Global bioeconomic SFC model for the study of financial instabilities

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Abstract

This paper presents a global macroeconomic model that combines the economic impact of climate change with different agroforestry policies.The aim is to integrate climate damage and a dimension of biodiversity loss into an economic growth model while stressing the importance of tropical reforestation policies for climate change mitigation. Using a Stock-Flow Consistent approach based on Goodwin-Keen logic, we couple the non-linear monetary dynamics of underemployment and income distribution while taking into account the role of private debt as a factor of financial instabilities. The calibration at the scale of world enables us to simulate different planetary scenarios.

Keywords: Bioeconomic model, agroforestry, climate damages, Goodwin, Keen, Stock Flow Consistent Dynamics, out of equilibrium

JEL classification codes: C53, D72, E12, F64, Q23, Q41

1 Introduction

In 1972 at Stockholm, the first of a long series of Earth Summits was organised to define the means to stimulate sustainable development. One of the aims of these summits was to demonstrate the ability of states to cooperate in managing global problems and to affirm the importance of respecting environmental constraints. At the same time, the Club of Rome, a think tank of scientists, economists, national and international civil servants, and industrialists from 52 countries, gained worldwide recognition for its first commissioned report "The Limits to the Growth", also known as the "Meadows Report". This report is based on the interpretation of the World3 model and notes the limits of the dominant industrial model:

- accelerated industrialisation;
- strong growth of the world population;
- persistent malnutrition;
- depletion of non-renewable natural resources;
- environmental degradation.

These events are precursors in the understanding of sustainable development and had participated to the schism between environmental economics and ecological economics. In addition, the 2015 Paris agreements have politically crystallised the imperatives of a low-carbon economic transition. According to Global Commission on the economy and climate (2014), 90 trillion dollars would be needed globally to finance infrastructure to achieve the zero emission target.

In parrallel to these climatic considerations, the anthropogenic deterioration of natural environments reaches a critical state. The public consciousness of the impact of human activities on ecosystems can be partly attributed to Carson (1962) with the pubication of her famour book "Silent Spring" but more contemporarily the ntergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) regulary produces assessments of knowledge on biodiversity and ecosystem services and their interlinkages at the global level. According to their recent report (Díaz et al., 2019), 75% of the Earth's environment is "severely altered" by human activities and nearly one million animal and plant species are now threatened with extinction. These considerations underline the need to take biodiversity into account in models, our economic system is vitally embedded into ecosystems.

Healthy forest ecosystems play a significant role in the perpetuation of endemic species. Moreover, they also contribute to the production of ecosystem services and climate mitigation . Carbon (C) stocks in organic matter constitute one of the planet's main carbon reservoirs. About 20-30% of anthropogenic CO2 emissions are directly related to the destruction of forests for agricultural purposes (Houghton, 1991). With this in mind, Article 3 of the Kyoto Protocol states that afforestation, reforestation and other forestry activities must be taken into account by covered parties, including the United States, in meeting CO2 emission reduction targets (IPCC, 2000).

Thus, it is legitimate to ask the following questions: how will the world be able to finance the needs associated with these imperatives? Will it be able to assume the burden of private debt that will be associated with this financing? What financial instabilities are involved in a low-carbon transition of the economy? What is the role of forests in climate change mitigation? It is with these questions in mind that the interest of a global bioeconomic model integrating climate and forests arises. This paper is organized as follow : Section(2) briefly discuss the state of art in bioeconomic modelling and setup our modelling framework, Section(3) present the results of our main scenario. Our main conclusions and areas for future research are outlined in the final section.

2 Modeling framework

2.1 Bio-economic modelling

Many ecological and bio-economic models are spatially explicit. They use a spatial grid of the soil to characterise it according to several criteria (land use, humidity, soil erosion etc.). Satellite imagery is most commonly used for this type of study, but it is also often based on empirical data. Once the soil is characterised, the model makes temporal projections according to several scenarios built on extrapolations or variable endogenisations. One spatially explicit model that is widely used in the research community is the RUSLE soil erosion model (Panagos et al., 2018; Phinzi and Ngetar, 2019). The method generally consists of coupling RUSLE to a computational general equilibrium (CGE) model. They are multi-sectoral, *i.e.* they must have modules for each sector of the economy. This makes it possible, for example, to assess the market changes associated with a disturbance in the agricultural sector. In Panagos et al. (2018)'s article, the losses calculated through the general equilibrium model are much lower than those calculated through the cost benefit approach. According to the authors , this difference is due to the philosophy of the general equilibrium economic model. They argue that when the agricultural sector contracts, factors of production are free to relocate to other sectors, thereby mitigating the overall loss of GDP. Typically in CGE models, these adjustments tend to be low cost and almost frictionless. In fact, CGE models represent an idealised, fully competitive economy. They therefore conclude that the estimated GDP losses should be considered as the lower bound of economic losses. Thus, the CGE philosophy will not be used in our model.

Another family of models is the calculators. These tools have been developed to make temporal projections of several scenarios. The aim is to assess the impact of the scenarios in terms of carbon trajectory, biodiversity, energy mix, etc. They exist on a global scale (Strapasson et al., 2020b) , on a European scale (European Environment Agency, 2018; Yu and Clora, 2020; Baudry et al., 2020; Strapasson et al., 2020a) or on a city scale (Digiesi et al., 2015; Dahal and Niemelä, 2017). The main problem with these models is their multisectoral nature. The model is built in modules requiring a sectoral and not an aggregated macroeconomic mode.

The last family of bio-economic models is the integraded assessment models (IAM). They are built by combining different separate modules which aim to model different aspect of climate-environment-economy system. While some simpler IAMs remain fairly abstract, the more complicated models can provide an impressive range of projections at a very high resolution, down to the levels of an individual preferences, like electric vehicles or food regime. These IAMs are typically "optimal growth" models, maximising welfare over the long term. The core economic module used are general equilibrium or partial equilibrium approach (Alkemade et al. (2009) or (Elbehri and Food and Agriculture Organization of the United Nations, 2015, p.295-297)). Such IAMs exclude the possibility of crisis, degrowth due to overindebtness, mass unemployment or money endogenousity (Giraud and Grasselli, 2017).

It is for these reasons that recent research has contributed to building alternatives to such IAMs by incorporating Keynesian features (Barker et al., 2012) or more post-Keynesian insights (Dafermos et al., 2017). To our knowledge, none of its alternative models integrate global agro-forestry dynamics even though the latter represents an opportunity for climate mitigation (Raj et al., 2020).

2.2 Overview of the model

The model is part of the IAM family, which stands for Integrated Assessment Model, i.e. it tries to link the main characteristics of the society and the economy. Many criticisms of IAMS models exist in the literature. The main advantage of this kind of model is that they furnish an integrated system perspective (Schwanitz, 2013). It provides a framework in which coupling models is possible. In this paper, we present a model borned from the coupling of two existing

models. The first one "Coping with collapse" was built by Bovari (2018), a model that combines the economic impact of climate change with the pivotal role of private debt. Its climatic module is inspired by the searching work of Nordhaus (1992). It introduces a negative feedback loop of temperature on GDP and capital. Contrary to the core economic model of DICE model (Nordhaus, 1992), Bovari (2018)'s modelling approach is based on prey-predatory macrodynamics first introduced by Goodwin (1967) and then deepen by Keen (1995). This stock-flow consistent modeling framework (SFC) is fitted to study financial-real interaction with multiple long-run equilibria. It is also characterized by its private debt and underemployment endogenously determined.

The agroforestry module comes from Eriksson's FOR-DICE model. This module enables us to integrate the forest resource as a carbon sink and a source of emission through deforestation into our integrated assesment model. It incorporates three types of forest (boreal, temperate, tropical) as endogenous stocks of biomass in billion m^3. Tropical forest is the only biomass stock affected by deforestation[1]. However, each type of forest are affected by harvest through bioenergy and rounwood demands. Unlike the Eriksson's approach, the level of tropical deforestation and bioenergy harvest are not determined by solving an optimisation problem. The tropical deforestation is exogenous through different agroforestry scenarios and bioenergy harvest level is determined by energy requirements for world production. Bioenergy harvest is also influenced by a cost minimisation of industrial energy budget constraint under several exogenous carbon tax scenarios.

Public sector is not expicitly integrated in this IAM but public policies are materialized by a tropical deforestation control rate and different carbon price paths which impact the emission reduction rate and the share of fossil fuels in the energy mix. The model sequence is presented as following: Subsection(2.3) details the core economic module and the climate-related damages, Subsection(2.4) explicit the climate module and its associated carbon cycle, the Subsection(2.5)presents the agroforestry module which also include energetic equations and the last Subsection(2.6) show the stock-flow consistency of our model.

2.3 Economic module

2.3.1 *Production, damage and abatement*

The global production Y^0 (Eq.1) comes from the combination of capital K with constant capital to output ratio ν (Inklaar and Timmer, 2013) and labor L with constant Harrod-neutral productivity growth rate α.

$$Y^0 = min(\frac{K}{\nu}; aL) \tag{1}$$

$$L = \frac{K}{\nu a} \tag{2}$$

$$\frac{\dot{a}}{a} = \alpha \tag{3}$$

The rise in temperature T caused by the increasing amount of anthropic CO_2e released into the atmosphere impacts the proper functioning of the economy through climate damages. Multiple phenomena are involved in economy's disturbance through, among others, sea level rise, ocean acidification, degradation of arable lands, frequent droughts or frequent storms all with strong non-linear effects.

To integrate the latter effects into the economic dynamics, Nordhaus (2016) first introduces a

[1]Due to the fact that ongoing deforestation mainly impacts tropical forest (Murray et al.)

convex damage function designed to express damages in terms of current output fraction. Nevertheless, the Nordhaus' damage function was critized by Weitzman (2011) and Stern (2013) because of it underestimation of climate risk. They have therefore proposed more convex polynomial functions which will be used in our model (Eq.4):

$$D = 1 - \frac{1}{1 + \pi_1 T + \pi_2 T^2 + \pi_3 T^{\zeta_3}} \tag{4}$$

Dietz and Stern (2015) however rightly noted that production factors themselves might be damaged by climate change. It might be interpreted as a reduced stock of capital. The latter is simulated thanks to (Eq.5):

$$D^K = f_K D \tag{5}$$

$$D^Y = 1 - \frac{1 - D}{1 - D^K} \tag{6}$$

With f_K the share of capital damaged by climate such that $f_K \in \{0; 1/3\}$ according to Bovari et al. (2020).

