	-0.05
7 CAJANZ	-1	-0.14	-0.05
8 NAF	-1	-0.15	-0.05
9 MDE	-1	-0.15	-0.05
10 SSA	-1	-0.15	-0.05
11 SASIA	-1	-0.11	-0.1
12 CHINA	-1	-0.21	-0.05
13 EASIA	-1	-0.16	-0.07
14 LACA	-1	-0.11	-0.1

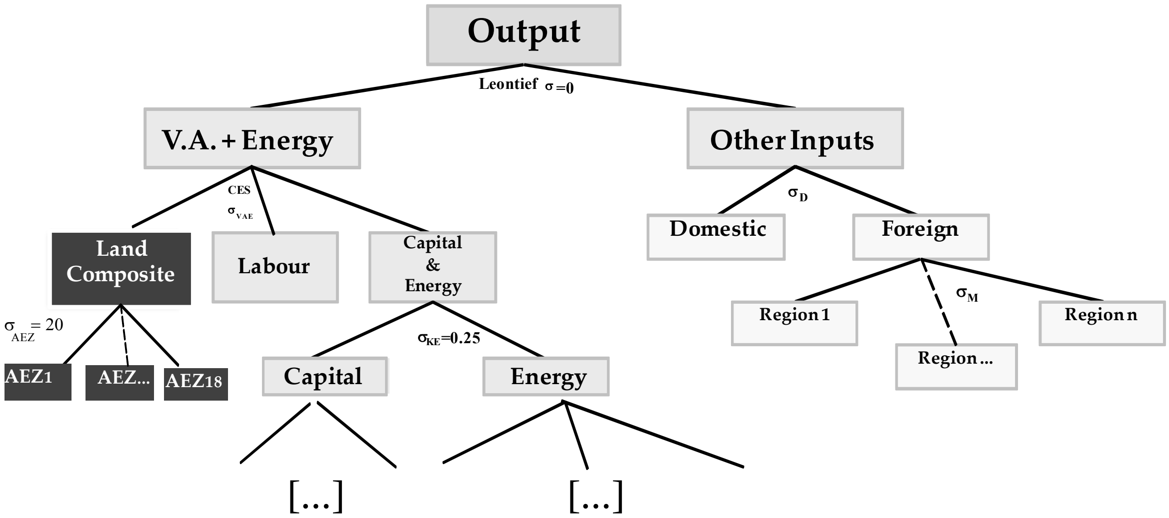
Source: Authors' elaboration from Bouet *et al.* (2010)

4.1.2. Substitutability in firms' land demand

As for the sectoral output, firms' demands for inputs are modelled by means of nested Constant Elasticity of Substitution functions (CES),[12] which specify the range of substitution possibilities between either primary factors, intermediate inputs, or even both of them.[13]

Within the production function, land substitutability across AEZs has been added to allow producing a same land-using output (e.g., rice) on different AEZs. For all land-using sectors but forestry, the production function is depicted in Figure 2 below.[14]

Figure 2: Nested tree structure for production in sector j



Source: Elaboration from Hertel *et al.* (2008)

Value added nest

In the value-added nest, primary factors taking part in the production process include the composite land, the composite capital and energy, natural resources, and labour, which are combined according to the elasticity of substitution σ_{VAE}. While in the previous version of the ICES model this elasticity was set different across sectors but equal across regions, in ICES-AEZ the new parameters are also allowed to vary across regions.[15] Moreover, they have been recalculated so as to achieve specific values for the supply

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[12] The CES production function is continuous and differentiable, monotonic and strictly quasi-concave, defined for positive inputs levels. As generally assumed in perfect-competition CGE-models, it exhibits constant returns to scale.

[13] See Appendix A for a more detailed overview of the production side.

[14] Below the Capital and Energy nest, a further nested structure is specified for fossil fuels and non-fossil fuels resources. Given that such structure has not been significantly changed in this new version of the ICES model, its illustration has been omitted. Nevertheless, interested readers can refer to Appendix A.

[15] To derive the new values for σ_{VAE}, we apply the formula that can be obtained from proposition 2 in McDougall (2009):

$$\frac{q_o - q_x}{p_o} \frac{S_x}{1 - S_x^A} = \sigma_{\text{VAE}}$$

Where q_o and q_x are the log-differentials of the final output and the fossil fuel input respectively; p_o is the log-differential of the final-output price; S_x is the share of the fossil fuel input while S_x^A is the same share in the money values of the value-added aggregate. By rearranging terms in the previous equation we can derive the elasticity of supply for fossil fuels σ_S: $\frac{q_o - q_x}{p_o} = \sigma_{\text{VAE}} \frac{1 - S_x^A}{S_x} = \sigma_S$

elasticities in the coal, oil, and gas sectors, with respect to those assumed in the traditional GTAP-E framework.

The new supply elasticities for coal and oil, which are derived from Beckman *et al*. (2011), are claimed to better replicate the past volatility of the world petroleum market. They are set equal to 1 for coal, instead of the range [0.5-0.61] previously varying across regions; and to 0.25 for oil instead of [0.5-0.63]. Finally, for gas we followed Burniaux (2001), setting the value to 4 instead of [1-18].

Capital and energy bundle and inter-fuels substitution

Below the value added nest, other elasticity parameters, also taken from Beckman *et al*. (2011), govern the nesting structure of the capital and energy bundle. A substitution of 0.25 is assumed between capital and energy, while inter-fuels substitution is set to 0.07 between coal and non-coal, 0.016 between electric and non-electric inputs, and 0.25 between remaining fossil fuels (oil, gas, and other petroleum products).

Land Aggregate

As for the land bundle, the representative firm in a land-using sector *j* purchases this input from the regional landowner. According to the specific output (rice, cereals, among others), the firm will require the appropriate land-cover type. For example, the rice producer will ask for land suitable to grow such crop type, for instance, cropland rather than forest or grazing land. Formally, in this improved version of ICES, for each land-using sector *j* excluding forestry (*j* = agricultural and grazing sectors), the following additional CES nest is introduced to the aim of distinguishing land into different AEZs:

$$Land_{jr} = A\left[\sum_i \beta_{ij} AEZ_{ijr}^{\frac{\sigma_{AEZ}-1}{\sigma_{AEZ}}}\right]^{\frac{\sigma_{AEZ}}{\sigma_{AEZ}-1}} \qquad \text{(E5)}$$

Land used in sector *j* is therefore demanded from *i* different AEZs. In each sector, its distribution across land types is driven by the producer's cost minimisation problem as reported below:

$$\begin{aligned} &\underset{AEZ_{ij}}{Min} \sum_i p_{ijr} AEZ_{ijr} \\ &s.t. Land_{jr} = A\left(\sum_i \beta_{ij} AEZ_{ijr}^{\frac{\sigma_{AEZ}-1}{\sigma_{AEZ}}}\right)^{\frac{\sigma_{AEZ}}{\sigma_{AEZ}-1}} \end{aligned} \qquad \text{(E6)}$$

By solving and rearranging terms, conditional demands for AEZ_i can be derived as homogeneous of degree one with respect to production levels, and homogeneous of degree zero with respect to inputs prices:

$$AEZ_{ijr} = \frac{Land_{jr}}{A}\left(\frac{\beta_{ij}}{p_{ijr}}\right)^{\sigma_{AEZ}}\left(\sum_i \beta_{ij}^{\sigma_{AEZ}} p_{ijr}^{1-\sigma_{AEZ}}\right)^{\frac{\sigma_{AEZ}}{1-\sigma_{AEZ}}} \qquad \text{(E7)}$$

This notation can be further simplified by making use of the constant return to scale (CRTS) assumption and unit cost function *c* which equals the marginal cost and is continuous, concave, and invariant to the production level:

$$c_{jr} = \frac{\sum_i p_{ijr} AEZ_{ijr}}{Land_{jr}} = \frac{1}{A}\left(\sum_i \beta_{ij}^{\sigma_{AEZ}} p_{ijr}^{1-\sigma_{AEZ}}\right)^{\frac{\sigma_{AEZ}}{1-\sigma_{AEZ}}} \quad \text{(E8)}$$

By rearranging the terms, we can express conditional demands as a function of the unit cost function above.

$$AEZ_{ijr} = Land_{jr}\left(\frac{\beta_{ij} c_{jr}}{p_{ijr}}\right)^{\frac{\sigma_{AEZ}}{\sigma_{AEZ}-1}} \quad \text{(E9)}$$

E9 shows that the changes in relative prices for conditional demands are influenced by the unit cost. Linearizing equation E9 to make it consistent with the ICES-AEZ structure the conditional demands can be written as:

$$\overset{\circ}{AEZ}_{ijr} = \overset{\circ}{Land}_{jr} + \sigma_{AEZ}\left(\overset{\circ}{\beta}_{ij} + \overset{\circ}{c}_{jr} - \overset{\circ}{p}_{ijr}\right) + (\sigma_{AEZ} - 1)\overset{\circ}{A} \quad \text{(E10)}$$

Where, given a variable *x* we have that $\overset{\circ}{x} = \frac{dx}{x}$. Changes in demands can be clearly decomposed into i) the scale effect of a change in the amount of land or $\overset{\circ}{Land}_{jr}$, ii) substitution effect expressed as the impact of a change in the relative prices or $\sigma_{AEZ}\left(\overset{\circ}{c}_{jr} - \overset{\circ}{p}_{ijr}\right)$, iii) factor technical changes $\sigma_{AEZ}\,\overset{\circ}{\beta}_{ij}$ and $(\sigma_{AEZ} - 1)\overset{\circ}{A}$.

