Climate change and Forest disturbances in Europe: an economic analysis of the losses

Abstract

Climate warming is expected to increase the frequency and magnitude of extreme events in the mid to long term (Lindner et al., 2010; Bolte et al., 2009; Morin et al., 2018; Dale et al., 2000; Seidl et al., 2011). Here, we combine a (dynamic general equilibrium) model of forest management with inter-country input-output tables (Remond-Tiedrez et al., 2019) to estimate the economic effect on the EU-28 and USA economies of changes in the output of the forestry and logging sectors due to extreme forest disturbance events. Given our model results, we estimate that the impact on the EU-28 economy will be equivalent to the value of wood damaged multiplied 3.32 fold [3.00-3.44]. We find that the economic cost of a global pan-European extreme event (a pulse of 450 M m3) could be 120.4 billion Euros in the EU-28 and 1.7 billion in the USA (i.e. 0.926 and 0.015% of their respective GDPs). Finally, we explore how to design incentives to increase the economic resilience of the response of forestry and logging companies to expected future climate change. Using a heterogeneous companies model, we show that payments to landowners to conserve forest increase economic resilience.

Keywords: Climate warming, Forestry disturbances, (DICE) models, FIGARO input-output

1. Introduction

Forests cover approximately 215 million ha in Europe, i.e. 33% of total continental European land (EFI and Unece, 2015). EU forested areas (Böttcher et al., 2012) sustain a major timber industry (Hanewinkel et al., 2013) which produces an average of 562 million m3 of wood products per annum and provides direct jobs and income for at least 3 million people (EFI and Unece, 2015). However, despite their high ecological, economic and social value, forests are threatened by a wide variety of factors. Of particular importance are natural disturbances such as fire, wind and bark beetles, which have affected approximately 35 million m3 of timber over the last 50 years (Schelhaas et al., 2003), i.e. an average of 0.15% of the total standing volume of European forests per year and 8.1% of the total annual area felled by EU countries (Schelhaas et al., 2003).

Climate change exacerbates the effects of these disturbances, and has major economic effects. Extreme events such as storms, droughts, flooding, and heat waves are probably the biggest threats in temperate oceanic regions (Lindner et al., 2010). In Europe, climate warming is expected to increase the frequency and magnitude of such extreme events in the mid to long term (Lindner et al., 2010; Bolte et al., 2009; Morin et al., 2018) and therefore the impacts of forest disturbances.

Here, we assess the economic consequences of the occurrence of extreme fire, wind, and bark beetle event scenarios. We show that, given that forest companies use capital, labor, and intermediate inputs to harvest trees, the quantitative economic impact of natural disturbances is substantially amplified. In this framework, the economic impact of natural disturbances is not only the expected value of wood damaged, but also the reduction in wages and capital gains due to the decline in forest size. Given the results of our model, the economic losses of the forestry sector are equal to 2.25 [2.00 – 2.50] times the value of the wood damaged. Furthermore, the reduction in the output of the forestry sector also reduces its expenditures on other sectors, generating spillovers for the EU-28 economy. Under the scenario applied, those spillovers represent a further 0.69-1.10. Overall, the impact on the EU-28 economy is equivalent to the value of wood damaged multiplied 3.32 fold [3.00-3.44].

Finally, we build extreme disturbance event scenarios. We find that the economic cost of a global extreme event (a pulse equivalent to the 2010 annual roundwood output of 450 million m3) may be 120.4 billion Euros for the EU-28 and 1.7 billion for the USA. (i.e. 0.926 and 0.015 % of their respective GDPs).
2. Methods

Here, we calculate the impact of natural disturbances in forests (fire, wind, and bark beetles) on the EU-28’s output in two steps. First, we estimate a (general equilibrium) version of the harvesting problem solved by Reed (1984) to quantify the intertemporal impact of natural disturbances on the output of the forestry and logging sector. The model is estimated using (i) 45 years disturbed timber volume time series; (ii) yearly national roundwood output data; (iii) forestry and logging labor (working hours) time series; and (iv) age-structure forest area time series for a sample of 19 EU countries (see Supplementary Material 5.1). Second, we calculate the spillover effects from the forestry and logging sector for EU-28 (and US) GDP using (EU) inter-country input-output tables as per Remond-Tiedrez et al. (2019) (FIGARO). This database divides the industry into 64 activities and covers all EU Member States (EU-28) plus the USA.

Impact on Forestry Output: Disturbance multipliers

The impact of natural disturbances (wildfires, wind, storms, and/or insect outbreaks) on output depends on how each disturbance affects the quantities of capital and labor used by forestry companies to harvest trees.

If forestry companies do no react to (expected) future changes in forest size (wood disturbed reducing age-class [45-50] in the next 50 years), the change in output is proportional to the change in age-class [45-50] over the recovery period (solid red line in Figure 2), i.e. with a constant harvest rate $\Delta(\%)$ Wood damaged is equal to the $\sum_{t=0}^{T} \Delta(\%)$ Forestry Output$_t$.

Figure 2: Forestry output Impulse-response function. The figure shows the deviation from the steady state level when the disturbances reduce forest size by 1%. The y axis shows the value of the multiplier for each year t: In year 0 the IRF figures correspond to the impact multiplier. The change in output, $\Delta$Forestry Output$_t$, corresponds to the area above the IRF from $t=0$ to year $T$. The $\Delta$ Wood damaged corresponds to the red area.