The other phenomena triggered by climate change in our model is abatement effort. To reduce the burden of carbon tax[2], a fraction of current output A is redirected. It represents the intermediate cost of reducing CO_2e emissions through abatement technology and it depends also on the emission reduction rate choosen by the productive sector, *i.e* the fraction of production processes that is 'de-polluted'.

$$A = \frac{\sigma p_{BS}}{\theta} n^{\theta} \tag{7}$$

$$n = min\{(\frac{p_c}{p_{BS}})^{\frac{1}{\theta - 1}}; 1)\} \tag{8}$$

Note that σ latter involved is the carbon intensity of the economy[3] and θ a parameter controling the convexity of the cost.

The endogenously determined level of emission reduction rate n (Eq.8) derives from the cost minimisation between the abatement cost AY and the carbon tax $p_c E_{ind}$. Then, we substract the cost of the agroforestry policy MC to the real output which is thus defined as following:

$$Y = Y^0(1 - D^Y)(1 - A) - MC \tag{9}$$

The backstop technology p_{BS}[4]:

$$\frac{\dot{pBS}}{p_{BS}} = \delta_{p_{BS}} < 0 \tag{10}$$

In contrast, carbon tax can follow different scenari. They are treated as exponentional trajectories:

$$\frac{\dot{p_c}}{p_c} = \delta_{p_{car}}() \tag{11}$$

Note that with an initial value of 2 dollars per ton of $CO2e$ in 2016 , $p_c(2100) = \{50; 300\}$ with respect to $\delta_{p_{car}} = \{0.04; 0.06\}$

[2] which depends on total anthrogenic CO_2e emissions

[3] which slightly declines over time figuring out environnemental efficiency of the economy

[4] This can be translated as a new technology that produces a close substitute for an exhaustible resource using relatively abundant production inputs and renders the reserves of the exhaustible resource obsolete when the average cost of producing the close substitute falls below the spot price of the exhaustible resource Levy (2000) is accessible at a declining price as time goes on

2.3.2 *Profit, investment and inflation*

Profit Π (Eq.12) represents nominal output pY minus the costs of production, i.e. wages wL, debt interest rD, carbon tax $pT_f = pP_cE_{ind}$ and capital depreciation $p\delta_d K$:

$$\Pi = pY - wL - rD - pT_f - p\delta_d K \tag{12}$$

The profit share π is thus defined by:

$$\pi = \Pi / pY \tag{13}$$

It is assumed that real investment, I, is determined by the profit share, π, which reflects the risk appetite of firms. The marginal cost of avoiding deforestation MC is substracted to investement in order to take into account the cost of the chosen agroforestry policy[5]. The investments from which capital depreciation is subtracted thus determine the dynamics of capital.

$$I = \kappa(\pi)Y \tag{14}$$

with $\kappa()$ a bounded, increasing and linear function of the profit share π[6]

$$\dot{K} = I - \delta_D K \tag{15}$$

Changes in nominal corporate private debt D depend on the difference between current nominal profit, Π, and investment pI, plus nominal dividends paid to shareholders, $\Pi_d(\pi)$[7]:

$$\dot{D} = pI + \Pi_d(\pi) - \Pi - p\delta_D K \tag{16}$$

$$\Pi_d(\pi) = \Delta(\pi)pY \tag{17}$$

Note that the equation (Eq.16) implies that firms can borrow money to finance dividends. This is not surprising as the famous Modigliani-Miller theorem (Hellwig, 1981) states that equity and debt are equivalent ways of financing a company's expenses. Moreover, contemporary oil companies are known to issue debt to pay their shareholders (see 2016, "Oil Majors Continue To Take On Debt to Pay Dividends").

The next formula (Eq.18) encapsulates the dynamics of inflation. The price of consumption, p, converges to its long-run equilibrium value through a delayed exponential adjustment with a relaxation time $\frac{1}{\eta_p}$. The long-run equilibrium price is given by a mark-up m multiplied by the average unit cost of production c:

$$i = \frac{\dot{p}}{p} = \eta_p(mc - 1) \tag{18}$$

And the average unit cost of production is, in our model, the wage payments:

$$c = \frac{wL}{pY} \tag{19}$$

[5] MC as well as the various agroforestry policies will be defined in the Agroforestry Module

[6] Namely $\kappa(\pi) = \kappa_0 + k_\pi(\pi)$ with $\kappa(\pi) \in [\kappa_{min}; \kappa_{max}]$

[7] with $\Delta(\pi) = \Delta_0 + \Delta_\pi(\pi)$ with $\Delta(\pi) \in [\Delta_{min}; \Delta_{max}]$

2.3.3 *Labour market*

The dynamics of the global labour force are derived from the United Nations (2019) median scenario for 15-64 year olds. N, the global labour force is thus assumed to grow along a sigmoid curve:

$$\beta(N) = \frac{\dot{N}}{N} = q(1 - \frac{N}{N^{max}}) \tag{20}$$

with P^N the upper limit of the population and q the speed of convergence to N^{max}.

The employment (Eq.21) is determined by the ratio of employees L to the global available workforce N:

$$\lambda = \frac{L}{N} \tag{21}$$

The wage dynamics are derived from Philips curves with the functional form of Grasselli and Nguyen-Huu (2018)[8]. Workers negotiate their wages according to the employment rate:

$$\frac{\dot{\lambda}}{\lambda} = \phi(\lambda) \tag{22}$$

2.4 Climate module

The climatic module is inspired by the searching work of Nordhaus (1992). The negative feedback loop of temperature on GDP and capital introduced in Section(2.3.1) is possible thanks to the temperature dynamics embodied in this section. The rise on temperature comes from the rising anthropogenic $CO2e$ emissions.

2.4.1 *Emissions*

The carbon emission E (Eq.23) are composed by emissions from each forest stocks (sequestration) EF_n, ES emissions from manufactured forest products[9] and E_{ind} industrial emissions (from energy conversion):

$$E = E_E + \sum_n EF_n + ES \tag{23}$$

Industrial emissions EE, defined Section(2.5.4) are derived from the energy conversion needed to produce the level of total output. The amount of energy needed to produce Y^0 is defined as following, with σ, the carbon emission intensity of the economy[10] and n, the industrial mitigation efforts accounted by the emission reduction rate (defined Eq.8):

$$Energy = Y^0 \sigma \xi (1 - n) \tag{24}$$

$$\frac{\dot{\sigma}}{\sigma} = g_\sigma \tag{25}$$

$$\frac{\dot{g_\sigma}}{g_\sigma} = \delta_{g_\sigma} \tag{26}$$

where the production, Y^0, leads to carbon emissions through the exogenous carbon ratio, σ.

The carbon emission output is declining over time due to an increase in carbon efficiency.

[8] with $\phi(\lambda)$ a linear fonction of employment rate, $\phi\lambda = \phi_0 + \phi_\lambda(\lambda)$. Note that the behavioral functions, $\kappa()$ and $\phi()$, have been bounded to avoid inconsistent behaviors that might fall far outside the estimation range. See Nguyen-Huu and Pottier (2016)

[9] EF_n and ES defined section.2.5 with as mentionned above $n = (BOR, TEM, TRO)$

[10] exogenously defined by g_σ, ξ the energy parameter and δ_{g_σ}, see Bovari (2018)

This exogenous technology change also implies that the energy efficiency increases over time. The carbon emissions from production is further reduced by the industrial mitigation efforts accounted by the emission reduction rate, n, which represents non carbon-based technologies used to produce energy. These technologies include, for example, solar power, geothermal energy and nuclear power. The carbon emissions from production are converted back to energy units by the energy-emissions parameter.

2.4.2 *Carbon cycle*

The carbon cycle is composed of 3 communicating layers: the atmosphere (AT), the upper ocean and biosphere (UP) and the deep ocean (LO). Their dynamics are translated by the following system of differential equations:

$$\begin{pmatrix} \dot{CO_2^{AT}} \\ \dot{CO_2^{UP}} \\ \dot{CO_2^{LO}} \end{pmatrix} = \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \Phi \begin{pmatrix} CO_2^{AT} \\ CO_2^{UP} \\ CO_2^{LO} \end{pmatrix} \tag{27}$$

With Φ, the matrix modeling carbon diffusion through the three layers:

$$\Phi = \begin{pmatrix} -\phi_{12} & \phi_{12} C_{UP}^{AT} & 0 \\ \phi_{12} & -\phi_{12} C_{UP}^{AT} - \phi_{23} & \phi 23 C_{LO}^{UP} \\ 0 & \phi_{23} & -\phi 23 C_{LO}^{UP} \end{pmatrix} \tag{28}$$

where

$$C_i^j = \frac{C_{j_{p_{ind}}}}{C_{i_{p_{ind}}}}, (i,j) \in \{AT, UP, LO\}^2 \tag{29}$$

$CO2e$ therefore diffuses from one layer to another in such a way that the relative pre-industrial concentrations $C_{i_{p_{ind}}}, i \in \{AT, UP, LO\}$ in each layer are respected at equilibrium. The accumulation of greenhouse gases changes the atmospheric chemical properties and thus the energy balance of this layer, triggering an increase in radiative forcing[11] . The latter consists of the industrial radiative forcing F_{ind} due to anthropogenic emissions and a residual forcing F_{exo}[12]:

$$F = F_{ind} + F_{exo} \tag{30}$$

$$F_{ind} = \frac{F_{2xCO2}}{log(2)} log\left(\frac{CO_2^{AT}}{C_{AT p_{ind}}}\right) \tag{31}$$

F_{2xCO2} in Eq.(31) represents the increase in radiative forcing resulting from a doubling of the pre-industrial CO2e concentration.