Within the land composite producers are allowed to demand land located in different AEZs according to an elasticity of substitution equalling 20 ($\boldsymbol{\sigma}_{AEZ}$), as suggested by Hertel *et al*., (2008). This high value for the production of a homogeneous commodity assures the equalisation of the percentage change in the rents of land across AEZs. This guarantees that, within the same use of land, the land returns will move together.

The total land demand in region *r*, equalling the total land supply in E1, is derived as the sum, across all sectors, of the sectoral amounts of land required:

$$Land_r = \sum_j Land_{jr} = \sum_i AEZ_{ir} \quad \text{(E11)}$$

4.2. Modelling the forest sector and related mitigation measures

The regional production function of the forest sector has been modified following Hertel *et al*., (2008). Forestry sectoral output is still a function of primary inputs and intermediate goods although a major modification is included within the value-added/energy nest, whose CES-functional form is reported below.

$$VAE_j = A\left[\sum_i \delta_{ij} X_{ij}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}}\right]^{\frac{\sigma_{VAE}}{\sigma_{VAE}-1}} \qquad \text{(E12)}$$

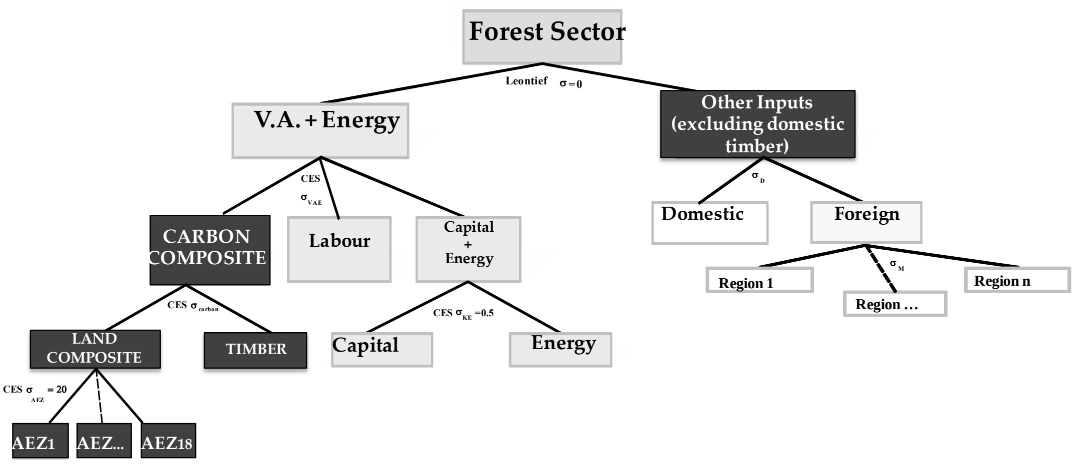
Conversely to the traditional GTAP model, own-use of forestry products by the forest sector has been subtracted from the “other inputs” nest to be included in a new “carbon composite” nest ($Carbon_{jr}$), along with a land composite (see Figure 3). This new merged input is used for production purposes to an extent depending on the elasticity of substitution $\boldsymbol{\sigma}_{VAE,}$ which governs the trade-offs in costs among the new composite, labour, natural resources, and capital/energy inputs.

In a following sub-nest the composite land ($Land_{jr}$) is allowed to substitute in production with the own-use of forestry products (T) by means of the substitution elasticity $\boldsymbol{\sigma}_{CARBON}$.

$$Carbon_{jr} = A\left[\alpha_{Lj} Land_{jr}^{\frac{\sigma_{carbon}-1}{\sigma_{carbon}}} + \alpha_{Tj} T_{jr}^{\frac{\sigma_{carbon}-1}{\sigma_{carbon}}}\right]^{\frac{\sigma_{carbon}}{\sigma_{carbon}-1}} \qquad \text{(E13)}$$

Finally, similar to the other land-using sectors, the composite land is broken down into 18 AEZs (see equation E5), which compete with each other according to the elasticity of substitution $\boldsymbol{\sigma}_{AEZ}$ (20). These changes in the production function allow to replicate the two ways in which carbon can be accumulated in forestry, namely, trough the intensive (T_{jr}) and extensive ($Land_{jr}$) margins, according to equation E13. Intensive margin relates to the increase in biomass of existing forestland as a result of implementing forest-management practices (for instance, change of rotation period). In particular, this implies maintaining the acreage extension of forestland constant while increasing the volume of timber per hectare, resulting in a higher carbon intensity. Conversely, extensive margin involves carbon accumulation due to land conversion from agriculture and grazing to forestry uses.

Figure 3: Forestry sector production function



Source: Hertel *et al.* (2008)

4.3. Calibration strategy

The inclusion of a subsidy of 100$/tC for the European forest sectors represents one of the policy scenarios simulated in the context of this exercise (see Section 5 for a full description of all policy scenarios assumed). This section describes the calibration strategy adopted to adjust the path of forest carbon emissions under this policy scenario.

Responses to the forest-carbon subsidy are calibrated according to the data derived from the modified GTM model of Sohngen-Mendelsohn (2007) and reported in Golub *et al*., (2010).[16] These values, which can be seen in Table 5, express the changes in forest-carbon sequestration resulting over a period of 20 years, from the introduction of a 100$/tC subsidy to the forest sector.

Table 5: Present Value Carbon from Forestry for a subsidy of 100$/tC ($MtCO_2$-eq and MtC-eq over 20 years)

	Intensive		Extensive	
	CO_2	C	CO_2	C
US	698	190	5,378	1,467
China	3,505	956	1,885	514
Brazil	2,884	787	2,819	769
Canada	467	127	439	120
Russia	5,949	1,622	14	4
EU 25	51	14	38	10
Other Europe	1	0	-1	0
Other CEE	35	10	7	2
Central America	368	100	1,889	515
Rest of South America	4,541	1,238	8,717	2,377
Sub Saharan Africa	3,728	1,017	2,378	649
Southeast Asia	6,411	1,748	336	92
Oceania	25	7	1,818	496
Japan	233	64	295	80
North Africa and Middle East	9	2	42	11
East Asia	510	139	538	147
South Asia	420	115	229	62
India	6,153	1,678	4,355	1,188

Source: from Golub *et al.*, (2010)

We first reallocate these values to our regions according to the regional comparison reported in Appendix B. Hence, to calibrate the ICES-AEZ regional responses to the forest-carbon supply curves in Table 5 we implement a modified version of the procedure described in Hertel *et al*. (2008). To mimic the

[16] GTM is a dynamic, long-run, partial equilibrium model for the forest sector which derives optimal agents' responses to incentives for carbon sequestration. Harvest age, harvest area, land use change, and timberland management are endogenously derived as incentives to store carbon in forests are introduced. They adjust to maximise the net revenues from the timber market and from carbon sequestration. Specifically, carbon sequestration is calculated as the difference between forest carbon stocks at the end of two subsequent periods. Therefore data presented in this context result from a difference between two decades of carbon accumulation (cumulative sequestration), which have been actualised at a 5% discount rate. For this reason they can be referred to as present value carbon-equivalent amounts (see the following section for more details on equivalent carbon amounts).

effects derived from the GTM forestry model, we impose the ICES-AEZ model to run in a partial equilibrium mode. To this aim we fix all non-land endowment prices, as well as all land rents but forestry land rents, and also utility. In addition, we fix the quantity of imported timber input used by forestry, to avoid that forest carbon incentives result in the increase of imported timber from abroad rather than in the enhancement of the volume of forest biomass associated to a given extension of forestland (carbon intensity).