However, the model estimated shows that companies change their harvest rates after a disturbance. To mitigate the impact of disturbances on forest owner companies, they increase their forest harvest rate (by reducing labor and capital proportionally by less than the reduction in forest size due to the disturbance). In other words the impact disturbance muli-
Table 1: EU disturbance multipliers: average of the median and confidence intervals (10% and 90% of the posterior distribution) of the 17 IRF’s estimated (Austria, Switzerland, Poland, Czechoslovakia, Hungary, Finland, Norway, Sweden, Denmark, France, Germany and Netherlands, United Kingdom, Ireland, Spain, Portugal and Italy).

|                  | Impact at time of disturbance \( t = 0 \) | Cumulative \( T = 50 \) |
|------------------|------------------------------------------|-------------------------|
|                  | inf (lower 10%) | Median | sup (upper 90%) | inf (lower 10%) | Median | sup (upper 90%) |
| \( \Delta \)Forestry Output\(_{10} \) | -0.7406 | -0.8326 | -0.9292 | -1.9973 | -2.2454 | -2.5062 |
| \( \Delta \)Wood damaged\(_{10} \) | 1.0000 | 0.0000 | 0.0000 | 6.7164 | 6.7164 | 6.7164 |
| Impact multiplier | -0.7406 | -0.8326 | -0.9292 | -1.9973 | -2.2454 | -2.5062 |

\( \Delta \text{Forest Output}_{t} = \Delta \text{Wood damaged}_{t} \) (we consider that \( t = 2\% \))

\[ \text{Impact multiplier} = \frac{\Delta \text{Forest Output}_{t=0}}{\Delta \text{Wood damaged}_{t=0}} \]

\( \sum_{t=0}^{T} (1 + i)^{-t} \Delta \text{Forest Output}_{i} \)

\( \sum_{t=0}^{T} \Delta \text{Wood damaged}_{t} \)

Cumulative multiplier = \( \frac{\sum_{t=0}^{T} (1 + i)^{-t} \Delta \text{Forest Output}_{t}}{\sum_{t=0}^{T} \Delta \text{Wood damaged}_{t}} \),

to measure the amplification factor (see Table 1). The impact of disturbances on the forest amplifying its economic impact. We use the cumulative disturbance multiplier

\( \frac{\Delta \text{Forest Output}_{t=0}}{\Delta \text{Wood damaged}_{t=0}} \)

which measures the impact at the time when the disturbance occurs is lower than one. Increasing the harvesting rate at the time of the disturbance delays the rate of forest recovery (the IRF of the forest size is lower than the IRF of newborn trees). That is, companies smooth the loss of wealth arising from the natural disaster over the 50 years needed for the full recovery of the forest, amplifying its economic impact. We use the cumulative disturbance multiplier

Table 2: Structure of the FIGARO Input-Output Table. Rows report income received. Columns report expenditures of each sector on intermediate goods.

| Intermediate Use | Final Use | Output (X) |
|------------------|-----------|------------|
| country 1 x prod 1 | (X\(_i \)) | (X\(_j \)) |
| country 1 x prod 2 | (F\(_i \)) |
| country 29 x prod 1 |           |
| country 29 x prod 64 |          |

Full International and Global Accounts for Research in Input-Output analysis (FIGARO) is a project of the European Statistical Programme that draws up European Union (EU) inter-country input-output tables for a better understanding of international value chains. This database divides the industry into 64 activities and covers the EU Member States (EU-28) plus the USA. See https://ec.europa.eu/eurostat/web/experimental-statistics/figaro.

3). Note that economic integration has led to international production value chains, and therefore natural disturbances impact on sectors that may be located in countries far from the zone directly affected by them.

Impact on other sectors: Spillover multipliers

International trade and interdependencies between sectors greatly influence the economic consequences of forest disturbances. We use FIGARO to estimate the spillover effect of changes in the output of the forestry and logging sector. These spillovers affect the sectors linked via supply and demand to the forestry and logging sector, but also other national economies where those sectors are located.

Data shows that the spillovers are higher in those countries where forestry uses more intermediate inputs (see figure 3). This radar-plot shows the (average) expenditures on forestry products, logging and related services (A02, FIGARO) for each € produced; The XY plot shows that the Spillover impact is positively correlated with the size of expenditures from forestry output in other sectors/countries.
On average, the input-output multiplier amplifies the reduction in the forestry expenditures on intermediate inputs (induced by the disturbance) by a factor of 1.9 [1.73-2.03].

For instance the impact of a €1 reduction in the output of the EU-28 forestry and logging sector (proportionally to the relative weight of each country’s forestry and logging sector in the total forestry and logging sector of the EU) and logging sectors reduces output in the USA economy by around 4 percent (see Figure 5).

Moreover, countries which account for smaller proportions of total EU forestry output, such as the UK, experience high spillover effects. This is due to the structure of the intermediate input expenditures from EU forestry output. Table 13 in the Supplementary Materials shows that 30% of total expenditure is related to services (wholesale trade services, repair and installation services for machinery, transport services and financial services, etc).

Figure 4: Input-output multipliers of the Forestry Sector. This figure shows the impact on the outputs of the EU-28 (panel a) and USA (panel b) of a €1 reduction in the output of forestry and logging products for each EU country.

Table 3: Input-output multiplier

| Spillover per Δ forestry output$^{-1}$ | inf (lower 10%) | Median | sup (upper 90%) |
|---------------------------------------|----------------|--------|-----------------|

Figure 5: Impact of a €1 reduction in the output of the forestry and logging sectors of the 28 countries of the EU (proportionally to the relative weight of each country’s forestry and logging sector in the total forestry and logging sector of the EU).
3. Economic impact of extreme disturbances regimes

Extreme events such as storms, droughts, flooding, and heat waves are probably the most important threats in temperate oceanic regions (Lindner et al. (2010)). In Europe, climate warming is expected to increase the frequency and magnitude of such extreme events in the mid to long term (Lindner et al. 2010; Bolte et al. 2009; Morin et al. 2018) and, in consequence, the impacts of forest disturbances.