2.4.3 *Temperature*

The change in radiative forcing directly impacts the global average surface temperature T and the average deep ocean temperature T_0 :

$$C\dot{T} = F - \rho T - \gamma^* (T - T_0) \tag{32}$$

$$C_0 \dot{T_0} = \gamma^* (T - T_0) \tag{33}$$

[11] "*The radiadive forcing is the net change in the energy balance of the Earth system due to some imposed perturbation. It* [...] *quantifies the energy imbalance that occurs when the imposed change takes place. Though usually difficult to observe, calculated RF provides a simple quantitative basis for comparing some aspects of the potential climate response to different imposed agents, especially global mean temperature, and hence is widely used in the scientific community. Forcing is often presented as the value due to changes between two particular times, such as pre-industrial to present-day, while its time evolution provides a more complete picture*" (Myhre et al., 2013, p. 664)

[12] The residual forcing results from various residual factors such as non-CO2-e long- lived greenhouse gases and other factors such as albedo changes, or the cloud effect. For simplicity, it is taken here as exogenous, as IPCC (Myhre et al., 2013, p. 681) showed it to be negligible and in line with representative concentration pathways. Here, Nordhaus (2016)'s representation is used: a linear trajectory up to 2100

with ρ, the radiative feedback parameter; γ^*, the heat exchange coefficient between the two layers; C, the heat capacity of the atmosphere, land surface, and upper ocean layer; and C_0, the heat capacity of the deep ocean layer.

The global thermal behaviour results from a coupled two-layer energy balance model that stands for: (i) the atmosphere, land surface and upper ocean with a mean temperature, T, and (ii) the deeper ocean with a mean temperature, T_0. In this framework, the latter layer includes the long-term thermal inertia effects of the climate system. The mean astmospheric temperature change induces the two-frequency deviation responses: a transient climate response (TCR) and an equilibrium climate sensitivity (ECS)[13] (Geoffroy et al., 2013).

2.5 Agroforestry module

The purpose of this module is to integrate the forest resource as a carbon sink on the one hand, and as a source of GHG[14] emission/sequestation on the other. It is based on the model FOR-DICE developed by Eriksson (2015) whose neoclassical core DICE (Nordhaus (1992), Nordhaus and Boyer (2000), Nordhaus (2008), Nordhaus (2017)) is replaced and adjusted for our continuous post-Keynesian framework. It incorporates three forest types in the form of biomass stock[15] $S = (Boreal, Temperate, Tropical)$. The boreal and temperate forest stocks are affected by agroforestry harvesting (for the production of manufactured goods and bioenergy) while the tropical forest stock is also controlled by its deforestation rate[16].

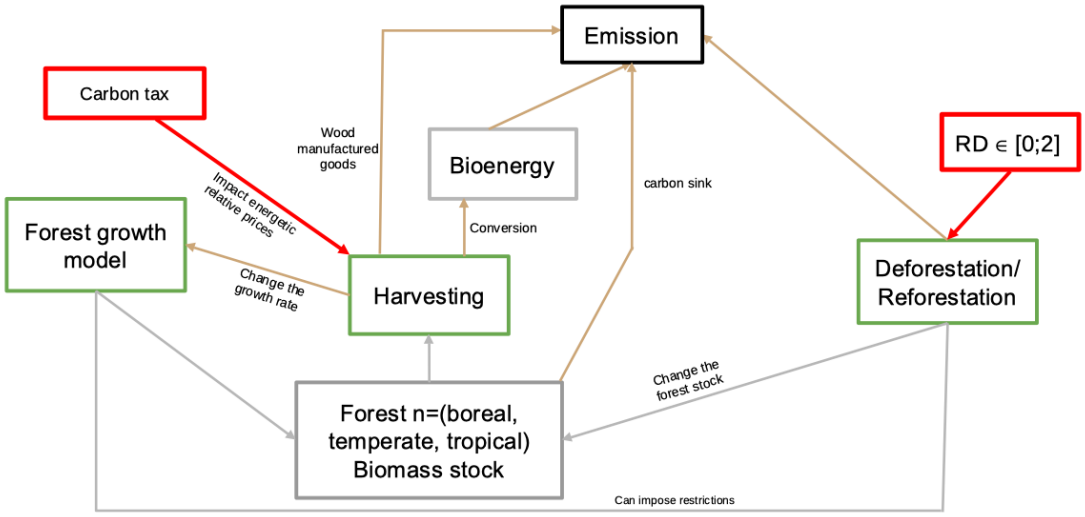

Figure 1: Agroforestry module flowchart
Green - Forest dynamics ; *Red* - Exogenous policies

2.5.1 *Growth of forest stocks*

In the FOR-DICE model, forest stocks are subject to growth as defined by the logistic growth equation of Clark (1990). Even if harvest decreases the biomass stock, it also increases its growth.

[13] The TCR represents the deviation at the end resulting from a linear doubling of the atmospheric CO2-e concentration, while the ECS accounts for the new equilibrium of the system, reached decades later due to its thermal inertia. Note that the TCR induced by our model is in line with IPCC results (Myhre et al., 2013)

[14] greenhouse gas

[15] in m^3 and therefore not spatially explicit

[16] Indeed, most of the world's deforestation takes place in South America, Africa and South and South-East Asia; that is, tropical forests. (Murray et al., 2009)

Indeed, an ageing forest, reaching its maximum carrying capacity, sees its growth rate decreases. That is why forest stock growth reaches its upper limit when the stock is at its minimum capacity. Note that the maximum carrying capacity F_S^{MAX} decreases with deforestation D_S and is defined as:

$$\dot{F_S^{MAX}} = -\frac{F_S^{MAX}}{F_S} D_S \tag{34}$$

with $S \in (BOR, TEM, TRO)$. Since only the tropical forest stock is subject to deforestation, the maximum capacities of the temperate and boreal forest stocks are constant. The dynamics of forest biomass F_S depends on the intrinsic growth of forest ψ_S, the maximum carrying capacity Eq.(34), harvest H_S and deforestation D_S:

$$\dot{F_S} = \psi_S F_S \left[1 - \frac{F_S}{F_S^{MAX}}\right] - H_S - D_S \tag{35}$$

2.5.2 *Deforestation*

Baseline exogenous GHG emissions from land in the DICE model (Nordhaus, 2016) are used as an approximation of the emissions due to tropical deforestation:

$$\frac{\dot{E_{TRO}}}{E_{TRO}} = \delta_{E_{TRO}} \tag{36}$$

These baseline emissions are converted to effective biomass deforested:

$$D_{TRO} = \frac{E_{TRO}}{\theta_{TRO}}(1 - RD_t) \tag{37}$$

with θ_{TRO}, the tropical carbon intensity parameter[17] and RD, the control variable of deforestation[18]. From the deforestation rate RD_t, we deduct the reduction of direct carbon emissions from deforestation due to the chosen agroforestry policy:

$$RE = E_{TRO} RD_t \tag{38}$$

In order to estimate the financial impact that industries benefiting from deforestation will suffer in the case of reduced deforestation, a marginal cost function was calibrated by Mathilda Eriksson. However, this function was calibrated for a modelling time step of 10 years. It was therefore necessary to recalibrate it to follow the estimates made by Kindermann et al. (2008) for our continuous framework:

$$MC = \phi_1 e^{\phi_2 RE} \tag{39}$$

This cost of avoiding deforestation is then taken into account in the output dynamic (Eq.9).

2.5.3 *Harvesting*

In our model, forest harvest H_S is dedicated on the one hand to the production of bioenergy HB_S[19] and on the other hand to the production of manufactured goods HS:

$$H_S = HB_S + HS_S \tag{40}$$

[17] average amount of carbon per volume of growing tropical forest biomass

[18] Note that $RD_t \in (0; 2)$. When $RD_t = 0$, there is no control on deforestation rate. For $RD_t = 1$, there is no more deforestation. If $RD_t > 1$, we have a reforestation and when $RD_t = 2$, we reforest at a rate similar to the baseline deforestation rate.

[19] defined Section2.5.4

Production of wood product HS is assumed to grow linearly following the global workforce growth:

$$\dot{HS} = \sum_S \chi_S HS\eta \left(\frac{\dot{L}}{L} + 1\right) - HS \tag{41}$$

with χ_S the share of boreal, temperate and boreal forest and η a preference parameter[20].

2.5.4 *Energy*

The equation E.24 provides us the energy equivalent for producing Y^0. The carbon based energy is composed exclusively of fossil fuel carbon FO and bioenergy (forest biomass harvest intended for energy production) BI[21]. This energy is modelled by a Cobb-Douglas function with constant returns to scale[22]:

$$Energy = \zeta FO^{\beta} BI^{1-\beta} \tag{42}$$

where ζ is a scale parameter, β and $1-\beta$ are respectively the elasticities of substitution of FO and BI. Note that fossil energies are limited resources:

$$FO^{max} \geq \sum_t^T FO_t \tag{43}$$

BI, bioenergy is also modelled by a Cobb-Douglas function with constant returns to scale, it is composed of the biomass harvested HB_S for each forest type with $S = (TRO, BOR, TEM)$ associated with their respective elasticities of substitution κ, Φ and $1-\kappa-\Phi$ and with ω a scale parameter:

$$BI = \omega HB_{TRO}^{\kappa} HB_{BOR}^{\Phi} HB_{TEM}^{1-\kappa-\Phi} \tag{44}$$

2.5.5 *GHG emissions*

The total greenhouse gas emissions are composed of:

- emissions from energy conversion E_E (fossil and biomass);
- emissions from forest harvest and decomposition of wood products E_S;
- emissions from the change of biomass stock contained in the different types of forest E_F;

$$E_E = FO + \sum_S HB_S \Theta_S \tag{45}$$

with Θ_S a biomass-to-emissions conversion parameter for $S \in (BOR, TEM, TRO)$.

Bio-fuels and fossil fuels release carbon immediately when burned. In contrast, manufactured wood products can store CO2 for a considerable time. This time will depend on the use of the wooden object in question. To describe the release of carbon in wooden objects, the half-life of products HL is commonly used. It reflects the average time it will take for half of the carbon in the manufactured products to be released. The decay equation:

$$\delta_{CH} = \frac{ln(2)}{HL} \tag{46}$$

[20] Here assumed to be constant but could vary with changes in demand for different types of wood

[21] A reasonable estimate as in 2018, 81.3% of the energy mix comes from fossil fuels and 9.3% from biomass (IEA, 2020)

[22] Note that the carbon tax will impact the fossil fuel and bioenergy demand. See detail Appendix(A)

represents the fraction of carbon released in each period. The amount of CO2 stored in wood products CH is modelled to decrease with the decay equation and to increase with the manufacture of new forest products $Inflow$:

$$\dot{CH} = -\delta_{CH} CH + Inflow \tag{47}$$

$$Inflow = \nu \sum_{S} HS_S \Theta_S \tag{48}$$

ν represents the share of carbon from harvested wood that will go into long-lasting manufactured products. Much of the agroforestry biomass is lost in industrial processes[23]. Thus we can obtain the amount of carbon from industrial roundwood harvest:

$$E_S = CH\delta_{CH} + (1-\nu) \sum_{S} HS_S \Theta_S \tag{49}$$

The emissions/sequestrations of forest biomass stocks are then worth:

$$E_{F_S} = (-\dot{F}_S - H_S)\Theta_S \tag{50}$$

By summing the three types of emissions EF, ES, EE, we obtain the total emissions (Eq.23).