The first calibration step is then to reproduce the extensive margin sequestration related to the amount of carbon only corresponding to the land conversion from agricultural activities to forestry. For this purpose the substitution between the land composite and the timber intermediate is temporarily deactivated. It is assumed that $\boldsymbol{\sigma}_{AF}$ in the land supply tree can take positive values (fixed at the values reported in Table 4), while $\boldsymbol{\sigma}_{CARBON}$ in the forest production function equals 0. In this case, the introduction of forest carbon incentives will only impact forest profitability maintaining the same management practices. This leads therefore to an increased forest land having the same carbon intensity per hectare. This procedure gives calibration values for regional forests carbon intensities that allow reproducing the extensive-margin responses from the GTM model given a 100$/tC subsidy.

In the second calibration step, the intensive-margin sequestration responses are reproduced. The opportunity to convert agricultural and grazing lands to forests is made unattainable by setting $\boldsymbol{\sigma}_{AF}$ equal to 0, so that there are no changes in the available land distribution. In addition, and while using the new forest-carbon intensities found in the previous step, we fix the price of forestry to obtain the corresponding value for $\boldsymbol{\sigma}_{CARBON}$. This allows reproducing the intensive margin from GTM, by increasing the own-use of timber augmenting the carbon intensity in managed forests. The results for the forest carbon intensities and substitution elasticities for the carbon composite of the two-step procedure are shown in Table 6.

Table 6: Regional forest carbon intensities and elasticities of substitution for the carbon composite

Region	Forests Carbon Intensity	σ_{CARBON}
USA	0.2820	0.027
Med_Europe	0.0014	0.500
North_Europe	0.0009	0.476
East_Europe	0.0004	0.626
FSU	0.0143	3.497
KOSAU	0.5322	0.042
CAJANZ	0.0965	0.135
NAF	0.0197	0.044
MDE	0.0102	0.085
SSA	0.0356	0.264
SASIA	1.9054	0.238
CHINA	0.1133	0.386
EASIA	0.0385	1.434
LACA	0.0607	0.119

Source: Own Elaboration

4.4. Forest carbon reversibility and additionality

Both Non-permanence (or potential reversibility) and additionality are serious concerns, which increase the risk of making forest-based mitigation opportunities less attractive. The scientific community interested in analysing forest-mitigation potential in time, has been attempting to address these two issues when deriving forestry emissions and sequestration paths.

Unlike emissions reductions in the energy-intensive sectors (achieved by, for example, a change in technology), carbon sequestered in forests could be subject to non-permanency. Forest fires, harvesting activities, extreme events or other disturbances may cause previously stored forest carbon to be successively released into the atmosphere. On the containment of reversibility risks three main carbon-accounting schemes have been proposed to assign credits to the forest-based mitigation projects: i) comprehensive, ii) ex ante discounting, and iii) temporary crediting (see Murray, 2007 for more details on crediting systems). Among these, the temporary crediting scheme has emerged as the leading system for managing credits related to activities such as afforestation and reforestation. Broadly speaking, this system assumes that sequestration projects have a finite life. Hence, as the project expires new credits for new projects must be purchased or GHG emissions must be reduced to meet the targets.

The principle of Additionality, introduced by the Kyoto Protocol, requires that offset credits are granted only if forest-carbon sequestration, resulting from forest projects, is additional to the amount of carbon stored in case those projects would have not taken place. In this respect, baseline emissions must be calculated to attest that there was an effective additional amount of carbon stored by forests due to the implementation of certified projects.

In the context of this exercise, as previously mentioned, we calibrated our results to the GTM forestry model. The GTM framework develops a modelling method which addresses both aspects. First they calculate cumulative carbon gains ($C^G{}_t$) as the variation in carbon stocks between the baseline ($S^B{}_t$) and the carbon price scenario ($S^S{}_t$):

$$CG_t = S_t^B - S_t^S \tag{E14}$$

From cumulative carbon gains annual net sequestration (ANSt) is derived. Since the GTM model is solved in decadal time-steps, the difference of cumulative carbon gains associated to two subsequent periods of time is dived by 10 to obtain an annual value.

$$ANS_t = \frac{(CG_t - CG_{t-1})}{10} \tag{E15}$$

Hence, the annual net sequestration, estimated over a 20-year time horizon, can be defined as the present value of carbon sequestered, which is exactly what we calibrated our model to (see Table 5):

$$PVC = \frac{(CG_t - CG_{t-1})}{10}\frac{1}{(1+r)} \tag{E16}$$

The annual amount of carbon, whose present value exactly equals the value in E16 is defined as the annual equivalent carbon (AEC) sequestered.

Then, as it is shown below, the present value of carbon can be conceived as the discounted value of the annual amount of carbon sequestered over a period of 20 years. In particular we can write:

$$AEC\left[\frac{1}{r}\frac{1}{r(1+r)^{t}}\right]=PVC \tag{E17}$$

By measuring carbon storage per year, the GTM model allows to accurately capture the timing of carbon flows accumulation. Moreover, by discounting over a 20-year period the annual values of above-baseline carbon sequestration, this approach allows overcoming both the problem of additionality and of non-permanence.

Given a carbon price scenario, considering only above-baseline values for forest-carbon sequestration, allows overcoming the problem of additionality. On the other hand, by taking into account what occurs over the 20-year period, the issues of non-permanence over this period are also addressed. Finally, they assume a payment system, which is consistent with the temporary crediting mechanism previously described. In fact, only net carbon gains are credited and they are paid only during the time in which forest carbon remains stored.

Given that our model variables have been calibrated to replicate GTM outcomes, and given that GTM results account for the issues of additionality and non-permanency, we are confident that results on carbon storage implied by our model implementation do not need further corrections on either of the two concerns.

4.5. Woody biomass

The use of woody biomass to produce electricity may consist of a relevant component of forestry mitigation in the future. However, for the reasons stated below, we consider it reasonable not to account for this forest-related mitigation activity.

Although the European Commission is studying the opportunity of reinforcing the use of forestry as energy biomass in its 2020 GHG target, a clear framework for a biomass policy is still not defined. Clear limits on how and to what extent woody biomass can be sustainably harvested and supplied have not been set thus far. Indeed, only at the beginning of 2011, the European Commission started a public consultation in preparation of a report concerning additional sustainability measures at the European level for both solid and gaseous biomass used for electricity production, second generation biofuel production, heating and cooling.

At the same time, a number of studies have recently pointed out possible drawbacks deriving from the implementation of wood as biomass. For example, the EU-wood project (Mantau *et al.*, 2010) suggests that only if a number of challenging conditions are satisfied it will be possible to meet the renewable energy target in 2020 by making use of the wood component in a way which does not negatively affect the wood supply of the traditional industries. Hence, at a more stringent target on emissions (30%) would be associated a more likely risk of affecting European industries supplying or importing timber, and of having repercussions on rural income, landscape, and biodiversity. Similarly, other studies have shown that harvesting wood for biomass use can have negative consequences on both environmental as well as social grounds given that, at the current state, biomass policies are not aligned with sustainable forest management (see UN-ECE\FAO projections).[17]

Existing projections on the use of promising technologies have been claimed to be largely speculative (Sedjo, 2011). For example, projections on the biomass-integrated gasification combined cycle (BIGCC) or the co-firing of coal with woody biomass seem to be based on an unfounded statement. Supposing that carbon released by biomass combustion is re-sequestered during the biomass re-growth, implies that woody biomass may provide a carbon-neutral source of energy.[18] It has also been declared that while the use of woody biomass can lead to lower atmospheric GHGs emissions over time, immediate carbon neutrality is not likely to be guaranteed given that its use could result in a worse climate in the short-term.[19] Other aspects hindering the development of such technologies relate to costs evaluations. Wood energy production appears to be more expensive than coal-based energy production given that even raw wood for direct combustion costs much more than coal (Sedjo, 1997). Indeed, several models have concluded that the use of biomass as a renewable energy is likely to become economically relevant only after 2020, assuming a more dominant role by the middle of the century (Edenhofer et al 2010).

For these reasons, it is difficult to envision a development of the use of wood for energy production in the near future, especially during the 20-year period assumed in our exercise. Hence, we have focused our analysis on forestry options whose implications have already been analysed in a number of studies, are available in short-term, and might still play a significant role in a 2020 EU climate policy.

5. BUSSINESS AS USUAL AND POLICY SCENARIOS

We develop a business as usual scenario (BAU) and 2 sets of policy scenarios. Our results derive from the difference between the baseline and the counterfactual set-up.