Table 4: Scenarios: volume of wood damaged

| Scenario | wood damaged (M m³) |
|----------|---------------------|
| SCE:1 | | |
| "fire" Zone | "wind" Zone | "bark beetles" Zone |
| Austria | – | 7.4 | 2.5 | 9.9 |
| Belgium | – | – | – | 4.9 |
| Bulgaria | – | – | – | 5.7 |
| Cyprus | – | – | – | 9.0 |
| Czech Republic | – | 12.8 | 3.6 | 16.4 |
| Germany | – | 73.8 | 10.0 | 83.8 |
| Denmark | – | 3.5 | – | 3.5 |
| Estonia | – | – | – | 7.1 |
| Spain | 5.9 | – | – | 5.9 |
| Finland | – | 7.0 | – | 7.0 |
| France | 3.1 | 139.6 | 2.0 | 144.7 |
| UK | – | 6.0 | – | 6.0 |
| Greece | – | – | – | 1.0 |
| Croatia | – | – | – | 4.5 |
| Hungary | – | – | – | 5.8 |
| Ireland | – | – | – | 2.6 |
| Italy | 1.3 | – | – | 1.3 |
| Lithuania | – | – | – | 7.2 |
| Luxembourg | – | – | – | 0.5 |
| Latvia | – | – | – | 12.7 |
| Malta | – | – | – | – |
| Netherlands | – | – | – | 1.13 |
| Poland | – | 2.0 | 2.7 | 4.7 |
| Portugal | 24.3 | – | – | 24.3 |
| Romania | – | – | – | 13.3 |
| Sweden | – | 75.0 | 0.5 | 75.5 |
| Slovenia | – | – | – | 3.0 |
| Slovakia | – | – | – | 9.7 |
| United States of America | – | – | – | – |
| Total | 34.5 | 327.0 | 21.4 | 462.1 |

Table 5: Economic consequences of extreme events

| Scenario 1 | Scenario 2 |
|------------|------------|
| "fire" Zone | "wind" Zone | "bark beetles" Zone |
| Forestry Output | | |
| EU-28 | 7412 | 53870 | 3018 |
| USA | 19.61 | 91.27 | 6.29 |
| Total | 81367 | | |
| Spillover | | |
| EU-28 | 2485 | 23303 | 1687 |
| USA | 15 | 197 | 11 |
| Total | 20647 | | |
| Total EU-28 | 382.7 | | |
| USA | 1312 | 12161 | 827 |
| Intermediate inputs | | |
| EU-28 | 1312 | 12161 | 827 |
| USA | 15 | 197 | 11 |
| Total | 20647 | | |
| Total EU-28 | 120415 | | |
| USA | 60 | 796 | 44 |
| Total | 1751 | | |
| Total EU-28 | 0.9250 | | |
| USA | 0.0151 | | |

Table 6: Amplification

| Scenario 1 | Scenario 2 |
|------------|------------|
| "fire" Zone | "wind" Zone | "bark beetles" Zone |
| Expenditures per 1 | | |
| Forestry sector | 0.1770 | 0.2258 | 0.2741 |
| Spillover multiplier | 1.8945 | 1.9161 | 1.9425 |
| Spillover EU-28 per € 1 wood damaged | 0.6962 | 0.8982 | 0.9965 |
| Total impact EU-28 per € 1 wood damaged | 2.9983 | 3.2167 | 3.4409 |

Portuguese wild fires in 2003, Lothar and Martin cyclones in France in 1999 and the major insect outbreak associated with 1992 are the biggest continental disturbance events.

Here, we build four scenarios to assess the impact of extreme events on the EU-28 economy. To explore how the impact depends on the damaged area, we use the geographical damage distribution. In the first three local scenarios we thus simulate the impact of the maximum reported national disturbed timber volume damaged from 1960 to 2005 for fire (SC1: "fire" Zone), wind (SC1: "wind" Zone), and bark beetles (SC1: "bark beetles" Zone). In developing the scenarios we only consider the subset of countries where the maximum damage is significant for each agent (see Table 4). Note that the scenarios are not similar in terms of size.

We also build up a global scenario (SC2: EU-28) to assess the impact of incidence of a simultaneous pan-European scale extreme event. SC2 is built up as the sum of the wood damaged in SC1. This scenario involves the destruction of 382.7 million m3, which is 101.5% of the total amount of roundwood produced in Europe in 2010. Throughout SC2, for countries where disturbance data was not available on SC1 damage is assigned as 101.5% of the national roundwood output in 2010.

We use the cumulative multiplier together with the input-output methods (described in the Supplementary Material 5.3) to estimate the impact of forest disturbances on the EU-28 and USA economies. Table 5 shows the scale of the economic losses (in millions of € 2010) of the extreme event considered in each scenario.

The reduction in forestry output generates spillovers for the EU economy which, under the scenario applied, account for a further 0.69 to 1.10 percent on top of the figure for the cumulative multiplier. Overall, the impact on the total output of the EU economy multiplies the value of damaged wood 3.32-fold [3.00-3.44].

Figures 6 and 7 show that the amplification effect is not homogeneous across scenarios or zones. The heterogeneity observed suggests that the make-up of final goods (how domestic goods are combined with other domestic goods) and international value chains (how domestic goods are com-
bined with foreign goods) of national forestry sectors is a key element in understanding the economic consequences of unexpected extreme events.

Figure 6: Wood damaged and Spillovers in each Scenario.
Figure 7: Ecological zones: Alpine: Austria; Atlantic: United Kingdom and Ireland; Central-Mediterranean: Croatia, Italy and Slovenia; Eastern-Mediterranean: Bulgaria, Cyprus, Greece and Malta; Northern: Finland and Sweden; Panonic: Estonia, Hungary, Lithuania, Latvia, Poland, Romania and Slovak Republic; Sub-Atlantic: Belgium, Germany, Denmark, France, Luxembourg and Netherlands; Western-Mediterranean: Spain and Portugal.