2.6 Stock-flow consistency

Our model's stock-flow consistency is shown in the next page (2.6). Here the accounting concept "investment Equals saving" is always true. Indeed, our economy's monetary counterpart may now be identified: M stands for total deposits, which equals M^h, household deposits, plus M^f, productive sector deposits.

Households own both types of equities, E^f and E^b, because dividends from both financial and non-financial businesses are transferred to them. As the banks' financial balance is always zero, their equity, E^b, can be safely assumed to remain constant. Similarly, we assume that the producing sector's equity has a constant market value (*e.g.*, because stock markets are closed in this model).

In addition, it follows from Eq.(16) and the accounting identity:

$$pY = \Pi + W + rD + pT_f + pMC + \delta_D pK = pC + pI \tag{51}$$

that

$$W + \Pi_d + rD + pT_f + pMC = \dot{D} + pC \tag{52}$$

We thus have $\dot{M}^h = \dot{D} = \dot{L} - \dot{M}^f$, the change in company's debts is equivalent to the change in household savings.

[23] Approximately 36% of the original tree volume is converted into long-life products (Ingerson, 2009)

	Households	Productive sector		Banks	Sum
Balance sheet					
Capital stock			pK		pK
Deposits	M^h		M^c	$-M$	
Loans			$-L_c$	L_c	
Equities	E		$-E^f$	$-Eb$	
Sum (net worth)		X^h	$X^f = 0$	$X^b = 0$	X
Transactions		Current	Capital		
Consumption	$-pC$	pC			
Investment		pI	$-pI$		
Acc. memo [GDP]		$[pY]$			
Wages	W	$-W$			
Capital depr.		$-(\delta_k + D^K)pK$	$(\delta_k + DK)pK$		
Proactive policies	$pT_f + pMC$	$-pT_f - pMC$			
Int. on loans		$-r_c L_c$		$r_c L_c$	
Bank dividends	Π_b			$-\Pi_b$	
Productive sector dividends	Π_d	$-\Pi_d$			
Int. on deposits	$r^M M_h$	$r^M M_c$		$-r^M M$	
Column sum (balance)	S^h	Π_r	$-pI + (\delta_k + D^K)pK$	Sb	
Flow of funds					
Change in capital stock			$p\dot{K}$		$p\dot{K}$
Change in deposits	$\dot{M}^h$		$\dot{M}c$	$-\dot{M}$	
Change in loans			$-\dot{L}_c$	$\dot{L}_c$	
Column sum (savings)		S^h	Π_r	S^b	
Change in equities	$\dot{E}^f$		$-(\Pi_r + \dot{p}K$		
Change in bank equity	$\dot{E}^b$			$-Sb$	
Change in net worth	$S^h + \dot{E}$		0	0	$+\dot{p}K + p\dot{K}$

Table 1: Balance sheet, transactions and flows of fund

3 Results

Let us have a look at the numerical analysis up to 2100. To study the impact of agroforestry and public policies, two baseline scenario have been choosen. Both of them implied the Weitzman (2012)'s damage function and their difference is based on the presence or absence of damage on the capital, namely $f_k \in \{0; 1/3\}$) in Equation(5). From these two framework, we will then be able to establish the climate impacts of different carbon tax trajectories and agroforestry policies while stressing possible associated economic instabilities.

3.1 BASELINE - extrapolative deforestation

In order to correctly interpret the economical impact of climate change into our model, it is necessary to show its steady growth equilibrium without damages and without agroforestry policy. An exogenous carbon price trajectory is implemented at an initial value of 2010 US$ 2 $t/C0_2 - e$ and reaching 10 $t/C0_2 - e$ in 2100. Then, we introduce climate damages on production (*low damage*) and on the capital (*high damage*). The trajectory of the main economic variables is as follows:

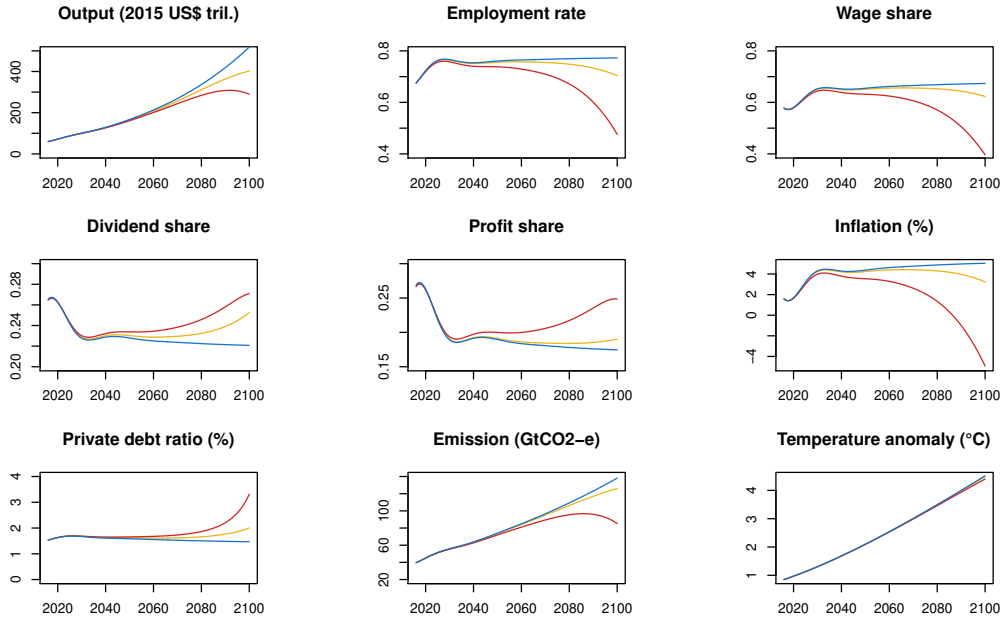

Figure 2: Main variables for the BASELINE framework
blue - *no damage* ; gold - *low damage* ; red - *high damage*

In the *No damage* case without carbon tax, the model converges to a Solovian steady state of growth. GDP increases exponentially as productivity also increases exponentially, reaching about USD 500 trillion in 2100, almost 10 times the current world output. The employment rate stabilises at around 70%, a result close to the OECD average. Inflation stabilises at around 5%. The ratio of private debt to GDP reaches around 150% in 2100, an average close to the current world powers[24]. In short, without climate damage, the economic model reaches a stable growth equilibrium. Note that in this case, we reach 130 GtC of GHG emissions in 2100, *i.e.* more than three times the amount of annual emissions in 2015. These emissions imply an increase of 4.35°C compared to the pre-industrial era.

[24] https://www.banque-france.fr/en/statistics/loans/debt-and-securities/debt-ratios-intitutional-sectors-international-comparisons

However, in the absence of proactive public policies, it turns out that the model converges in the long run toward a "bad" attractor in both *high* and *low* climate damage cases. This climate-induced degrowth is characteristic of Fisher's debt deflation theory (Fisher, 1933). The damages on production and the associated deflation inevitably impact the private debt to output ratio. Without policy implementation, the climate change is to create financial turmoil by the second half of the century.

In the baseline framework, the deforestation rate follows the exogenous path defined Equations (36;37). It is worth mentionning again that deforestation only takes place in tropical forests in our model. For the sake of clarity, the trajectory of the main variables of the agroforestry module is represented in the *low damage* case:

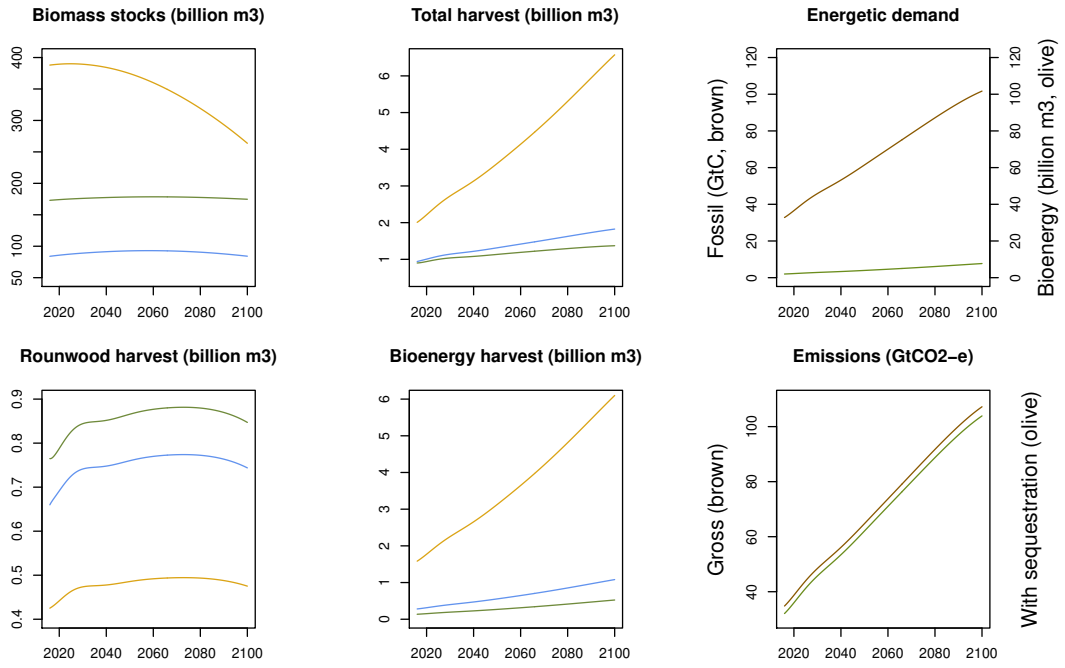

Figure 3: Agroforestry module variables - BASELINE - *low damage*
yellow - *Tropical* ; green - *Temperate* ; light blue - *Boreal*

In the baseline *low damage* case, with an extrapolative deforestation rate, the tropical stock of biomass is almost halved in 2100, namely 247.4 billion m^3, supposing serious biodiversity losses. The sequestration capacity of the whole stock of forest (*tropical, temperate and boreal*) reaches 3.33 $GtCO2$ thus giving a total emission of 112 $GtCO_2e$ at the end of the century. The temperature anomaly with the low carbon tax and given the latter amount of anthopogenic emissions is 4.23 C. Total harvest is growing due to the increasing bioenergy demand.