Specifically, the BAU in 2020 is the result of both exogenous and endogenous variables projections. Major exogenous paths are: i) the evolution of population (UNPD, 2008), ii) energy efficiency (Bosetti *et. al*., 2006), iii) and the land productivity (IMAGE 2.2, 2001). Land productivity is net of climate change effects and is assumed to be the same across sectors (including forestry and grazing), and AEZs. Apart from those assumptions, the rest of the variables in the model behave endogenously. Among those, some are calibrated to reproduce future expected trends. For example, GDP growth rates are calibrated according to the IPCC A2 scenario.[20] Fossil fuels price trends replicate EIA projections (EIA, 2007 & 2009). On forest-related variables, forest-carbon stock is calibrated by adding to the initial value in 2001 (benchmark year), the forest carbon sequestration between 2001 and 2020, derived from the Global Timber Model (Sohngen *et al*., 2008). This model provides annual information for 226 regions (in Million tons/yr), which have been aggregated into the 14 regions of the ICES-AEZ model. Main variables of the baseline scenario are reported in Table 7 below.

[17] On UN-ECE\FAO projections see:
[18] It neglects to account for emissions from biomass extraction (from both direct and indirect land use-change) and assumes that the difference between carbon released by biomass combustion and the one re-captured is '0'.
[19] The Manomet study, a recent report developed at the Centre for Conservation Sciences (Natural Capital Initiative Report NCI-2010-03) concludes that emissions from wood burning are initially higher than those from fossil fuels burning. It also claims that replacing a coal-fired or natural-gas burning power plant with a co-firing wood-burning one could take more than 20 and 90 years respectively, before any net benefits are realised (again, our time-horizon is less than 20 years).
[20] The resulting GDP values are slightly higher than those from the previous chapter due to the simultaneous calibration of the forest-related variables according to the new structure of the model.

Table 7: Growth rates for main variables and forest carbon stock in BAU (2001-2020)

Regional Disaggregation	Region Code	GDP (%)	Population (%)	Energy Efficiency (%)	Land Productivity (%)	Forest Carbon $Stock_{2020}$ (MtC)	Forest Carbon Seq 2001-2020 (MtC)	CO_2 emissions 2020	non-CO2 emissions 2020
United States	USA	**61.8**	18.9	11.5	37.6	**25,788**	**765.6**	**2,099**	**472.8**
Mediterranean Europe	MED_EU	**38.4**	6	15.4	18.2	**9,623**	**159.3**	**443.6**	**145.9**
Northern Europe	NORTH_EU	**55.7**	4.3	15.4	18.2	**15,322**	**108.7**	**734.5**	**156.7**
Eastern Europe	EAST_EU	**125.3**	-5.7	36.4	79.7	**12,897**	**114.6**	**267.5**	**96**
Former Soviet Union	FSU	**106.3**	-3.2	32.9	79.7	**32,623**	**763.5**	**811.8**	**357.1**
Korea, South Africa, Australia	KOSAU	**48.5**	10.4	24.7	69.1	**4,696**	**724.8**	**404**	**125.2**
Canada, Japan, New Zealand	CAJANZ	**40.4**	2.1	15.6	69.1	**14,778**	**54.2**	**610.2**	**108.1**
North Africa	NAF	**131.4**	31.9	24.1	105.8	**1,212**	**60.6**	**156.7**	**76.4**
Middle East	MDE	**220**	38	24.1	105.8	**3,899**	**70.8**	**717.2**	**330.3**
Sub Saharan Africa	SSA	**119.2**	58.1	19.8	105.8	**104,748**	**148.5**	**91.5**	**583.6**
Southern Asia	SASIA	**140.2**	32.9	40.2	96.9	**3,353**	**190.2**	**604.3**	**512.3**
China	CHINA	**219.6**	11.1	42.7	96.9	**22,237**	**853.8**	**2,417**	**1052.1**
Eastern Asia	EASIA	**189.7**	24.3	39.1	105.8	**32,620**	**336.2**	**422.5**	**468.8**
Latin and Central America	LACA	**100.6**	24.4	21.1	105.8	**274,668**	**298.7**	**537.1**	**671.3**

Note: In bold the endogenous behaviours.
Source: Own Elaboration.

In addition to the baseline previously described, two sets of policy scenarios were also developed:

- In a first set (referred to as "climate policy scenario: CP" from this point on) we assume that Europe commits independently from other countries to reduce CO_2 emissions by 20% and 30% compared with 1990 values, by 2020. This is modelled by imposing exogenous quotas within an Emission Trading Scheme (ETS) for the three European regions involved in a climate policy. From this quota ICES-AEZ derives an endogenous carbon price consistent with the emissions reduction targets to be met. This price, representing the common price at which the quotas are traded, has the effect of allocating emissions permits in a way that marginal abatement costs are equalised among those countries.
  The introduction of a quota increases European prices of polluting-energy inputs, imported by Europe or domestically purchased. These inputs can be demanded by households, firms, and the government, which are, therefore, all affected by the quotas. On the other hand, non-CO_2 emissions from agriculture are not subject to the emissions quotas. This choice is justified by the current exclusion of agricultural activities from the range of mitigation opportunities connected with a carbon market. Indeed, the policy decision of valuing terrestrial carbon coming only from some land-using activities could entail the perverse effect of generating

land-use shifts that ultimately increase rather than contain carbon emissions (Sands-Kim, 2008). Introducing this assumption in our analysis, and in line with the current state-of-the-art discussion on terrestrial carbon sinks, allows to measure whether this effect takes place.

- In a second set (referred to as "climate policy & subsidy scenario: CP&S" from this point on), in addition to the targets on emissions reduction, a carbon incentive of 100$/tC is only applied to the forest sectors. This is financed by European governments spending, and is received by firms in the forest sectors, which either increase the forest acreage extension or implement sustainable forest-management activities, thereby enhancing the demand of the carbon composite and therefore carbon sequestration.[21] To explore the sensitivity of major variables to different levels of forest-carbon incentives for Europe, we also simulate more modest carbon-sequestration subsidies in the order of 10$/tC and 50$/tC.

6. MAIN RESULTS

Results relate to three main areas of analysis. Paragraphs (a) and (b) look at policy costs and savings under different policy combinations and investigate the net impact on the economy for increasingly higher forest-sequestration subsidies. Carbon mitigation and the well-known leakage phenomenon are analysed in paragraph (c), while the policy effects on forestry and agriculture are dealt with in the final paragraph (d). Having calibrated our model with values, which are derived from a forest-partial equilibrium system, we are confident that the results presented below are reasonable.

6.1. The economics of climate policy and of forest-sequestration subsidies

As expected, the introduction of a quota on emissions for Europe translates in the decline of its economy which amounts to 2.4% (309 USD bn) and 3.9% (501 USD bn) of real GDP for the 20% and 30% emissions reduction target respectively with a more accentuated effect for East_Eu (6.5% and 10.7% of its GDP).[22] Indeed, for East_Eu an emissions reduction of 20% and 30% relative to its 1990 values corresponds to an effective effort of respectively 27% and 40% (with respect to 2001), while for the other two regions the mitigation effort remains below 25%.

These policy costs estimates lie above the average figures presented within the CGE literature thus far. This is the consequence of three major aspects. First, the GDP growing path for Europe has not been calibrated taking into account the recent recessive economic situation, which would have surely lowered the estimated cost of climate policy. Second, although our model accounts for non-CO_2 emissions projections in 2020, mitigation has not been allowed in a multi-gas perspective, given the current exclusion of agricultural activities from the range of mitigation opportunities connected with a carbon market. Introducing this element of flexibility within the portfolio of mitigation strategies could reduce the climate policy costs further. A third and most important aspect regards our assumptions on substitution parameters, which have been changed with respect to the traditional values in the previous ICES version, and those used in the original GTAP-E model. The new values for these parameters, changed according to Beckman *et al.* (2011), are found to shift the European mitigation costs upwards. To prove the validity of this last deduction we present, in Section 7, a sensitivity analysis assessing the responsiveness of climate abatement costs to different assumptions on those substitution parameters.

[21] It is assumed that expanding the forest carbon stock by one ton corresponds to a reduction in carbon emissions by one ton.
[22] Policy costs are measured as the reduction in real GDP in 2020 compared with the business as usual set up, and are expressed in 2001USD.

The introduction of incentives to store carbon in forests generates three main direct effects. First, it lowers policy costs, allowing savings ranging between 8.8 and 10.8 USD billions, depending on the considered scenario (Table 8, column 4).