Table 7: Economic consequences of extreme events by Ecoregions (as % of GDP)

| Scenario 1 | Scenario 2 |
|------------|------------|
| Fire Zone  | Wind Zone  | Bark Beetles Zone |
| Alpine     | 0.01       | 1.96             | 2.14 | 1.17 |
| Northern   | 0.00       | 5.51             | 0.02 | 2.45 |
| Panonic    | 0.01       | 1.27             | 0.01 | 0.55 |
| Atlantic   | 2.08       | 0.09             | 0.02 | 0.72 |
| Sub-Atlantic | 0.05     | 2.03             | 0.27 | 1.01 |
| Eastern-Med | 0.00      | 0.04             | 0.01 | 0.56 |
| Western-Med | 0.24     | 1.36             | 0.27 | 0.93 |
| EU         | 0.00       | 0.02             | 0.00 | 0.02 |

Table 8: Ecological zones: Alpine: Austria; Atlantic: United Kingdom and Ireland; Central-Mediterranean: Croatia, Italy and Slovenia; Eastern-Mediterranean: Bulgaria, Cyprus, Greece and Malta; Northern: Finland and Sweden; Panonic: Estonia, Hungary, Lithuania, Latvia, Poland, Romania and Slovak Republic; Sub-Atlantic: Belgium, Germany, Denmark, France, Luxembourg and Netherlands; Western-Mediterranean: Spain and Portugal.
### Table 9: Economic consequences of extreme events (by countries)

| Country | EU-28 | **Impact on Forestry Output (million €)** | **Total losses (as % of national GDP)** |
|---------|-------|------------------------------------------|-----------------------------------------|
|         | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
|         | "fire" Zone | "wind" Zone | "bark beetles" Zone | EU-28 | "fire" Zone | "wind" Zone | "bark beetles" Zone | EU-28 |
| **Alpine** | Austria | 2031 | 697 | 2725 | 5 | 446 | 116 | 663 |
| **Atlantic** | United Kingdom | 1199 | 1199 | 4832 | 8 | 102 | 5 | 2023 |
| **Sub-Atlantic** | Belgium | 0 | 918 | 17 | 309 | 15 | 1263 |
| **Sub-Atlantic** | Germany | 7035 | 953 | 7988 | 56 | 4287 | 530 | 5435 |
| **Sub-Atlantic** | Denmark | 1136 | 1136 | 3 | 590 | 6 | 685 |
| **Sub-Atlantic** | France | 617 | 28039 | 405 | 29606 | 276 | 10218 | 176 | 11090 |
| **Sub-Atlantic** | Luxembourg | 50 | 5 | 99 | 5 | 150 |
| **Sub-Atlantic** | Netherlands | 371 | 26 | 383 | 26 | 1196 |
| **Western-Mediterranean** | Spain | 984 | 984 | 350 | 464 | 24 | 1011 |
| **Western-Mediterranean** | Portugal | 5547 | 5547 | 1594 | 40 | 2 | 1657 |
| **Central-Mediterranean** | Croatia | 631 | 7 | 1 | 242 |
| **Central-Mediterranean** | Italy | 263 | 263 | 75 | 650 | 48 | 1059 |
| **Central-Mediterranean** | Slovenia | 515 | 1 | 22 | 3 | 155 |
| **Eastern-Mediterranean** | Bulgaria | 888 | 1 | 15 | 2 | 322 |
| **Eastern-Mediterranean** | Cyprus | 46 | 0 | 4 | 0 | 28 |
| **Eastern-Mediterranean** | Greece | 273 | 2 | 31 | 2 | 84 |
| **Northern** | Malta | 0 | 0 | 6 | 0 | 15 |
| **Northern** | Finland | 1172 | 1172 | 2 | 290 | 4 | 391 |
| **Northern** | Sweden | 10589 | 18867 | 5 | 1506 | 10 | 1628 |
| **Panonic** | Czech Republic | 2409 | 614 | 3023 | 3 | 1663 | 407 | 2152 |
| **Panonic** | Estonia | 960 | 0 | 9 | 1 | 494 |
| **Panonic** | Hungary | 0 | 813 | 2 | 82 | 11 | 508 |
| **Panonic** | Lithuania | 0 | 494 | 0 | 17 | 1 | 236 |
| **Panonic** | Latvia | 0 | 1998 | 0 | 9 | 1 | 940 |
| **Panonic** | Poland | 257 | 348 | 605 | 5 | 346 | 163 | 853 |
| **Panonic** | Romania | 0 | 2040 | 3 | 52 | 5 | 1260 |
| **Panonic** | Slovak Republic | 0 | 2214 | 1 | 105 | 21 | 474 |
| **US** | United States | 0 | 50 | 796 | 45 | 1752 |

Total losses (million €):
- **Scenario 1**
  - Alpine: Austria 3392
  - Atlantic: United Kingdom 4436
  - Sub-Atlantic: Belgium 13424
  - Sub-Atlantic: Germany 1821
  - Sub-Atlantic: France 40150
  - Sub-Atlantic: Luxembourg 1567
  - Western-Mediterranean: Spain 1995
  - Western-Mediterranean: Portugal 7204
  - Central-Mediterranean: Croatia 1873
  - Northern: Finland 1564
  - Northern: Sweden 12295
  - Panonic: Czech Republic 5175
  - Panonic: Estonia 1396
  - Panonic: Hungary 1211
  - Panonic: Lithuania 730
  - Panonic: Latvia 2938
  - Panonic: Poland 1258
  - Panonic: Romania 5336
  - Panonic: Slovak Republic 2668
  - US: United States 1752

Total losses (% of national GDP):
- **Scenario 1**
  - Alpine: Austria 0.0017
  - Atlantic: United Kingdom 0.0022
  - Sub-Atlantic: Belgium 0.0022
  - Sub-Atlantic: Germany 0.0014
  - Sub-Atlantic: France 0.0443
  - Sub-Atlantic: Luxembourg 0.0101
  - Sub-Atlantic: Netherlands 0.0047
  - Western-Mediterranean: Spain 0.1217
  - Western-Mediterranean: Portugal 3.9673
  - Central-Mediterranean: Croatia 0.0005
  - Northern: Finland 0.0011
  - Northern: Sweden 0.0014
  - Panonic: Czech Republic 0.0015
  - Panonic: Estonia 0.0007
  - Panonic: Hungary 0.0022
  - Panonic: Lithuania 0.0015
  - Panonic: Latvia 0.0006
  - Panonic: Poland 0.0018
  - Panonic: Romania 0.0010
  - Panonic: Slovak Republic 0.0020
  - US: United States 0.0004