3.2 FOREST POLICY A - smooth reforestation

Now we implement a first agroforestry policy, namely a linearly increasing deforestation control rate with $RD(2100) = 2$ still in the *low damage* case. Here deforestation is stopped around 2058 and then starts a process of reforestation until 2100. In addition to this policy, we want to study the impact of a more convex carbon tax (dotted lines)[25] on our variables. The trajectory of the main variables is as follow:

[25] namely tax(2100) = 300 $/tonC

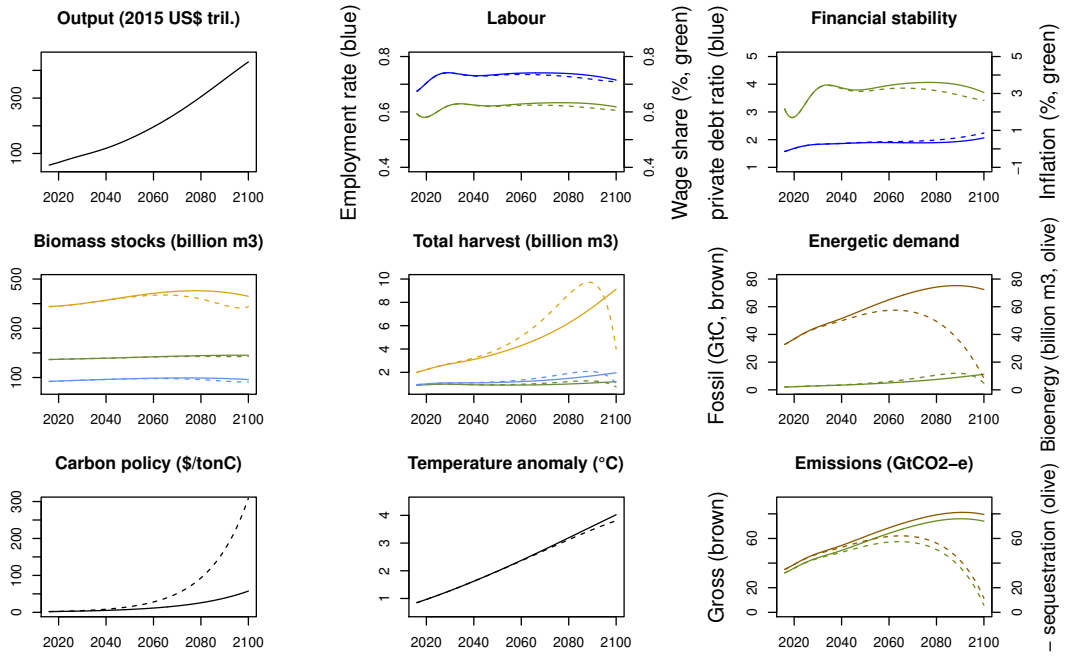

Figure 4: Main variables - FOREST POLICY A - *low damage*
yellow - *Tropical* ; green - *Temperate* ; light blue - *Boreal*

In presence of the smooth carbon policy, namely $tax(2100) = 50\$/tC$, and our first forestry policy, the stock of tropical forest is equal to 110.81% of the 2015 stock, supposing a slight biodiversity recovery. The whole forest sequestration capacity reaches an amount of 5.48 GtC per year which represent about twice the European Union emissions in 2020[26]. With these policies, the total amount of emissions is about 74 $GtC0_2e$ per year at the end of the century, approximately twice the amount of 2015. In comparison with the baseline scenario, the mean temperature anomaly is lowered by 0.2 °C, namely +4.02°C in comparison with preindustrial era mean temperature. Total harvest is growing due to the increasing energetic demand. There is a soft substitution from fossil energies towards bioenergy due to the carbon tax added to the fossil energies' price (see Appendix(A)).

By implementing a more convex carbon tax, namely $tax(2100) = 300\$/tC$, financial stability marginally changes. The financial burden of the policy increases the private debt ratio of about 10% in comparison with the latter carbon tax. In both carbon policy cases, inflation is about 3% at the end of the century. Interestingly, the more convex carbon policy has adverse effects on forest stocks. There is a stronger carbon based energy substitution due to a higher energetic relative prices. The higher bioenergy demand thus implies a higher level of forest harvesting before 2096. In consequence, the 2100 stock of tropical forest is reduced to about 11% in comparison with the soft carbon policy case. However, in this case, there is a higher emission reduction rate due to the more convex carbon policy. This implies a strong substitution from carbon based energies toward non-carbon based energies (see Eq(24). In consequence, the demand for bioenergy[27], the demand for fossil energies and the level of carbon emission significantly decrease at the end of the century.

[26] See https://www.statista.com/statistics/450017/co2-emissions-europe-eurasia/
[27] and accordingly the level of harvesting dedicated to bionergy

3.3 FOREST POLICY B - ambitious reforestation

Now we implement a more ambitious agroforestry policy, namely a linearly increasing deforestation control rate with $RD(2100) = 3$ still in the *low damage* case. Here deforestation is stopped around 2038 and then starts a process of reforestation until 2100. In the same vein as the latter scenario we implement two carbon tax policies (dotted and non dotted lines). The trajectory of the main variables is as follow:

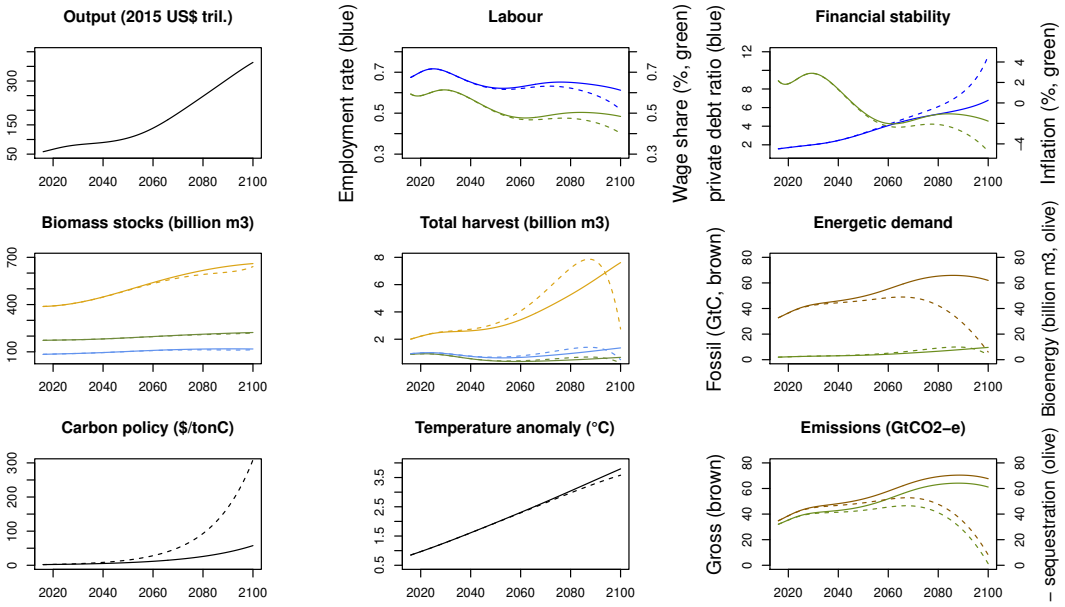

Figure 5: Main variables - FOREST POLICY B - *low damage*
yellow - *Tropical* ; green - *Temperate* ; light blue - *Boreal*

In presence of the smooth carbon policy, namely $tax(2100) = 50\$/tC$, and as a result of the reforestation policy, the stock of tropical forest is equal to 170% of the 2015 stock showing a great policy efficiency. This policy thus enhances the sequestration capacity of the forest stocks, namely 6.50 GtC/year[28]. The effect of the reforestation policy in terms of mean temperature, in comparison with the extrapolative deforestation scenario, *ceteris paribus*, is about -0.3°C. Here, we see the importance of such policy to alleviate climate change. Once again, the adverse effects of a more convex carbon policy (dotted lines) appear in this scenario, the carbon-based energy substitution implies a higher level of harvesting which in turns results in a lower stock of forest biomass.

The higher cost of this more ambitious agroforestry policy increases the burden of private debt ratio. In both carbon policy cases, the private debt to output ratio is higher than 600% at the end of the century. It turns out that the model converge to deflation in the long term. This results highlights the possibily of financial turmoil by the second half of the 21^{th} century if the economic growth our society is based on is not questioned. However, in the modelling framework, the carbon tax has a significant effect on the level of emission due to the associated emission reduction rate chossen by industries.

[28] Which represents more than half of 2020 China emission. See https://www.statista.com/statistics/239093/co2-emissions-in-china/

4 Conclusion

SCENARIO	BASELINE	FOREST A		FOREST B	
2100 carbon tax	10 $/$tonC$	50 $/$tonC$	300 $/$tonC$	50 $/$tonC$	300 $/$tonC$
Temperature anomaly [°C]	+4.23	+4.02	+3.81	+3.80	+3.58
Sequestration [GtC/year]	-3.33	-5.48	-5.76	-6.50	-6.86
Emission [$GtC0_2e$/year]	112.05	74.01	5.73	61.14	1.19
Tropical forest stock [2015 %]	63.8	110.81	99.96	170.17	165.22
Cost of forest policy [UStril.$]	-	5.22	5.22	17.83	17.83
Private debt ratio	1.49	2.06	2.24	6.79	11.56

Table 2: Main variables in 2100

Combining environmental and financial effects in a macroeconomic SFC model makes it possible to determine the conditions for future economic growth that depends on climate damage. In our model, the carbon price trajectory is a tool that activates two levers: the emission reduction rate chosen by the industrialists on the one hand and the favouring of bio-energy over fossil fuels through the industrial minimisation of energy costs on the other. In addition, it is possible to study the consequences of different agroforestry policies on financial instabilities and carbon sequestration.