Table 8: Real GDP and cost of the policy under different CP and CP&S scenarios

	BAU	Real GDP under CP (Billion $)		Real GDP under CP&S (Billion $)		Saving in policy costs due to forest subsidy (Billion $)		Increase in policy costs: from -20% to -30% target (%)	
		-20%	**-30%**	**-20%**	**-30%**	**-20%**	**-30%**	**CP**	**CP&S**
Med_Eu	4,569	4,467	4,404	4,470	4,408	3.0	3.7	62.77	62
North_Eu	7,998	7,847	7,754	7,851	7,759	4.4	5.3	92.88	92
East_Eu	862	806	770	807	772	1.4	1.8	35.33	35
Total	*13,429*	*13,120*	*12,928*	*13,128*	*12,939*	8.8	10.8	191	189

Source: Own Elaboration

Second, it redirects public spending, as savings in policy costs come at the expenses of a European government disbursement of about 1.56 USD bn.

Third, it generates impacts on the carbon market whose size depends on the exchange price of emissions permits, namely, the marginal abatement cost. In fact, European regions participating in a coordinated climate policy are allowed to trade those permits within the simulated ETS. The European carbon price following the climate policy results around 136 $/tCO_2$ in the 20% mitigation scenario and 218 $/tCO_2$ in the 30% one.[23] At these prices between 19.3 and 20.5 million tons of carbon are traded, with a market volume ranging between 9.6 and 16.4 USD bn. Supporting forest-carbon sequestration implies a reduction in carbon prices ranging from 2% to 3% in the two CP&S scenarios. Conversely to North_Eu, a net credits seller, East_Eu and Med_Eu result net buyers, having reduced emissions for an amount, which is respectively 4 and 3 MtC lower than their quotas. For Med_Eu the reduction in the carbon price translates to a savings ranging between 0.8 and 1.1 USD bn in the 20% and 30% abatement scenarios, respectively. Interestingly, the lower carbon price induces East_Eu to purchase additional carbon credits for 0.4 and 0.6 USD bn as it is asked to reduce emissions for a level which is 60% higher than the Med_Eu one.

6.2. Net impact on the economy for increasing levels of a forest-sequestration subsidy

From the simulations of more modest forest-sequestration incentives, for a 30% climate policy, we observe that for increasing values of forest-carbon subsidy the required climate mitigation effort reduces for all European regions. As a consequence, greater savings in policy costs are attainable although they are associated to growing governmental expenses. Interestingly, the net final effects on the regional economies result positive, although they are marginally decreasing (see Table 9).

[23] These price estimates, which could appear high at first glance, represent the direct consequence of using new values for the elasticity parameters, which, as previously mentioned, have the effect of shifting the European mitigation costs upwards.

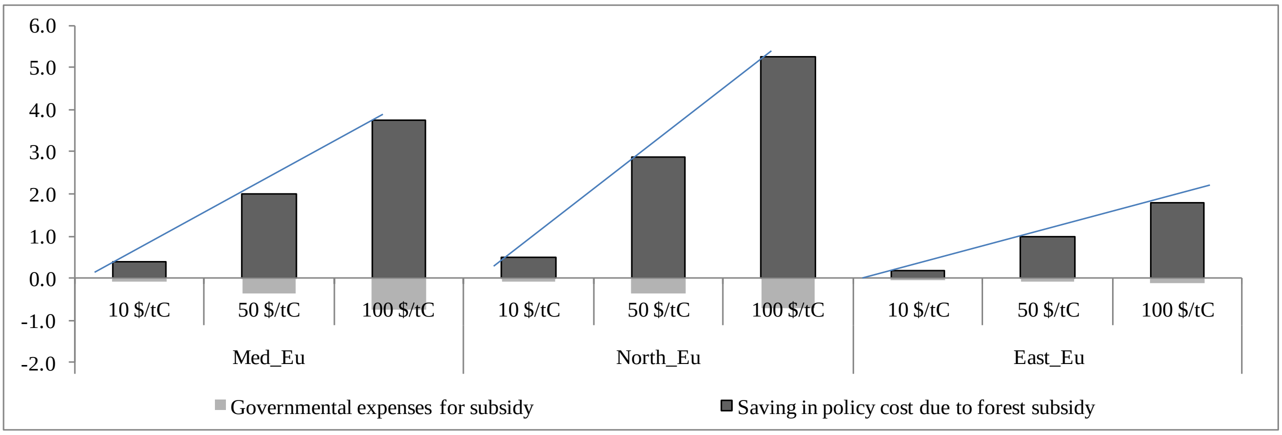
Table 9: Effects of different subsidy levels under a 30% climate policy (USD billions)

	Med_Eu			North_Eu			East_Eu		
BAU	4,569			7,998			862		
Real GDP under CP	4,404			7,754			770		
Forest-carbon Subsidy	**10 $/tC**	**50 $/tC**	**100 $/tC**	**10 $/tC**	**50 $/tC**	**100 $/tC**	**10 $/tC**	**50 $/tC**	**100 $/tC**
Real GDP under CP&S	4,405	4,406	4,408	7,754	7,757	7,759	770.422	771.214	772
Saving in policy cost due to forest subsidy	*0.4*	*2.0*	*3.7*	*0.6*	*2.9*	*5.3*	*0.2*	*1.0*	*1.8*
Governmental expenses for subsidy	*-0.07*	*-0.37*	*-0.74*	*-0.07*	*-0.35*	*-0.70*	*-0.01*	*-0.07*	*-0.13*
Net Impact of subsidy	***0.33***	***1.64***	***3.01***	***0.51***	***2.51***	***4.56***	***0.19***	***0.92***	***1.65***

Source: Own Elaboration

The marginal climate abatement cost is comparatively lower in regions that are more polluted. Precisely for this reason and despite the higher abatement effort requested, policy costs in East_Eu are rather low. In addition, forestland in East_Eu covers less than half that of Med_Eu and North_Eu. East_Eu detains a contained opportunity to use forest-carbon sequestration. This entails that a savings in policy costs for East_Eu remains limited in comparison with results achieved elsewhere (Figure 4).

Figure 4: Net impact of the subsidy under a 30% climate policy (USD billion $)