Total losses (million €) EU-28:
- **Scenario 2**
  - Alpine: Austria 3392
  - Atlantic: United Kingdom 4436
  - Sub-Atlantic: Belgium 13424
  - Sub-Atlantic: Germany 1821
  - Sub-Atlantic: France 40150
  - Sub-Atlantic: Luxembourg 1567
  - Western-Mediterranean: Spain 1995
  - Western-Mediterranean: Portugal 7204
  - Central-Mediterranean: Croatia 1873
  - Northern: Finland 1564
  - Northern: Sweden 12295
  - Panonic: Czech Republic 5175
  - Panonic: Estonia 1396
  - Panonic: Hungary 1211
  - Panonic: Lithuania 730
  - Panonic: Latvia 2938
  - Panonic: Poland 1258
  - Panonic: Romania 5336
  - Panonic: Slovak Republic 2668
  - US: United States 1752

Total losses (% of national GDP) EU-28:
- **Scenario 2**
  - Alpine: Austria 0.0017
  - Atlantic: United Kingdom 0.0022
  - Sub-Atlantic: Belgium 0.0022
  - Sub-Atlantic: Germany 0.0014
  - Sub-Atlantic: France 0.0443
  - Sub-Atlantic: Luxembourg 0.0101
  - Sub-Atlantic: Netherlands 0.0047
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  - Panonic: Hungary 0.0022
  - Panonic: Lithuania 0.0015
  - Panonic: Latvia 0.0006
  - Panonic: Poland 0.0018
  - Panonic: Romania 0.0010
  - Panonic: Slovak Republic 0.0020
  - US: United States 0.0004
4. Discussion

The use of an age-structured model and historical maximum disturbance data means that we are probably underestimating the economic cost of forest disturbances. On one hand, in the model wood damaged is measured based on the future volume lost (opportunity cost). However, the data available uses the “current” volume of wood damaged, so our amplification results are conservative. More research on cut-off ages and volumes is needed to obtain a more reliable measure of amplification. On the other hand, our scenarios are based on historical country maximums. However Lindner et al. (2010); Bolte et al. (2009); Morin et al. (2018) show that in Europe global warming is expected to increase the frequency, magnitude and therefore impact of forest disturbances in the medium and long term. For instance, Seidl et al. (2014) calculate that in 2021–2030 there will be losses of 11.7 m3/year from fire, 44.5 m3/year from wind, and 17.9 m3/year from bark beetle. That would mean (average) losses per annum of € 3.36, 10.50 and 5.45 billion respectively and a possible total of 0.15% of the EU-28 GDP. Note that our extreme global pan-European scenario is less than seven times this yearly average.

Given these high economic costs of forest disturbances, measures need to be taken to mitigate their effects. A policy of payments to landowners may be successful in protecting biodiversity as it leads to an ex-post faster recovery once a disturbance has happened (see Muñoz-Piña et al. (2008); Banks-Leite et al. (2014); Alix-Garcia et al. (2012)).

We use a model of heterogeneous landowners (see supplementary material 5.4) affected by idiosyncratic disturbances to assess the resilience properties of incentive schemes based on paying landowners to conserve forests. On the basis of our model results, paying landowners to conserve forests reduces the vulnerability of forests to large, unexpected disturbances and, so such payments are an instrument conducive to the resilience of natural capital.

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5. Appendix

5.1. A recursive Harvesting Problem

A general description of the economic model includes the specification of a set of households that own firms in the timber and logging industry. These firms demand labor supplied by the households, which is traded in the labor market in exchange for wages. Firms decide their demand for labor by maximizing profits. Households receive the profits obtained by the firms and are also paid wages. Income from profits and wages is used by households both to pay for consumption and to invest. Households decide investments and consumption following an optimal rule that maximizes their welfare by comparing the value of consuming in the current period with expected future returns on investment. Figure 8 summarizes the logic of the model.

Household welfare is measured in terms of utility. The representative household derives utility from consumption, \( C_t \), and disutility from labor, \( L_t \). Households receive income from wages earned, \( w_t L_t \), and rental rates on physical capital \( R_t K_t \), which is used by households to purchase consumption goods and to invest, \( I_t \). Formally, the representative household selects its lifetime consumption and labor supply paths by solving the following intertemporal decision problem,

\[
\max_{\{C_t, L_t, K_{t+1}\}_{t=0}^{\infty}} \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \{ \log C_t - e^{\nu t} B L_t \},
\]

subject to

\[
C_t + I_t = R_t K_t + w_t L_t, \quad K_{t+1} = (1 - \lambda) K_t + I_t,
\]

where \( \mathbb{E}_t \) represents the expectation given the information available at period \( t \), \( B \) is the weight of labor in terms of consumption, \( \beta \) is the discount factor, \( \lambda \) is the capital depreciation rate, and \( R_t = r_t + \lambda \) is the gross capital gains rate.

Logging firms produce the planned added value of the economy, \( Y_t \), with a Cobb-Douglas technology that uses labor and physical capital as inputs. Formally, firms choose input amounts that minimize costs such that:

\[
\min_{L_t, K_t} \mathbb{E}_t \{ w_t L_t + r_t K_t \} \quad s.t. \quad Y_t \leq A_t K_t^\alpha L_t^{1-\alpha},
\]

where \( A_t \) is the total factor productivity (TFP). At the same time, logging firms choose their forest harvesting rates, \( h_t \), such that the total wood removed is proportional to the total value added planned, i.e.

\[
\sum_a (1 - e^{Z_{a,t}}) X_{a,t} \propto Y.
\]

Given the forest harvesting rate, \( h_t \), the forest dynamics is given by:

\[
X_{a+1, t+1} = e^{Z_{a,t}} X_{a,t},
\]

\[
Z_{a,t} = s_a h_t + m_a + \epsilon_{a,t}
\]
Notice that $\varepsilon_{a,t}$ is a disturbance (unexpected shock) that must be understood as a reduction in the forest size. Finally, it is assumed that the TFP of the economy, $A_t$, is related to the size of the stock of trees and exogenous forest size growth, i.e.

$$A_t = e^{\theta_t \left( \sum_{a=1}^{N} w_a X_{a,t} \right)^{\alpha_{stock}}},$$

$$\log X_{1,t+1} = (1 - \rho) \log X_1 + \rho \log X_{1,t} + \varepsilon_{1,t+1}.$$
We estimate the model by Bayesian methods (see Figure 9), using country level historical data. The Bayesian estimation involves combining the estimation of the parameters by maximum likelihood using the observed set of data with the information obtained from prior distributions defined for the same parameters. The standard practice in the estimation of DSGE models is followed in selecting the prior distributions for estimating the model. For each case (country and disturbance), the calibration of the model keeps some parameters fixed and estimates those related to the dynamics of the model. In particular, we keep fixed parameters are kept here for the production function (factor share), the investment function (depreciation of physical capital), the utility function (labor desutility), the discount factor, and the selectivity logging parameters. For each case, the parameters estimated are those related to the impact of a disturbance on forest size and stock dynamics. Once the model is estimated, the (Bayesian) impulse response functions (IRF) are used to compute the estimated impact multiplier and the cumulative multiplier of a natural disturbance.