With regard to all the scenarios, it appears that the + 1.5°C objective defined in the Paris Agreements seems to be strongly compromised. Indeed, even assuming a drastic reduction in emissions after 2050 until a quasi carbon-neutral society is reached in 2100, the temperature will probably reach more than 3.5°C after the pre-industrial era. According to the World Meteorological Organisation, it is likely (40%) that we will reach +1.5°C during the next decade[29]. It should be noted that beyond the coupling of the economic and climate model with the agroforestry model, two scenarios had emerged that had not been studied in the litterature of this modelling framework: reforestation policies. These scenarios (see FOREST A and B, Subsection{3.2;3.3} make it possible to understand the importance of implementing a global agroforestry policy. In the more ambitious scenario, reforestation would make it possible to achieve a carbon sequestration of 18% of current annual anthropogenic emissions by 2100.

This model allows for a better understanding of economic (growth, underemployment) and financial (private debt) interactions with climate instabilities. In this framework, it is clear that a global economic recession remains likely if we do not manage to decouple production from carbon emissions. Strong financial instabilities may arise through the gradual increase of private debt ratio. In spite of these considerations, many improvements seem possible for this model. For example, it would be possible to add a redistribution tool (such as a subsidy) in parallel to the carbon tax. One could also imagine an endogenisation of population dynamics, by integrating family policies for example. Finally, it would also be interesting to integrate an additional indicator of forest biodiversity. A bird population dynamic might be relevant for this purpose.

[29] See https://public.wmo.int/fr/medias/communiqu%C3%A9s-de-presse/selon-de-nouvelles-pr%C3%A9visions-du-climat-il-est-davantage-probable-que?fbclid=IwAR1vkxZh7-sjzQqAZBY1JAyore9Ok7XQoWVZ2kXcQRhAfEkm2vWZMOs1nAo

References

Oil Majors Continue To Take On Debt to Pay Dividends, August 2016. URL https://energyfuse.org/oil-majors-continue-take-debt-pay-dividends/. Section: Oil and the Economy.

Rob Alkemade, Mark van Oorschot, Lera Miles, Christian Nellemann, Michel Bakkenes, and Ben ten Brink. GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. *Ecosystems*, 12(3):374–390, April 2009. ISSN 1432-9840, 1435-0629. doi: 10.1007/s10021-009-9229-5. URL http://link.springer.com/10.1007/s10021-009-9229-5.

Terry Barker, Annela Anger, Unnada Chewpreecha, and Hector Pollitt. A new economics approach to modelling policies to achieve global 2020 targets for climate stabilisation. *International Review of Applied Economics*, 26(2):205–221, March 2012. ISSN 0269-2171. doi: 10.1080/02692171.2011.631901. URL https://doi.org/10.1080/02692171.2011.631901. Publisher: Routledge _eprint: https://doi.org/10.1080/02692171.2011.631901.

Gino Baudry, Onesmus Mwabonje, Alexandre Strapasson, and Jeremy Woods. Mitigating GHG Emissions through Agriculture and Sustainable Land Use. page 11, 2020.

Emmanuel Bovari. Coping With Collapse_ A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, page 16, 2018.

Emmanuel Bovari, Gäel Giraud, and Florent McIsaac. Financial impacts of climate change mitigation policies and their macroeconomic implications: a stock-flow consistent approach. *Climate Policy*, 20(2):179–198, February 2020. ISSN 1469-3062, 1752-7457. doi: 10.1080/14693062.2019.1698406. URL https://www.tandfonline.com/doi/full/10.1080/14693062.2019.1698406.

Rachel Carson. *Silent Spring*. Houghton Mifflin, Boston, 1962.

Colin W. Clark. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. Wiley, March 1990. ISBN 978-0-471-50883-0. Google-Books-ID: HnjwAAAAMAAJ.

Yannis Dafermos, Maria Nikolaidi, and Giorgos Galanis. A stock-flow-fund ecological macroeconomic model. *Ecological Economics*, 131:191–207, January 2017. ISSN 0921-8009. doi: 10.1016/j.ecolecon.2016.08.013. URL https://www.sciencedirect.com/science/article/pii/S0921800916301343.

Karna Dahal and Jari Niemelä. Cities' Greenhouse Gas Accounting Methods: A Study of Helsinki, Stockholm, and Copenhagen. *Climate*, 5(2):31, April 2017. ISSN 2225-1154. doi: 10.3390/cli5020031. URL http://www.mdpi.com/2225-1154/5/2/31.

Simon Dietz and Nicholas Stern. Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. *The Economic Journal*, 125(583):574–620, March 2015. ISSN 0013-0133, 1468-0297. doi: 10.1111/ecoj.12188. URL https://academic.oup.com/ej/article/125/583/574/5076996.

S Digiesi, G Mossa, G Mummolo, and R Verriello. A Carbon Footprint Calculator for the Municipal Waste Collection System of Bari. page 6, 2015.

Sandra Díaz, Josef Settele, Eduardo Brondízio, Hien T Ngo, Maximilien Guèze, John Agard, Almut Arneth, Patricia Balvanera, Kate Brauman, Robert T Watson, Ivar A Baste, Anne Larigauderie, Paul Leadley, Unai Pascual, Brigitte Baptiste, Sebsebe Demissew, Luthando Dziba, Günay Erpul, Asghar Fazel, Markus Fischer, Ana María, Madhav Karki, Vinod Mathur, Tamar Pataridze, Isabel Sousa Pinto, Marie Stenseke, Katalin Török, and Bibiana Vilá. Résumé à l'intention des décideurs du rapport sur l'évaluation mondiale de la biodiversité et des services écosystémiques de la Plateforme intergouvernementale scientifique et politique sur la biodiversité et les services écosystémiques. Technical report, May 2019.

URL https://www.arb-idf.fr/fileadmin/DataStorageKit/ARB/Articles/fichiers/Rapport_de_IPBES_un_taux_d_extinction_des_especes_sans_precedent___/ipbes_7_10_add.1_fr.pdf.

Aziz Elbehri and Food and Agriculture Organization of the United Nations. *Climate change and food systems: global assessments and implications for food security and trade*. 2015. ISBN 978-92-5-108699-5. URL http://www.fao.org/3/a-i4332e/index.html. OCLC: 939538863.

Mathilda Eriksson. The Role of the Forest in an Integrated Assessment Model of the Climate and the Economy. page 35.

Mathilda Eriksson. THE ROLE OF THE FOREST IN AN INTEGRATED ASSESSMENT MODEL OF THE CLIMATE AND THE ECONOMY. *Climate Change Economics*, 06(03): 1550011, August 2015. ISSN 2010-0078, 2010-0086. doi: 10.1142/S2010007815500116. URL https://www.worldscientific.com/doi/abs/10.1142/S2010007815500116.

European Environment Agency. *Trends and projections in Europe 2018: tracking progress towards Europe's climate and energy targets*. 2018. ISBN 978-92-9480-007-7. URL https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2018-climate-and-energy/at_download/file. OCLC: 1076542838.

FAO, editor. *Forestry for a low-carbon future: integrating forests and wood products in climate change strategies*. Number 177 in FAO forestry paper. Food and Agriculture Organization of the United Nations, Rome, 2016. ISBN 978-92-5-109312-2. OCLC: 969830350.

Irving Fisher. The Debt-Deflation Theory of Great Depressions. *Econometrica*, 1(4):337–357, 1933. ISSN 0012-9682. doi: 10.2307/1907327. URL https://www.jstor.org/stable/1907327. Publisher: [Wiley, Econometric Society].

O. Geoffroy, D. Saint-Martin, D. J. L. Olivié, A. Voldoire, G. Bellon, and S. Tytéca. Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical Solution and Parameter Calibration Using CMIP5 AOGCM Experiments. *Journal of Climate*, 26(6):1841–1857, March 2013. ISSN 0894-8755, 1520-0442. doi: 10.1175/JCLI-D-12-00195.1. URL http://journals.ametsoc.org/doi/10.1175/JCLI-D-12-00195.1.

Gaël Giraud and Matheus Grasselli. The macrodynamics of household debt, growth, and inequality. 2017. URL https://ms.mcmaster.ca/~grasselli/Giraud-Grasselli-inequality.pdf.

Global Commission on the economy and climate. *The New Climate Economy Report*. 2014. ISBN 978-0-9906845-1-0. URL http://archives.enap.ca/bibliotheques/2014/09/030678240.pdf. OCLC: 921953464.

Matheus R. Grasselli and Adrien Nguyen-Huu. Inventory growth cycles with debt-financed investment. *Structural Change and Economic Dynamics*, 44:1–13, March 2018. ISSN 0954349X. doi: 10.1016/j.strueco.2018.01.003. URL https://linkinghub.elsevier.com/retrieve/pii/S0954349X16300947.

Martin F. Hellwig. Bankruptcy, Limited Liability, and the Modigliani-Miller Theorem. *The American Economic Review*, 71(1):155–170, 1981. ISSN 0002-8282. URL https://www.jstor.org/stable/1805047. Publisher: American Economic Association.

R. A. Houghton. Releases of carbon to the atmosphere from degradation of forests in tropical Asia. *Canadian Journal of Forest Research*, 21(1):132–142, January 1991. ISSN 0045-5067. doi: 10.1139/x91-017. URL https://cdnsciencepub.com/doi/abs/10.1139/x91-017. Publisher: NRC Research Press.

International Energy Agency IEA. Key World Energy Statistics 2020. page 81, 2020.

Ann Ingerson. Wood Products and Carbon Storage:. *Wilderness Society*, page 47, 2009.

R. Inklaar and L. Timmer. Inklaar, R., Timmer, M., 2013. Capital, labor and tfp in pwt8. University of Groningen (unpublished). 2013. URL http://www.piketty.pse.ens.fr/files/InklaarTimmer13.pdf.

IPCC. *Land use, land-use change, and forestry: summary for policymakers : a special report of the Intergovernmental Panel on Climate Change*. WMO (World Meteorological Organization) : UNEP (United Nations Environment Programme), Geneva, 2000. ISBN 978-92-9169-114-2. OCLC: 716493724.

Steve Keen. Finance and Economic Breakdown: Modeling Minsky's "Financial Instability Hypothesis". *Journal of Post Keynesian Economics*, 17(4):607–635, July 1995. ISSN 0160-3477, 1557-7821. doi: 10.1080/01603477.1995.11490053. URL http://www.tandfonline.com/doi/full/10.1080/01603477.1995.11490053.

G. Kindermann, M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Rametsteiner, B. Schlamadinger, S. Wunder, and R. Beach. Global cost estimates of reducing carbon emissions through avoided deforestation. *Proceedings of the National Academy of Sciences*, 105 (30):10302–10307, July 2008. ISSN 0027-8424, 1091-6490. doi: 10.1073/pnas.0710616105. URL http://www.pnas.org/cgi/doi/10.1073/pnas.0710616105.