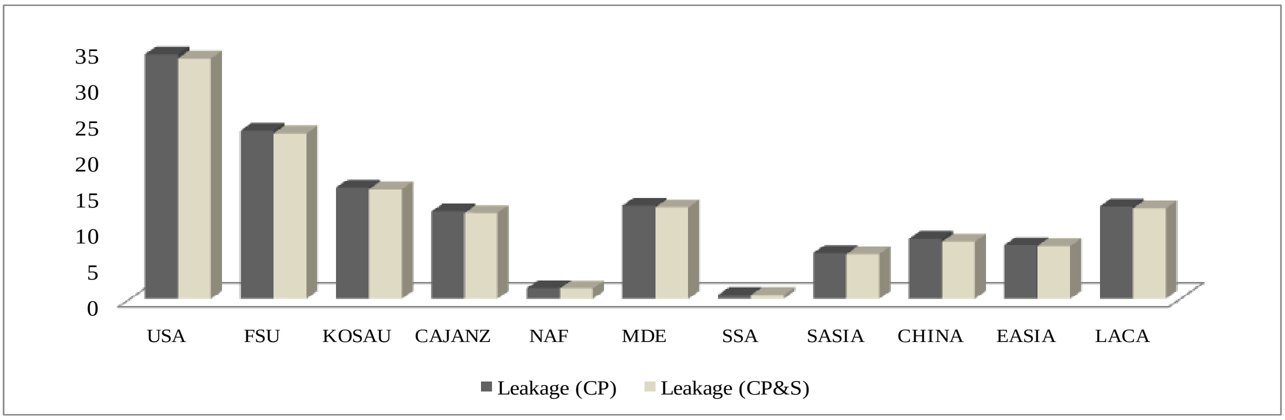


Source: Own Elaboration

6.3. Emissions and leakage effects

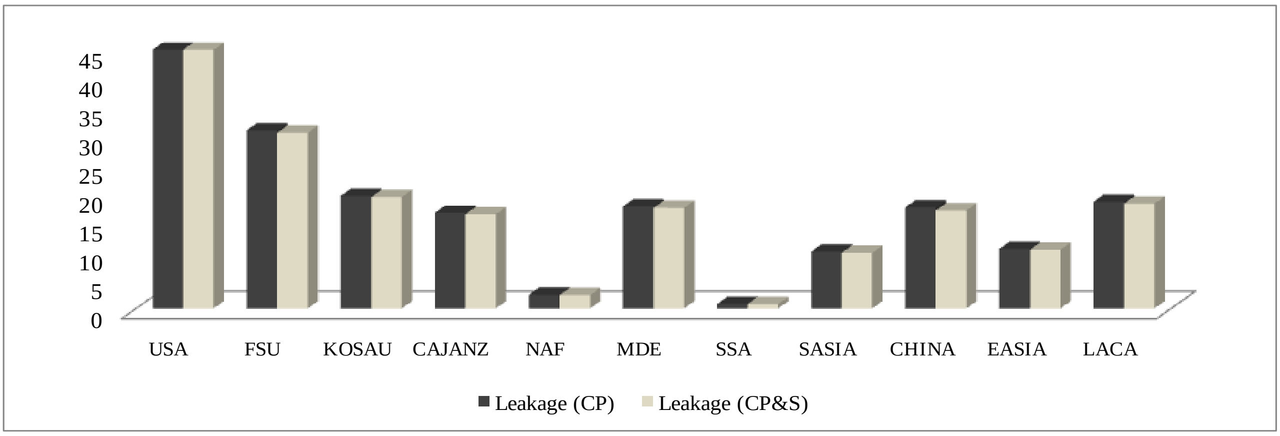
The risk entailed by a unilateral European climate policy implementation is the well-known problem of carbon leakage. This is driven by the increase in fossil fuels demands and relative emissions outside the borders of the climate policy (outside Europe), due to the comparatively lower costs of such productive inputs (notice that only European use of fossil fuels is charged with an environmental tax). This effect primarily translates to the increase of production, and therefore GDP growth rates for all but the European regions. Secondly, it has the additional impact of boosting CO_2 emissions outside Europe. As expected, this effect is proportionally higher as the policy burden rises from the 20% to 30% emissions reduction target (See Figures 5 and 6). This result is more evident for regions such as the Former Soviet Union and China, for which fossil fuels imports increase more than in other regions due to prices differentials.

Figure 5: Leakage distribution wrt BAU: 2020-20% (Mt C)



Source: Own Elaboration

Figure 6: Leakage distribution w.r.t. BAU: 2020-30% (Mt C)



Source: Own Elaboration

The amounts of carbon emissions released in the atmosphere by non-European countries are reported in Table 10. These figures show that the forest sequestration subsidy allows to decrease the perverse leakage effect. Even though the effect is negligible, it renders the reduction in emissions a more easily achievable mitigation target for Europe.

Table 10: Leakage effect under different scenarios

	CP case			**CP&S**		
	Increase outside (MtC)	**EU-reduction (MtC)**	**Leakage**	**Increase outside (MtC)**	**EU-reduction (MtC)**	**Leakage**
-20%	134.94	391.63	**34.5%**	132.22	385.50	**34.3%**
-30%	190.43	509.73	**37.4%**	187.34	503.55	**37.2%**

Source: Own Elaboration

In fact, using forest-carbon sequestration as an additional abatement technology entails for European energy-intensive sectors the opportunity of releasing additional carbon for 6 MtC (within the 20% reduction in emissions), and 6.2 MtC (in the more stringent policy target).

6.4. Effects on forest and agricultural sectors:

The introduction of climate policies for Med_Eu and East_Eu generates a reduction in timber supply by less than 1% and 3% in the 20% and 30% targets respectively. The small magnitude of this rationing does not involve any boosting effect on deforestation outside Europe. In addition, with the inclusion of the forest-carbon sequestration, this decline is slightly attenuated in both regions as a result of the increase in the carbon composite demand. Conversely, North_Eu experiences an increase in timber supply in both policy scenarios, due to the comparatively lower production costs in forest rather than in agricultural sectors.

Carbon sequestration resulting from the 100$/tC subsidy is entirely driven by the GTM model results to which our data are calibrated, and is directly connected to the changes in the carbon composite demanded from the representative firms in European forest sectors. More specifically, forest-carbon sequestration has to be seen as the combined effect of extensive and intensive forest margins. To get a sense of its distribution, we can observe the endogenous variations in its two forest-margin components once the subsidy is introduced. In particular, Med_Eu shows an expansion of its forestland coverage, while in East_Eu the land demand reduces. At the same time, timber management intensity is lowered in Med_Eu and slightly increased in East_Eu. Summarising, the bigger effects on timber supply and forest-carbon sequestration changes seem to be driven by land conversion for Med_Eu and higher forest-management activities for East_Eu. As for North_Eu, the already high level of timber production makes the effects of having more favourable timber prices negligible, leaving the situation substantially unchanged. In contrast, in North_Eu the important contraction in agricultural production due to the documented increase in timber supply following the implementation of both climate policies is attenuated by the inclusion of a subsidy, which lowers the mitigation effort required.

As for agricultural production in the remaining European regions, two different and competing effects take place after the inclusion of the forest subsidy. On the one hand, forest-sector production increases subtracting land from agriculture. It follows a decrease in agricultural production driven by the higher demand for forestland, which translates into an increase of agricultural prices. On the other hand, fostering the implementation of forestry practices also has the effect of alleviating production costs in the agricultural sectors, which are charged for using fossil fuels in the production process. While the resulting net effect is therefore mixed, our results show that the second one dominates over the former, generating a negligible yet positive impact on agricultural production and a negative impact on prices. In general, resulting land competition between agriculture and forestry does not entail significant variation in agricultural food prices and quantities outside Europe, although a very small decrease in both of them applies. This minor impact, supporting the thesis that no perverse implications on food security occur, can be seen as a direct consequence of the limited role envisaged for European forests in 2020 by Sohngen-Mendelsohn (2007).

7. SENSITIVITY ANALYSIS ON SUBSTITUTION PARAMETERS

The size of substitution elasticity parameters in the value-added and lower nests becomes central to determine the magnitude of the abatement effort (see Jacoby *et al.*, 2006). In fact, the rise in relative prices of carbon-based fuels encourages economic agents using those products to avoid the additional burden by using less carbon-content fuels (e.g., substitute coal with natural gas). Moreover, agents can decide to substitute energy-based inputs with capital, and indirectly with other production factors such as land and labour. The magnitude of the corresponding elasticities of substitution drives the policy burden in such a way that the higher the substitution flexibility, the lower the policy costs. As claimed in Beckman *et al.*, (2011), the original version of GTAP-E presents overvalued substitution parameters of price elasticity for energetic-input demands, which do not perform well against real historical data. This results in a great underestimation of the climate abatement efforts. As a consequence, simulations with new validated parameters are expected to produce higher climate policy costs.

To corroborate this statement, the following paragraphs show the responsiveness of policy costs to changes in different elasticities. Simulations presented relate to a base scenario and 4 settings associated to different assumptions on substitution elasticities. The base scenario (Old Elasticities) reproduces the old ICES structure. The second setting (New VA nest Elasticities) leaves all the parameters unaltered with the exception of the value-added nest substitutions, which have been calibrated assuming supply elasticities suggested by Beckman *et al*. (2011). The third setting (New Capital & Energy Elasticity) replaces the old substitution between Capital and Energy with a new one, leaving the rest unaffected. The fourth (New Inter-fuels elasticities) assumes new values only for the inter-fuels substitution. At last, the final scenario (which we referred to within this paper), combines new elasticities for all the levels of the nested production structure. The table below reports assumed old and new elasticity values for all the production nests.[24]

Table 11: Revised values for demand and supply elasticities

		Old	new
		Supply elasticities	
	coal	0-5-0.61	1
	oil	0.5-0.63	0.25
	Gas	1-18	4
		Factor demand elasticities	
	Capital & Energy	0.5	0.25
Inter-fuel substitution	**(non) Electric**	1	0.16
	(non) Coal	0.5	0.07
	Remaining fossil fuels	1	0.25

Source: Own Elaboration

Comparing the base scenario with the other settings it is possible to draw conclusions on the elasticities that mostly affect results on climate abatement effort. Results below only refer to the more stringent climate policy effort. Certainly, conclusions can also be extended to the 20% emissions reduction case. The sensitivity analysis clearly confirms that the lower the factor demand elasticities, the higher the abatement effort required to achieve the emissions reduction targets (see Table12 columns 3 and 4).

Table 12: Abatement costs, w.r.t. BAU, for different substitution scenarios (30% Climate Policy)

	Old Elasticities (Base case)	Base vs KE case	Base vs Inter-fuels case	Base vs VA case	Base vs Combined effects (Final Case)
Med_Europe	**-2.28%**	-3.03%	-2.96%	-2.01%	-3.60%
North_Europe	**-2.03%**	-2.62%	-2.60%	-1.80%	-3.05%
East_Europe	**-5.97%**	-8.18%	-8.16%	-5.41%	-10.69%

Source: Own Elaboration

[24] The new formulation of the value-added elasticities (σ_{VAE}), contemplating two dimensions (region and sector), results in a matrix format and is therefore omitted for purposes of brevity.