5.2. Disturbance Data in m3

We calculate average wood volume (m³/ha) using country level historical age-class data on the total forest area (ha) of 19 European countries from 1960 to 2005 and roundwood felled or otherwise harvested and removed (in m³) from FAO. We use standard cohort analysis. Let $\text{Stock}_t = \sum_{i=5}^{16} a_{5,i} h_{a,i}$ be the total number of hectares of forest available for harvesting at period $t$ (where $a_{5,5}$ and $a_{16,16}$ represent age-classes 5 and 16 respectively and $h_{a,i}$ the number of hectares at year $t$). The extent of forest removed is $\text{Removals (ha)}_t = \text{Stock}_t - \text{Stock}_{t-1} + \sum_{i=5}^{16} N_{a,i}$. We compute the averaged volume of wood damaged by fire per country and ecological region as the ratio

$$\frac{\text{Roundwood removed (m³)}}{\text{Removals (ha)}_t}$$

where Roundwood removed (m³) is the total roundwood felled or otherwise harvested and removed (code-5516, item-1861) from FAO.
Table 10 summarizes the ratios of the volume of roundwood removed per forest area harvested (m³/ha). These ratios are used to estimate the volume affected by wildfires in m³ based on the reported wooded forest area burned in hectares per country obtained from the Database of Forest Disturbances provided by the European Forest Institute (EFI). Finally, Table 11 summarizes the damage used to compute the scenarios. To calculate the value of the damaged wood we use the implicit prices obtained for each country as:

\[
\text{implicit wood price} = \frac{\text{Output of the Forestry Output (FIGARO)}}{\text{Roundwood Production 2100 (FAO)}}.
\]

### Table 10: Averaged volume of wood damaged by fire per country and ecological region.

| Ecological Region | Country         | Disturbed roundwood volume (m³/ha) |
|-------------------|-----------------|------------------------------------|
| Alpine            | Austria         | 51.51                              |
|                   | Switzerland     | 83.71                              |
| Pannonic          | Czechoslovakia  | 44.87                              |
|                   | Poland          | 28.05                              |
|                   | Hungary         | 35.7                               |
| Northern          | Finland         | 22.61                              |
|                   | Norway          | 21.58                              |
|                   | Sweden          | 35.41                              |
| Sub-Atlantic      | Denmark         | 63.45                              |
|                   | Germany         | 43.68                              |
|                   | France          | 37.21                              |
|                   | Luxembourg      | 30.76                              |
|                   | Belgium         | 41.86                              |
|                   | Netherlands     | 33.56                              |
| Mediterranean     | Portugal        | 39.13                              |
|                   | Spain           | 22.49                              |
|                   | Italy           | 12.17                              |
| Atlantic          | Great Britain   | 27.89                              |
|                   | Ireland         | 38.53                              |

### Table 11: Disturbances in m³ and value of wood damaged.

| Country | Fire | Wind | Bark |
|---------|------|------|------|
| CZE     |      |      |      |
| POL     |      |      |      |
| HUN     |      |      |      |
| Pannonic|      |      |      |
| AUT     |      |      |      |
| CHE     |      |      |      |
| Alpine  |      |      |      |
| PRF     |      |      |      |
| ESP     |      |      |      |
| ITA     |      |      |      |
| Medite  |      |      |      |
| GBR     |      |      |      |
| IRE     |      |      |      |
| Atlantic|      |      |      |
| DNK     |      |      |      |
| DEU     |      |      |      |
| FRA     |      |      |      |
| LUX     |      |      |      |
| BEL     |      |      |      |
| NLD     |      |      |      |
| SubAtlan|      |      |      |
| FIN     |      |      |      |
| NOR     |      |      |      |
| SWE     |      |      |      |
| Northern|      |      |      |
| Total 19| 345   | 237  | 211  |

Table 10 summarizes the ratios of the volume of roundwood removed per forest area harvested (m³/ha). These ratios are used to estimate the volume affected by wildfires in m³ based on the reported wooded forest area burned in hectares per country obtained from the Database of Forest Disturbances provided by the European Forest Institute (EFI). Finally, Table 11 summarizes the damage used to compute the scenarios. To calculate the value of the damaged wood we use the implicit prices obtained for each country as:

\[
\text{implicit wood price} = \frac{\text{Output of the Forestry Output (FIGARO)}}{\text{Roundwood Production 2100 (FAO)}}.
\]

| Country | Obs. | Total | Median | Max    |
|---------|------|-------|--------|-------|
| CZE     | 2    | 57.736| 28.868 | 54.232|
| POL     | 19   | 5.200.064| 194.874| 415.324|
| HUN     | 4    | 122.072| 23.385 | 61.416|
| Pannonic| 25   | 5.379.872| 247.127| 555.324|
| AUT     | 7    | 39.637 | 5.192  | 11.748|
| CHE     | 19   | 920.944| 24.260 | 224.346|
| Alpine  | 26   | 960.582| 29.452 | 863.610|
| PRF     | 19   | 73.188.751| 2.207.453| 24.298.722|
| ESP     | 44   | 58.431.497| 940.762 | 5.986.519|
| ITA     | 35   | 20.779.361| 485.060 | 1.298.218|
| Medite  | 98   | 152.399.610| 3.633.275| 1.000.000|
| GBR     | 15   | 236.732| 12.340 | 39.171|
| IRE     | 6    | 48.603 | 8.273  | 13.608|
| Atlantic| 21   | 285.335| 20.613 | 863.610|
| DNK     | 13   | 22.590 | 365    | 11.966|
| DEU     | 28   | 915.889| 23.665 | 173.230|
| FRA     | 16   | 8.830.384| 244.407| 3.072.616|
| LUX     | 9    | 1.015  | 62     | 308   |
| BEL     | 1    | 38     | 38     | 38    |
| NLD     | 36   | 131.853| 1.159  | 37.109|
| SubAtlan| 103  | 9.901.769| 269.697| 99.870|
| FIN     | 44   | 766.851| 12.542 | 99.870|
| NOR     | 15   | 134.378| 4.502  | 31.541|
| SWE     | 13   | 905.859| 56.831 | 201.024|
| Northern| 72   | 1.897.088| 73.875 | 99.870|
| Total 19| 345  | 170.734.257| 237    | 829.017.523|
5.3. Input-Output analysis