Anna Kożuch and Jan Banaś. The Dynamics of Beech Roundwood Prices in Selected Central European Markets. *Forests*, 11(9):902, August 2020. ISSN 1999-4907. doi: 10.3390/f11090902. URL https://www.mdpi.com/1999-4907/11/9/902.

Amnon Levy. From Hotelling to Backstop Technology. page 16, 2000.

Brian C Murray, Ruben Lubowski, and Brent Sohngen. Including International Forest Carbon Incentives in Climate Policy: Understanding the Economics. page 64.

Brian C Murray, Ruben Lubowski, and Brent Sohngen. Including International Forest Carbon Incentives in Climate Policy: Understanding the Economics. *NICHOLAS INSTITUTE REPORT*, page 64, 2009.

Gunnar Myhre, Drew Shindell, François-Marie Bréon, William Collins, Jan Fuglestvedt, Jianping Huang, Dorothy Koch, Jean-François Lamarque, David Lee, Blanca Mendoza, Teruyuki Nakajima, Alan Robock, Graeme Stephens, Hua Zhang, Borgar Aamaas, Olivier Boucher, Stig B Dalsøren, John S Daniel, Piers Forster, Claire Granier, Joanna Haigh, Øivind Hodnebrog, Jed O Kaplan, George Marston, Claus J Nielsen, Brian C O'Neill, Glen P Peters, Julia Pongratz, Venkatachalam Ramaswamy, Raphael Roth, Leon Rotstayn, Steven J Smith, David Stevenson, Jean-Paul Vernier, Oliver Wild, Paul Young, Daniel Jacob, A R Ravishankara, and Keith Shine. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. page 82, 2013.

Adrien Nguyen-Huu and Antonin Pottier. Debt and Investment in the Keen Model: a Reappraisal of Modeling Minsky. page 15, 2016.

W. D. Nordhaus. An Optimal Transition Path for Controlling Greenhouse Gases. *Science*, 258 (5086):1315–1319, November 1992. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.258.5086.1315. URL https://www.sciencemag.org/lookup/doi/10.1126/science.258.5086.1315.

William D. Nordhaus. *A question of balance: weighing the options on global warming policies*. Yale University Press, New Haven, 2008. ISBN 978-0-300-13748-4.

William D Nordhaus. Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies. page 50, 2016.

William D. Nordhaus. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, 114(7):1518–1523, February 2017. ISSN 0027-8424. doi: 10.1073/pnas.1609244114. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5321009/.

William D. Nordhaus and Joseph Boyer. *Warming the world: economic models of global warming*. MIT Press, Cambridge, Mass, 2000. ISBN 978-0-262-14071-3.

Panos Panagos, Gabriele Standardi, Pasquale Borrelli, Emanuele Lugato, Luca Montanarella, and Francesco Bosello. Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. *Land Degradation & Development*, 29(3):471–484, 2018. ISSN 1099-145X. doi: https://doi.org/10.1002/ldr.2879. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/ldr.2879. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ldr.2879.

Kwanele Phinzi and Njoya Silas Ngetar. The assessment of water-borne erosion at catchment level using GIS-based RUSLE and remote sensing: A review. *International Soil and Water Conservation Research*, 7(1):27–46, March 2019. ISSN 2095-6339. doi: 10.1016/j.iswcr.2018.12.002. URL https://www.sciencedirect.com/science/article/pii/S2095633918300583.

Abhishek Raj, Manoj Kumar Jhariya, Dhiraj Kumar Yadav, and Arnab Banerjee. *Climate Change and Agroforestry Systems: Adaptation and Mitigation Strategies*. CRC Press, February 2020. ISBN 978-1-00-000192-1. Google-Books-ID: tTb3DwAAQBAJ.

Valeria Jana Schwanitz. Evaluating integrated assessment models of global climate change. *Environmental Modelling & Software*, 50:120–131, December 2013. ISSN 13648152. doi: 10.1016/j.envsoft.2013.09.005. URL https://linkinghub.elsevier.com/retrieve/pii/S1364815213001965.

Nicholas Stern. The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, 51(3):838–859, September 2013. ISSN 0022-0515. doi: 10.1257/jel.51.3.838. URL https://pubs.aeaweb.org/doi/10.1257/jel.51.3.838.

Alexandre Strapasson, Jeremy Woods, Jerome Meessen, Onesmus Mwabonje, Gino Baudry, and Kofi Mbuk. EU land use futures: modelling food, bioenergy and carbon dynamics. *Energy Strategy Reviews*, 31:100545, September 2020a. ISSN 2211467X. doi: 10.1016/j.esr.2020.100545. URL https://linkinghub.elsevier.com/retrieve/pii/S2211467X20300985.

Alexandre Strapasson, Jeremy Woods, Vanessa Pérez-Cirera, Alejandra Elizondo, Diego Cruz-Cano, Julien Pestiaux, Michel Cornet, and Rajiv Chaturvedi. Modelling carbon mitigation pathways by 2050: Insights from the Global Calculator. *Energy Strategy Reviews*, 29:100494, May 2020b. ISSN 2211-467X. doi: 10.1016/j.esr.2020.100494. URL https://www.sciencedirect.com/science/article/pii/S2211467X2030047X.

United Nations. *World Population Prospects 2019: Data Booklet*. Statistical Papers - United Nations (Ser. A), Population and Vital Statistics Report. UN, June 2019. ISBN 978-92-1-004247-5. doi: 10.18356/3e9d869f-en. URL https://www.un-ilibrary.org/content/books/9789210042475.

Martin L. Weitzman. Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change. *Review of Environmental Economics and Policy*, 5(2):275–292, July 2011. ISSN 1750-6816, 1750-6824. doi: 10.1093/reep/rer006. URL https://www.journals.uchicago.edu/doi/10.1093/reep/rer006.

Martin L. Weitzman. GHG Targets as Insurance Against Catastrophic Climate Damages. *Journal of Public Economic Theory*, 14(2):221–244, 2012.

ISSN 1467-9779. doi: 10.1111/j.1467-9779.2011.01539.x. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-9779.2011.01539.x. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1467-9779.2011.01539.x.

Wusheng Yu and Francesco Clora. Implications of decarbonizing the EU economy on trade flows and carbon leakages. *European Union's Horizon 2020 research and innovation programme*, page 11, 2020.

A Appendix II - Calibration details

A.1 Cobb-Douglas function and energy demand cost minimisation

In our model, we have the carbon energy needed to produce Y composed of fossil fuels and bioenergy through the Cobb Dougla function:

$$Energy = \zeta FO^{\beta} BI^{1-\beta} \tag{53}$$

Constant returns to scale are assumed, i.e. energy varies in the same proportion as the factors of production used. The cost also remains constant. This translates mathematically into the fact that the sum of the exponents is 1. We calculate β as the share of fossil energy in our energy mix in 2015. The total energy needed to produce Y in 2015 is 517 TJ. In the same year 466.45 TJ of fossil energy were consumed. This gives us:

$$\beta = \frac{466.45}{517} = 0.902 \tag{54}$$

Like the FOR-DICE model of Eriksson (2015) the fossil energy demand FO is expressed in GtC and the bioenergy demand in m^3. Thus we calculate the calibration parameter ζ ($TJ.m3 - 1.GtC - 1$) with FO[30] and BI[31] data from 2015:

$$\zeta = \frac{Energy}{FO^{\beta} BI^{1-\beta}} = 20.7239777065467 \tag{55}$$

The Cobb-Douglas energy function is now parameterised. It appeared interesting to impact the fossil energy demand with the carbon price. To do so, it is assumed that industrialists choose their fossil energy and bioenergy demand according to their budget constraint C[32] :

$$C = p_{FO} FO + p_{BI} BI \tag{56}$$

If we replace BI by its value corresponding to the Cobb-Douglas function:

$$BI = \left(\frac{E}{\zeta}\right)^{1-\beta} FO^{\frac{-1}{1-\beta}} \tag{57}$$

And if we calculate the minimum cost $\frac{\partial C}{\partial FO} = 0$, we obtain the demand for fossil energy as a function of the relative price $\frac{p_{FO}}{p_{BI}}$:

$$FO = \left(\frac{p_{FO}}{p_{BI}} \frac{1-\beta}{\beta}\right)^{\beta-1} \frac{E}{\zeta} \tag{58}$$

So we can add the carbon tax to pFO and impact on demand:

$$FO = \left(\frac{p_{FO} + p_{car}}{p_{BI}} \frac{1-\beta}{\beta}\right)^{\beta-1} \frac{E}{\zeta} \tag{59}$$

[30] See IEA (2020) p.53

[31] FAO 2015, see http://www.fao.org/faostat/en/#data/FO

[32] With p_{BI} (\$/billion m³) and p_{FO} (\$/GtC) the respective prices of bioenergy and fossil fuels

As an example, in the *no damage + deforestation* case, the impact of the carbon tax on carbon based energy demands is as follow:

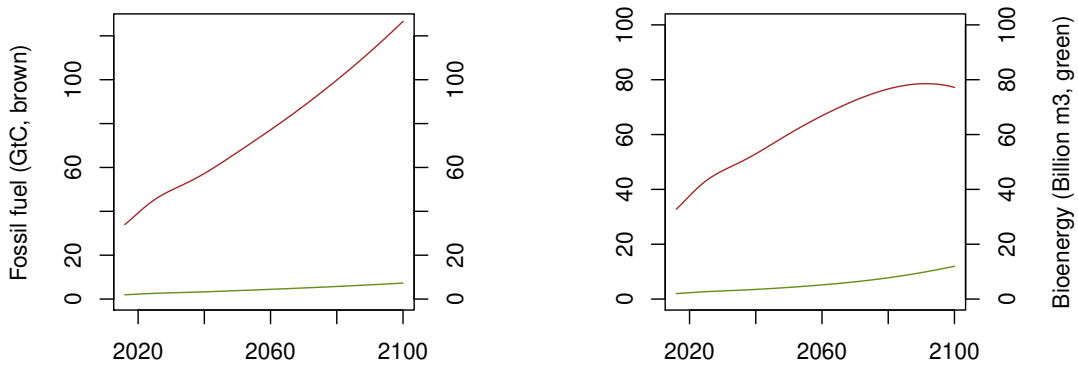

Figure 6: Carbon based energy demands - *no damage*
left without carbon tax - *right* with $p_{car}(2100) = 50\$/tonC$

A.2 Details on bioenergy prices and fossil fuels

It seems sensible to analyse the plausibility of the ratio $\frac{p_{FO}}{p_{BI}}$ that results from the cost minimisation calculation.