Lower substitution between capital and energy generates an increase in policy costs, with respect to the base case, ranging between 0.6% and 2.2%. Similarly, smaller inter-fuel elasticities produce an additional increase in costs of substantially the same magnitude (see Table 13, columns 2 and 3). Finally, the new value-added nest elasticities imply, for most regions and sectors, larger substitution possibilities (greater flexibility to mix inputs). This result is predominantly due to the more elastic supply assumed for coal, which is the most carbon-intensive input. This assumption, which lowers the impact of emissions tax on market prices, translates into a reduced abatement effort compared with the base case (see Table 12 column 1). The combined effect on policy costs (see Table 12 column 5), results in a final increase of the mitigation effort. This outcome shows that the upward effects on costs from inter-fuels and capital and energy substitutions outweigh the downward impacts generated by the change in the value-added nest elasticities.

Table 13: Differences w.r.t. base case (30% Climate Policy)

	Base vs KE case	Base vs Inter-fuels case	Base vs VA case	Base vs Combined effects (Final Case)
Med_Europe	*0.8%*	*0.7%*	*-0.3%*	*1.3%*
North_Europe	*0.6%*	*0.6%*	*-0.2%*	*1.0%*
East_Europe	*2.2%*	*2.2%*	*-0.6%*	*4.7%*

Source: Own Elaboration

8. CONCLUSIONS

This paper has extended the traditional ICES CGE model in order to analyse the potential role of European forests within climate mitigation. This has been done by enhancing both the database and the modelling framework. The new version (ICES-AEZ) accounts for land heterogeneity across and within regions, and for land mobility across different uses. The forest-sector production function has been notably improved to track forest-carbon sequestration resulting from both intensive and extensive forest margins. A specific calibration procedure has been developed to make our values on forest sequestration coherent with those resulting from GTM, a sectoral forestry model specifically designed to capture forestry dynamics (Sohngen-Mendelsohn, 2007).

Two different scenarios have been simulated in addition to the business as usual. In a first climate policy scenario Europe, divided into 3 macro regions, unilaterally commits to reduce CO_2 emissions by 20% and 30%, in 2020. In a second scenario, additionally to a climate policy, forest-carbon sinks in Europe are conceived as an abatement "technology" and are supported by the inclusion of progressively higher values of subsidies for the forest sector.

Results show that the slowdown of the European economy follows to the inclusion of emissions quotas. European regions experience a GDP reduction of 2.4% and 3.9% in 2020. A sensitivity analysis on relevant substitution parameters justifies these costs estimates, highlighting that lower substitution elasticities are associated with more elevated policy costs.

Allowing the use of forest-carbon stock within the European compliance strategy reduces the cost of climate policy by 8.8 and 10.8 USD bn, depending on the considered abatement scenario. Also, it reduces the price of carbon at which emissions credits are traded on the ETS (by 2% and 3%, depending on the severity of the emissions reduction target). Finally, it redirects public spending as it entails a disbursement of 1.56bn $ at European level.

For increasing values of forest-carbon subsidies, the required climate mitigation effort reduces for all European regions. Greater savings in policy costs are attainable, even though they are associated with growing governmental expenses. Distributional effects across the different European regions depend on the region-specific position on the carbon market and on the region-specific mitigation effort relative to the other regions. Despite these disparities, as a forest-carbon subsidy is included, the final net impact on regional economies (considering government expenditures and savings in policy costs) is positive for every region.

Negligible effects are reported on food security and deforestation outside Europe, due to the contained effect entailed by the introduction of a subsidy on European forests only. However, the implementation of an independent climate policy has some drawbacks outside Europe, characterized by leakage effects in the order of 34.5% and 37.4% for the 20% and 30% emissions reduction quotas, respectively. In this regard, while the introduction of a forest subsidy is expected to contain this effect, our results do not show significant evidence on this direction.

Summarising, European forests can alleviate the burden on energy intensive sectors, leading to a lower GDP contraction when a carbon tax applies. However, their contribution as a stand-alone abatement strategy is insufficient to comply with the emissions reduction targets of 20% and 30%. The limited role envisioned for European forest carbon by the GTM model, which was reproduced in our analysis, suggests that a better result would be reached when other regions were allowed to take part in a climate stabilization agreement. The idea that the abatement effort should be shared amongst several regions is also supported by the high leakage effect resulting from simulating an independent European effort. This perverse consequence would be proportionally reduced as more countries are involved in a formal agreement on climate mitigation.

Within our CGE framework, this exercise represents a first attempt to model endogenous agents' decisions on land allocation between agriculture and forestry, as well as forest-sector characteristics, along with the implementation of a European climate policy. Hence, it addresses one of the main conceptual challenges of modelling terrestrial mitigation options, which is simulating competition for land between different land-using activities.

Certainly a consistent and comprehensive representation of the forest sector in a CGE framework remains to be a demanding task. This is reflected in the little number of existing CGE studies focusing on this issue. Further work is therefore required to face common challenges in this literature and to offer a more in-depth analysis of the forest-sector mitigation potential.

Interesting improvements to our analysis could consider the modelling of the expansion to currently inaccessible or non-managed forest areas, and the development of a dynamically consistent evolution of forest-carbon flows within the CGE framework.

The first aspect is rarely addressed in CGEs, although it would deserve more attention given its ability to interestingly change results on mitigation paths and costs. The second aspect, attainable by including regional forest growth functions directly into the CGE model, would instead avoid calibrating ICES values with results from a forestry model. While we acknowledge the importance of both aspects we leave these improvements for our future work.

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APPENDIX A: MODEL DESCRIPTION

The current version of ICES is represented by a recursive-dynamic, multi-sector and multi-region computable general equilibrium model of the world economy developed at the Fondazione ENI Enrico Mattei to the aim of analysing climate change impacts and policies.

In this appendix we describe the general features of the ICES model version used in this context referring readers interested in technical details to Hertel (1997). Specifically, for this exercise the long-run state is represented by a static equilibrium of the macroeconomy where all past shocks have fully worked out through the system.

ICES set up is characterised by a microfounded representation of agents' behaviours optimizing welfare subject to preferences, endowments, resources constraints, or technologies. It makes use of the Walrasian perfect competition paradigm to simulate adjustment processes, although some elements of imperfect competition can also be included.

Although it bases on the traditional economic theories it has been notably enriched with important improvements to capture most of the relevant socio-economic aspects of the climate change dilemma. For example, firms' production function offers a detailed description of energy technologies.

It is based on the Global Trade Analysis Project (GTAP) database, version 6 (Dimaranan, 2006) which represents the world economy taking 2001 as reference year and allowing for a maximum level of disaggregation of 87 regions and 57 commodities. Given its global dimension and its high flexibility in terms of regional and sectoral disaggregation, ICES is particularly useful to deal with the complex nature of a global economic system, where the numerous variables of different market sectors and regions are at play.

Our simplified structure of the economy aggregates the GTAP database into 13 regions, 17 industry sectors, and 4 endowment factors, i.e., capital, labour, land, and natural resources. All the sectors employ capital and labour in the production process, buying them from households. Capital and labour are perfectly mobile domestically while labour alone, is immobile internationally. There is a unique input type for land, required only by five agricultural sectors for crop growing and for grazing raising. Natural resources are divided into forestry, fishing, and fossil fuels, and are employed respectively by the forestry, fishing, and fossil energy industries (see Table 14).

Table 14: Regional and Sectoral disaggregation of the ICES model

1	USA	United States	1	*Rice*	Agricultural sectors	Labour	Capital	Land
2	EU27	Europe 27 States	2	*Wheat*				
3	XEU	Rest of Europe	3	*Other Cereals*				
4	FSU	Former Soviet Union	4	*Vegetables & Fruits*				
5	KOSAU	Korea, South Africa, Australia	5	*Animals*				
6	CAJANZ	Canada, Japan, New Zealand	6	*Forestry*	Forestry			Natural Resources: *Forestry*
7	NAF	North Africa	7	*Fishing*	Fishing			Natural Resources: *Fishing*
8	MDE	Middle East	8	*Coal*	Fossil Fuels Industries			Natural Resources: *Fossil Fuels*
9	SSA	Sub Saharan Africa	9	*Oil*				
10	SASIA	Southern Asia	10	*Gas*				
11	CHINA	China	11	*Oil Products*	Heavy Industries			
12	EASIA	Eastern Asia	12	*Electricity*				
13	LACA	Latin and Central America	13	*Energy intensive Industries*				
			14	*Water*	Light Industries			
			15	*Other Industries*				
			16	*Mkt Services*				
			17	*Non Mkt Services*				

Source: Own Elaboration.

Below an overview of the main assumptions on functional forms used in the static core of the model is provided distinguishing between supply and demand sides.