Table 12: Structure of the Input-Output Table. The label on a column indicates who makes an expenditure and the label on a row indicates who receives it. The rows and columns are ordered so that the transactions can be divided into: intermediate inputs, final demands, and components of the value added.

| Intermediate Use | Final Use | Output (X) |
|------------------|-----------|------------|
| country 1 x prod 1 [... |  | (Z_{i,j}) |  |
| country 2 x product 2 |  | (F_I) |  |
| [... |  | (X_I) |  |
| country 29 x product 1 |  |  |  |
| [... |  |  |  |
| country 29 x product 64 |  |  |  |

Source: Figaro. Full International and Global Accounts for Research in Input-Output analysis (FIGARO) is a project of the European Statistical Programme that develops a European Union (EU) inter-country input-output tables for a better understanding of international value chains. This database divides the industry into 64 activities and covers the EU Member States (EU-28) plus the USA. See https://ec.europa.eu/eurostat/web/experimental-statistics/figaro.

We define the technical coefficients $a_{i,f,c} = \frac{Z_{i,f,c}}{X_{f,c}}$, the share of forestry sector's expenditure in sector $i$, $Z_{i,f}$ over the total expenditures of the forestry sector $X_f$. The vector

$$\text{Expenditures}^{ESC} = \begin{bmatrix} a_{1,1,1} \\ a_{i,f-1,c} \\ a_{i,f+1,c} \\ \sum_{c \in \text{ESC} \setminus \text{forestry}} Y_{f,c} \\ a_{i,64x29} \end{bmatrix}$$

is the expenditures of the forestry sector of country $c$ in non-forestry sectors (e.g. gas, electricity, machines, insurance, bank services, etc.) in the EU and US. The total impact of a reduction of 1 unit of intermediate production is:

$$\text{Spillover per } \Delta \text{ Production forestry}^{-1} = \Delta Y_{i,\text{forestry} \in \text{country } c} = \left[ I - A_{i,j,\#\text{forestry} \in \text{country } c} \right]^{-1} \text{Exp}_{\text{forestry},c},$$

where $A_{i,j,\#\text{forestry}}$ in country $c$ ∈ ESC.

Table 13: Expenditures of forestry, logging and related services. (FIGARO, CPA A02)

| PROD NA | Product classification                                      | pdf  | cdf  |
|---------|------------------------------------------------------------|------|------|
| CPA A02 | Products of forestry, logging and related services         | 37.43% | 37.43% |
| CPA G46 | Wholesale trade services, except of motor vehicles and motorcycles | 9.34% | 46.77% |
| CPA A01 | Products of agriculture, hunting and related services      | 5.88% | 52.66% |
| CPA C19 | Coke and refined petroleum products                         | 4.69% | 57.35% |
| CPA H49 | Land transport services and transport services via pipelines | 3.99% | 61.34% |
| CPA C33 | Repair and installation services of machinery and equipment | 3.56% | 64.90% |
| CPA K64 | Financial services, except insurance and pension funding    | 2.94% | 67.85% |
| CPA F   | Constructions and construction works                        | 2.74% | 70.59% |
| CPA G45 | Wholesale and retail trade and repair services of motor vehicles and motorcycles | 1.92% | 72.51% |
| CPA C28 | Machinery and equipment n.e.c.                              | 1.76% | 74.27% |
| CPA C16 | Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials | 1.70% | 75.97% |
| CPA L68 | Real estate services                                        | 1.60% | 77.57% |
| CPA D35 | Electricity, gas, steam and air conditioning                | 1.57% | 79.13% |
| CPA C20 | Chemicals and chemical products                             | 1.57% | 80.70% |
| CPA M69-70 | Legal and accounting services; services of head offices; management consultancy services | 1.56% | 82.26% |
| CPA C10T12 | Food, beverages and tobacco products                      | 1.47% | 83.73% |
| CPA G47 | Retail trade services, except of motor vehicles and motorcycles | 1.42% | 85.15% |
| CPA H52 | Warehousing and support services for transportation         | 1.30% | 86.45% |
| CPA N77 | Rental and leasing services                                | 1.29% | 87.74% |
| CPA N80T82 | Security and investigation services                       | 1.14% | 88.88% |
| CPA C25 | Fabricated metal products, except machinery and equipment  | 1.01% | 89.89% |
Table 14: Spillovers in EU and US economies (millions € 2010)

|               | Scenario 1 | Scenario 2 |          |
|---------------|------------|------------|----------|
|               | Fire       | Wind       | Bark     |
| PROD-NA       |            |            |          |
| CPA G46       |            |            |          |
| CPA A01       |            |            |          |
| CPA K64       |            |            |          |
| CPA H49       |            |            |          |
| CPA M69-70    |            |            |          |
| CPA C19       |            |            |          |
| CPA F         |            |            |          |
| CPA C1OT12    |            |            |          |
| CPA D35       |            |            |          |
| CPA H52       |            |            |          |
| CPA C20       |            |            |          |
| CPA L68       |            |            |          |
| CPA C33       |            |            |          |
| CPA C28       |            |            |          |
| CPA N8OT82    |            |            |          |
| CPA N77       |            |            |          |
| CPA G45       |            |            |          |
| CPA C25       |            |            |          |
| CPA M71       |            |            |          |
| CPA K65       |            |            |          |