It is assumed that fossil fuels have a price equivalent to oil of \$45/barrel. It is known that one barrel of oil is energetically equivalent to about 1700 kWh. Furthermore, one kilowatt-hour of oil, when consumed, corresponds to about 778 gCO2e.

We can then calculate the price of one GtC of oil: $pFO = 3.4024.10^{10}\$/GtC$. Now, we can calculate the ratio $\frac{p_{FO}}{p_{BI}}$ with the 2015 values in equation Eq.(58) above and we get $\frac{p_{FO}}{p_{BI}} = 0.5299$.

The price of one million m^3 of wood for bioenergy is recalculated using this ratio, giving $p_{BI} = 6.42.1010$ *billion* m^3 or 64.2 \$/m^3 or 57.8 eu/m^3[33].

Based on, for example, roundwood prices in European countries between 2005 and 2018[34]:

[33] Conversion with 2015 annual change rate https://fr.statista.com/statistiques/577988/taux-de-change-moyen-annuel-du-dollar-etats-unis-contre-l-euro/

[34] See Kożuch and Banaś (2020)

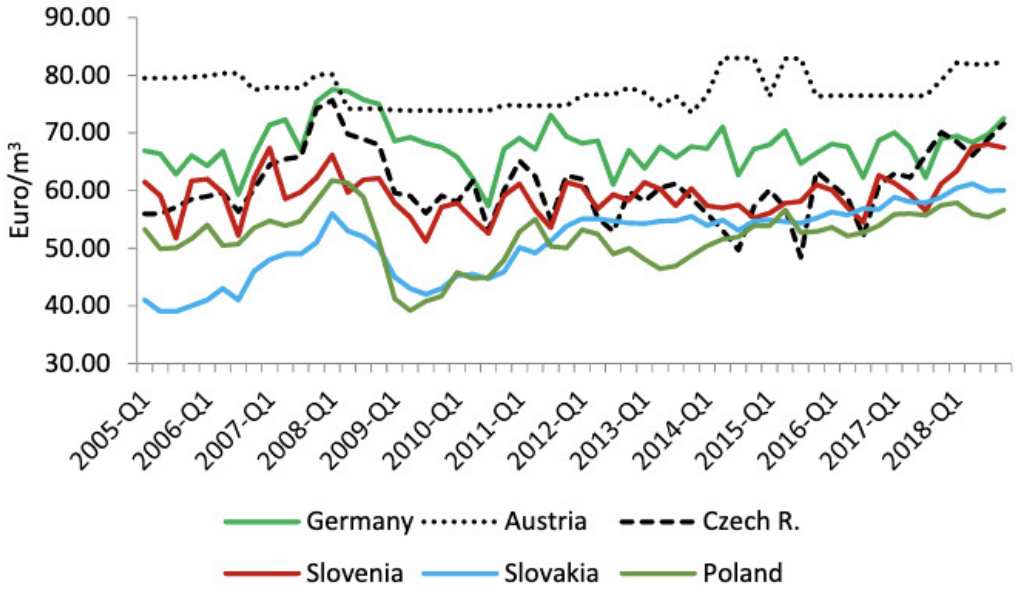

Figure 7: European nominal roundwood price 2005-2018
Source : Kożuch and Banaś (2020)

The calculated value corresponds to the order of magnitude of market prices before the pandemic.

B Appendix III - Notation

B.1 Variables

Symbol	Description	Initial value	Source
CO_2^{AT}	CO2-e concentration in the atmosphere	851 GtC	Nordhaus (2016)
CO_2^{UP}	CO2-e concentration in the biosphere and upper ocean	460 GtC	*ibidem*
CO_2^{LO}	CO2-e concentration in the deep ocean	1740 GtC	*ibidem*
d	private debt ratio	1.53	Bovari (2018)
E_{tro}	Exogenous emissions from deforestation	3.3 GtC	*ibidem*
F_{exo}	Exogenous radiative forcage	0.5 W/m2	Nordhaus (2016)
g_σ	Growth rate of the economy's emissions intensity	- 0.0152	*ibidem*
p	Price level	1	Normalisation
G_{pBS}	Price of the backstop technology	547.22	Nordhaus (2016)
n	Emission reduction rate	0.03	*ibidem*
N	Global workforce (billion)	4.84	Calibrated
N_g	World population (billion)	7.35	Calibrated
T	Mean world temperature	0.85°C	Nordhaus (2016)
T_0	Average temperature of the deep ocean layer	0.0068 °C	*ibidem*
Y	Gross domestic product ($USD tril.)	59.74	Calibrated
λ	Employment rate of the economy	0.675	Calibrated
ω	Wage share	0.518	Calibrated
F_{bor}	Boreal forest biomass stock (billion m3)	173	2015 adaptation of Eriksson (2015)
F_{tem}	Temperate forest biomass stock (billions m3)	84	*ibidem*
F_{tro}	Tropical forest biomass stock (billions m3)	388	*ibidem*
Ψ_{bor}	Growth of the boreal forest	0.01379341861	*ibidem*
Ψ_{tem}	Growth of the temperate forest	0.03362579279	*ibidem*
Ψ_{tro}	Growth of the tropical forest	0.04051984059	*ibidem*
HS_{bor}	Boreal industrial roundwood harvest	0,7649	*ibidem*
HS_{tem}	Temperate industrial roundwood harvest	0,6599	*ibidem*
HS_{tro}	Tropical industrial roundwood harvest	0,4252	*ibidem*
MC	Cost of agroforestry policy ($USD tril.)	0	Kindermann et al. (2008)
BI	Wood for bioenergy	1.9	FAO (2016)
X_{bor}	Share of the boreal forest	0.41	Eriksson (2015)
X_{tem}	Share of the temperate forest	0.36	*ibidem*
X_{tro}	Share of the tropical forest	0.23	*ibidem*
CH	Carbon stock in forest products	4.9	*ibidem*
Energy	Carbon energy needed to produce global GDP	517	IEA (2020)
FO	Carbon emissions from fossil fuels	33	*ibidem*
RD	Agroforestry policy variable	0	Eriksson (2015)

B.2 Parameters

Symbol	Description	Value	Source
C	Heat capacity of the atmosphere, biosphere and upper ocean	1/.098 SI	Nordhaus (2016)
C_0	Heat capacity of the deeper ocean	3.52 SI	*ibidem*
C_{ATpind}	CO2e preindustrial concentration in the atmosphere layer	588 GtC	*ibidem*
C_{UPpind}	CO2e preindustrial concentration in the biosphere/upper ocean	360 GtC	*ibidem*
C_{LOpind}	CO2e preindustrial concentration in the deeper ocean layer	1720 GtC	*ibidem*
Δ_0	Constant of the dividend function, $\Delta()$	0.138	Bovari (2018)
Δ_π	Slope of the dividend function, $\Delta()$	0.473	*ibidem*
$[\Delta_{min}, \Delta_{max}]$	Range of the dividend function, $\Delta()$	[0,.3]	*ibidem*
F_{2CO2}	Change in the radiative forcing resulting from a doubling of CO2e con.	3.681 W/m^2	Nordhaus (2016)
F_{exo}^{start}	Initial value of the exogenous radiative forcing	0.5 W/m^2	*ibidem*
F_{exo}^{end}	Value of the exogenous radiative forcing in 2100	1 W/m^2	*ibidem*
f_K	Fraction of environmental damage allocated to the stock of capital	$\{0; 1/3\}$	Dietz and Stern (2015)
N^{max}	Upper limit of the workforce dynamics in billions	7.056	Bovari (2018)
P_G^N	Upper limit of the total population dynamics in billions	12	*ibidem*
q	Speed of growth of the workforce dynamics	0.0305	*ibidem*
q_G	Speed of growth of the total population dynamics	0.027	*ibidem*
r	Short-term interest rate of the economy	0.03	*ibidem*
S	Equilibrium climate sensitivity	3.1 °C	Nordhaus (2016)
T_{preind}	Preindustrial temperature	13.74 °C	*ibidem*
α	Constant growth rate of labor productivity	0.02	Bovari (2018)
$\gamma*$	Heat exchange coefficient between temperature layers	0.0176 SI	Nordhaus (2016)
δ_K	Depreciation rate of capital	0.04	Inklaar and Timmer (2013)
δ_{ELand}	Growth rate of land use change CO2e emissions	-0.022	Nordhaus (2016)
$\delta_{g\sigma}$	Variation rate of the growth of emission intensity	-0.001	*ibidem*
δ_{pBS}	Exogenous growth rate of the back-stop technology price	-0.005	*ibidem*
ζ_3	Damage function parameter	6.754	Weitzman (2011) and Dietz and Stern (2015)
η	Relaxation parameter of the inflation	0.5	Bovari (2018)
θ	Parameter of the abatement cost function	2.6	Nordhaus (2016)
κ_0	Constant of the investment function, $\kappa()$	0.0318	Bovari (2018)
κ_π	Slope of the investment function, $\kappa()$	0.575	*ibidem*
$[\kappa_{min}, \kappa_{max}]$	Range of the investment function, $\kappa()$	[0,.3]	*ibidem*
μ	Mark-up of prices over the average cost	1.3	*ibidem*
ν	Constant capital-to-output ratio	2.7	Inklaar and Timmer (2013)
π_1	Damage function parameter	0/°C	Nordhaus (2016)
π_2	Damage function parameter	0.00236/°C^2	*ibidem*
π_3	Damage function parameter in the Weitzman case	0.00000507/°C$^{\zeta_3}$	Weitzman (2011)
ϕ_0	Constant of short-term Phillips curve, $\phi()$	-0.292	Bovari (2018)
ϕ_λ	Slope of short-term Phillips curve, $\phi()$	0.469	*ibidem*
Φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.024	Nordhaus (2016)
$\Phi 23$	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.001	*ibidem*
ξ	Energetic parameter	14.39687278	Calibrated
ζ	Energy scale parameter	20.7239777065467	Appendix(A)
ϕ_1	Cost of forest policy parameter	1.52638276079	Kindermann et al. (2008) adapted to our continuous framework
ϕ_2	Cost of forest policy parameter	1.18258619118984	Kindermann et al. (2008) adapted to our continuous framework