Supply Side

On the production side, a representative price-taker firm, for each industry, minimize costs for a given output level. Under the perfect competition postulation, a competitive equilibrium exists and has desirable properties.

The production structure of the standard GTAP model (Hertel, 1997) has been replaced by the more detailed GTAP-E specification (Burniaux-Truong, 2002), which among other things improves the modelling of the energy production through the combination of two different frameworks simultaneously solved. A bottom-up (engineering) approach, detailing the energy producing processes or technologies accounting for inter-fuel and fuel-factor substitution, is linked with a top-down (economic) one, describing the macro economy with behavioural responses.[25] More specifically, the production process develops in a series of nested functions, a convenient structure to adopt different assumptions about the substitutability between diverse pairs of inputs (see Figure 10 for major elasticities of substitutions between nests).

Given j sectors (j = 1,...,17), r regions (r = 1,...,13), and being $\alpha_{VAE,j,r}$ a share parameter, the upper-level nested specification of the production tree (see Figure 10) describes the final output (Y_j) as a function of the factor productivity (A), the aggregate value added-energy (VAE_j), and the other intermediate inputs (M_j) provided by the 17 market sectors. Below, omitting the r subscript for convenience, we report the expression for final output (E1.a) which takes the form of a Leontief production technology.

$$Y_j = A\left[\alpha_{VAE,j} VAE_j^{\frac{\sigma_M - 1}{\sigma_M}} + \alpha_{M,j} M_j^{\frac{\sigma_M - 1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M - 1}} \qquad \text{(E1.a)}$$

By assuming zero-substitution rate between the two composites VAE_j and M_{jr} , i.e., for $\frac{\sigma_M - 1}{\sigma_M} \rightarrow -\infty$, Y_j can be alternatively and equally represented by equation E1.a and the following, E2.a.

$$Y_j = A \min\{ \alpha_{VAE,j} VAE_j , \alpha_{M,j} M_j \} \qquad \text{(E2.a)}$$

The lower-levels of the production processes are represented by Constant Elasticity of Substitutions (CES) functions allowing for some degree of substitutability between production factors. Given the share parameter δ_{ij}, the aggregate value added-energy output, VAE_j, is produced with X_i primary factors (i = natural resources, land, labor, and capital-energy composite) which are allowed to substitute one with the other at the elasticity of substitution σ_{VAE}.

[25] See Burniaux-Truong, (2002) for more details.

$$VAE_j = A\left[\sum_i \delta_{ij} X_{ij}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}}\right]^{\frac{\sigma_{VAE}}{\sigma_{VAE}-1}} \tag{E3.a}$$

Similarly, the capital-energy composite (*KE*) is produced by combining capital (*K*) and energy (*E*) production factors as illustrated by E4.a.

$$KE_j = A\left[\alpha_{k,j} K_j^{\frac{\sigma_{KE}-1}{\sigma_{KE}}} + \alpha_{e,j} E_j^{\frac{\sigma_{KE}-1}{\sigma_{KE}}}\right]^{\frac{\sigma_{KE}}{\sigma_{KE}-1}} \tag{E4.a}$$

Whether capital and energy are complements rather than substitutes is an important issue determining the direction of the aggregate output adjustments to changes in energy prices. Although empirical estimations of the corresponding elasticity parameter (σ_{KE}) vary considerably in size and sign, capital and energy tend to be complements in the short-run and substitutes in the long-run. To account for this aspect, while we assume σ_{KE} to be positive (0.5 for all industries), its value is set to be lower than σ_{VAE} so that the overall elasticity of substitution between capital and energy can still be negative.

Below the *KE* nest, energy production, *E*, is modelled as the combination of Electricity (*EL*) with Non-Electric (*NEL*) energetic vectors which can be substituted at the elasticity of $\sigma_{ELY} = 1$.

$$E_j = A\left[\alpha_{EL,j} EL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}} + \alpha_{NEL,j} NEL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}}\right]^{\frac{\sigma_{ELY}}{\sigma_{ELY}-1}} \tag{E5.a}$$

In turn, non-electric energy (*NEL*) is composed of Coal and Non-Coal energy, assuming an elasticity of substitution of $\sigma_{COAL}=0.5$.

$$NEL_j = A\left[\alpha_{COAL,j} COAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}} + \alpha_{NCOAL,j} NCOAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}}\right]^{\frac{\sigma_{COAL}}{\sigma_{COAL}-1}} \tag{E6.a}$$

The combination among the rest of liquid fossil fuels (*NCOAL*), that can be substituted at the elasticity of $\sigma_{FF} = 1$, are modelled as follow:

$$NCOAL_j = A\left[\sum_i \beta_{i,j} F_{i,j}^{\frac{\sigma_{FF}-1}{\sigma_{FF}}}\right]^{\frac{\sigma_{FF}}{\sigma_{FF}-1}} \qquad i = \text{oil, gas, fuel products} \tag{E7.a}$$

Finally, at the latter nests, the "Armington" assumption makes domestic (*DOM*) and foreign (*IMP*) inputs imperfect substitutes, enabling us to account for products heterogeneity.

$$M_j = \left[\alpha_{dom,j} DOM_j^{\frac{\sigma_{dom}-1}{\sigma_{dom}}} + \alpha_{imp,j} IMP_j^{\frac{\sigma_{dom}-1}{\sigma_{dom}}}\right]^{\frac{\sigma_{dom}}{\sigma_{dom}-1}} \tag{E8.a}$$

Also, imported commodities are modelled as a composite that combines imports of commodity *j* from all regions (*s*).

$$IMP_j = \left[\sum_s o_{j,s} Y_{j,s}^{\frac{\sigma_{imp}-1}{\sigma_{imp}}} \right]^{\frac{\sigma_{imp}}{\sigma_{imp}-1}} \qquad \text{(E9.a)}$$

APPENDIX B: REGIONAL AGGREGATION

ICES-AEZ	GTM regions	Golub *et al.*, (2010)	Regions 87 regions
CAJANZ	Canada	Canada	Canada
	Japan	Japan	Japan
	Oceania	Oceania	New Zealand
CHINA	China	China	China
	Hong Kong	Hong Kong	HONG KONG, CHINA
	Southeast Asia	East Asia	Taiwan
Oceania	Oceania	Oceania	Rest of Oceania
EASIA	Southeast Asia	East Asia	Rest of East Asia
		Malaysia and Indonesia	Indonesia
			Malaysia
		Rest of South East Asia	Philippines
			Rest of Southeast Asia
			Singapore
			Thailand
			Viet Nam
East_Europe	EU25	European Union 27	Bulgaria
			Czech Republic
			Estonia
			Hungary
			Latvia
			Lithuania
			Poland
			Romania
			Slovakia
FSU	Other CEE	Other East Europe and Rest of Former Soviet Union	Rest of Former Soviet Union
	Russia	Russia	Russian Federation
KOSAU	Oceania	Oceania	Australia
	Southeast Asia	East Asia	Korea
	Sub Saharan Africa	Sub Saharan Africa	South Africa
LACA	Brazil	Brazil	Brazil
	Central America	Central and Caribbean Americas	Mexico
			Rest of Central America
			Rest of Free Trade Area of the Americas
			Rest of the Carrebean
	Rest of South America	South and other Americas	Argentina
			Chile
			Colombia
			Peru
			Rest of Andean Pact
			Rest of South America
			Uruguay
			Venezuela

MDE	Middle East and North Africa	Middle East and North Africa	Rest of Middle East
	Other CEE	Other East Europe and Rest of Former Soviet Union	Turkey
Med_Europe	EU25	European Union 27	Cyprus
			France
			Greece
			Italy
			Malta
			Portugal
			Slovenia
			Spain
	Other CEE	Other East Europe and Rest of Former Soviet Union	Albania
			Croatia
			Rest of Europe
NAF	Middle East and North Africa	Middle East and North Africa	Morocco
			Rest of North Africa
			Tunisia
North_Europe	Central America	Central and Caribbean Americas	Rest of North America
	EU25	European Union 27	Austria
			Belgium
			Denmark
			Finland
			Germany
			Ireland
			Luxemburg
			Netherlands
			Sweden
			United Kingdom
	Other Europe	Rest of European Countries	Rest of EFTA
			Switzerland
SASIA	East Asia	Rest of South Asia	Bangladesh
			Rest of South Asia
			Sri Lanka
	India	India	India
SSA	Sub Saharan Africa	Sub Saharan Africa	Botswana
			Madagascar
			Malawi
			Mozambique
			Rest of South African Customs Union
			Rest of Southern African Development Community
			Rest of Sub-Saharan Africa
			Tanzania
			Uganda
			Zambia
			Zimbabwe
USA	USA	United States	United States