| Product classification                      | Scenario 1 | Scenario 2 |          |
|--------------------------------------------|------------|------------|----------|
| Wholesale trade services, except of motor  | 10.07%     | 16.10%     | 10.76%   |
| vehicles and motorcycles                   |            |            | 13.94%   |
| Products of agriculture, hunting and       | 14.46%     | 22.38%     | 15.55%   |
| related services                           |            |            | 20.46%   |
| Financial services, except insurance and    | 19.81%     | 28.01%     | 19.88%   |
| pension funding                            |            |            | 25.68%   |
| Land transport services and transport       | 27.77%     | 32.49%     | 23.97%   |
| services via pipelines                     |            |            | 30.54%   |
| Legal and accounting services; services of | 40.04%     | 36.80%     | 27.28%   |
| head offices; management consultancy       |            |            | 35.15%   |
| services                                    |            |            |          |
| Coke and refined petroleum products         | 44.98%     | 40.81%     | 31.00%   |
| Constructions and construction works        | 49.85%     | 44.37%     | 38.07%   |
| Food, beverages and tobacco products        | 51.23%     | 45.64%     | 39.32%   |
| Electricity, gas, steam and air conditioning| 54.08%     | 48.41%     | 42.02%   |
| Warehousing and support services for        | 56.06%     | 51.19%     | 45.54%   |
| transportation                              |            |            | 52.73%   |
| Chemicals and chemical products             | 60.10%     | 53.71%     | 47.99%   |
| Real estate services                        | 61.87%     | 56.45%     | 51.15%   |
| Repair and installation services of         | 64.63%     | 58.67%     | 53.91%   |
| machinery and equipment                     |            |            | 60.73%   |
| Machinery and equipment n.e.c.              | 65.26%     | 61.55%     | 56.91%   |
| Security and investigation services;        | 67.83%     | 64.04%     | 58.86%   |
| services to buildings and landscape         |            |            | 65.31%   |
| Rental and leasing services                 | 68.85%     | 66.40%     | 61.71%   |
| Wholesale and retail trade and repair       | 70.65%     | 68.61%     | 64.23%   |
| services of motor vehicles and motorcycles  |            |            | 69.16%   |
| Fabricated metal products, except           | 71.90%     | 70.62%     | 66.87%   |
| machinery and equipment                     |            |            | 70.94%   |
| Architectural and engineering services;     | 76.21%     | 72.29%     | 68.47%   |
| technical testing and analysis services     |            |            | 72.68%   |
| Insurance, reinsurance and pension          | 78.06%     | 74.13%     | 69.58%   |
| funding services, except compulsory social  |            |            | 74.39%   |
| security                                   |            |            |          |
5.4. Resilience properties of payments to landowners

To assess the resilience of schemes for paying landowners, we assume that production is affected by natural disturbances which are considered household-specific, denoted by \( z \). In particular, each household faces an idiosyncratic risk that is modeled as a geometric Brownian motion.

The economy is in equilibrium when: i) Households choose consumption, labor, and natural capital contingent on the history of their idiosyncratic shocks so as to maximize their lifetime utility; ii) the labor market clears, i.e. the labor required to produce final goods equals the labor supply for households; iii) Output of the final good is equal to the household consumption plus capital depreciation. This is equivalent to solving the following set of equations:

\[
\rho v(z, k, t) = u'(c) + i(z, k, t) \frac{\partial}{\partial k} v(z, k, t) + \mu \frac{\partial}{\partial z} v(z, k, t) + \frac{\sigma^2}{2} \frac{\partial^2}{\partial z^2} v(z, k, t) + \frac{\partial}{\partial t} v(z, k, t)
\]

where \( u'(c) = \frac{\partial}{\partial c} v(z, k, t) \) and \( i(z, k, t) \), the investment rate, is given by \( i(z, k, t) = Rzk - \delta k + w - c \),

\[
\frac{\partial}{\partial t} g(z, k, t) = - \frac{\partial}{\partial k} [i(z, k, t) g(z, k, t)] - \frac{\partial}{\partial z} [\mu z g(z, k, t)] + \frac{\sigma^2}{2} \frac{\partial^2}{\partial z^2} g(z, k, t) - \epsilon [g(z, k, t) - g^*(z, k, t)]
\]

\[
\int \int n(z, k, t) g(z, k, t) dzdk = 1
\]

**Calibration** To parameterize the capital share \( \alpha \) we use National Accounts data from the Organization for Economic Cooperation and Development, OECD). The discount rate, \( \rho \), is 0.04, and the relative risk aversion parameter, \( \sigma \), is 2.5, corresponding to a situation of moderate risk aversion. We assume that the cross-section productivity heterogeneity is generated by an Ornstein-Uhlenbeck process, i.e. an AR(1) in discrete time. Finally, the depreciation rate, \( \delta \), is an endogenous object given by an arbitrage condition that equalizes the expected investment in logging firms with the return on a risk-free bond. We estimate from the literature that schemes for payments to landowners increase the capital share, \( \alpha \), by 24.5%.

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**Figure 10: IRF output** Resilience properties of payments to landowners. Cumulative multipliers are those above the IRF. Schemes for paying landowners reduce the losses from an (unexpected) economic disturbance by 51%.

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| Model elements | Analytical representation | Variables | Parameters |
|----------------|--------------------------|-----------|------------|
| Utility function (CRRA) | \( U(c) = \frac{c^{\gamma}}{\gamma} \) | \( c = \text{consumption} \) | \( \gamma = \text{risk aversion} \) |
| Technology (Cobb-Douglas) | \( y = z^\alpha k^{1-\alpha} \) | \( k = \text{capital} \) | \( \alpha = \text{capital share} \) |
| Natural capital adjustment | \( dz = \mu zdW \) | \( z = \text{disturbance} \) | Brownian motion |

| Impact multiplier | 0.079 | 0.8326 | 82% |
| Cumulative multiplier (50) | 0.912 | 0.462 | 51% |