Macroeconomic Impact of Climate Damage in France

Florian Jacquetin* and Gaël Callonnec*

Abstract – In order to assess the economic cost of climate inaction, we introduce the cost of the damage into the "ThreeME" macroeconomic model devised by ADEME (the French Agency for Ecological Transition). The traditional "Keynesian" framework of the model has been modified to take into account the risks weighing on certain sectors (agriculture and power generation) that would lead to pressures causing reductions in their production level. The damage includes not only chronic risks resulting from gradual changes, but also acute risks resulting from high intensity events of short duration, such as natural disasters. This damage is introduced in a "bottom-up" approach, i.e. at the level of both the supply and the demand of the stakeholders concerned. According to the simulations, compared to an anticipated and planned transition limiting global warming to 1.5°C by 2100, climate inaction could cost France almost 7 points of annual GDP by 2100.

JEL: Q54, Q43, O13, E12, E17
Keywords: macroeconomic modelling, climate change, cost of damage, physical risks and scenario analysis

** Agence de la transition écologique.* Correspondence: *florian.jacquetin@gmail.com*

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Scenario analysis is a method favoured among governmental and international organisations to anticipate, plan for and estimate the consequences of many possible future climate conditions. However, this type of analysis suffers from a number of methodological limitations: in relation to the realism of the scenarios envisaged (political uncertainty), the future change in temperatures (climate uncertainty) and the associated economic consequences (impact uncertainty). In France, it is the SNBC (*Stratégie nationale bas-carbone* – National Low-Carbon Strategy), a roadmap towards decarbonisation which incorporates macroeconomic effects, that is used. According to this assessment (Callonnec & Cancé, 2022), the transition to a carbon-neutral society could boost national GDP by three to four points by 2050. This scenario, while still open to debate (ADEME, 2020), does not include the cost of climate change damage and does not allow an assessment of all the benefits of ambitious climate action.

In order to quantify the cost of damage, economists have been able to use so-called "macroenvironmental" models. This type of model combines a traditional macroeconomic model with a representation of the climate. Historically, the first macroenvironmental models were Integrated Assessment Models (IAMs). In 1992, American economist William Nordhaus developed the first version of the DICE (Dynamic Integrated Climate Economics) model, a general and intertemporal equilibrium model that incorporates both mitigation costs (i.e. actions, in particular political actions, aimed at reducing greenhouse gas emissions) and the cost of the damage. According to the initial simulations performed with this model, the optimal global decarbonisation trajectory would result in an exceeding 3°C of global warming, compared to the pre-industrial era, by 2100. That trajectory would have been associated with a carbon price of \$20/tCO_2 and a 15% drop in global emissions but, most importantly, the macroeconomic impacts would have been virtually insignificant. In view of the increased occurrences of intense climatic episodes in the world in recent years, such results now appear unrealistic.

Although highly controversial (Pindyck, 2017; Dietz *et al.*, 2020), this original work laid significant foundations for further academic research. This is the first time that a model combined traditional macroeconomic models with a representation of the climate (albeit one that was very simplified). The model links economic production to greenhouse gas emissions, then introduces concepts linked to climate dynamics (links between atmospheric and submarine emissions and concentrations), climate sensitivity (links between concentrations, radiative forcing[1] and temperature) and climate damage (link between temperature and economic losses), allowing for the hypothesis that there is a direct feedback loop between macroeconomics and climate.

This "top-down" approach is based in particular on a macroeconomic "damage function". First defined by Nordhaus, damage functions are mathematical functions linking temperature changes to a loss of aggregate Gross Domestic Product (GDP) globally (Box 1).

The calibration of this function has been the focus of academic work not only by Nordhaus (2016), but also by the research community (Howard & Sterner, 2017). While the first so-called "enumerative" estimates (which group together and calibrate impacts using sources

1. *Radiative forcing (W/m²) is the difference in power per unit area between solar radiation and terrestrial radiation in the stratosphere. It relies, in particular, on concentrations of greenhouse gases, which reflect part of the Earth's radiation.*

Box 1 – **Form(s) of a Damage Function**

In the "top-down" approach introduced by Nordhaus (1992), a damage function generally takes the form of a polynomial function $f(T)$. It separates national (or global depending on the geographical field) activity $Y_{theoretical}$, i.e., the activity that would occur in the absence of climate change, from a fraction dependent on T, which is the change in temperature since the pre-industrial era, and results in actual activity Y:

$$Y = \left(1 - f\left(T\right)\right) \times Y_{theoretical}$$

where: $f(T) = aT + bT^2$ (a and b are estimated or calibrated parameters) and $0 \leq f(T) \leq 1$

In the "bottom-up" approach introduced by multi-sectoral modelling, (so-called "sectoral") damage functions are applied at the level of one or more sectors and no longer directly affect the overall level of activity, but on certain parameters that influence supply and demand behaviours: level of productivity, rate of capital depreciation, demand for certain goods and services, etc.

with varying degrees of precision) led to highly uncertain results, the following functions were based on more sophisticated methods, including econometrics or damage simulation in calculable general equilibrium models. However, this work has led to extremely heterogeneous ranges of impacts, not only due to the diversity of the approaches, but also because of the different areas of damage chosen (Howard & Sterner, 2017). It is from among these approaches that the NGFS (Network for Greening the Financial System) selected macroeconomic damage in its first baseline scenarios (NGFS, 2020): two damage functions from meta-analyses carried out by Nordhaus & Moffat (2017) and Howard & Sterner (2017), and one from Kalkuhl & Wenz (2020) based on panel econometrics. Here too, heterogeneity prevails: for a global warming scenario of +3.5°C compared to the pre-industrial era, these functions respectively indicate 3, 10 and 15 GDP points of damage by 2100 globally.

A second methodology, a "bottom-up" methodology, gradually began to emerge in the 2000s. This approach no longer presents the impacts of climate change at the level of aggregate production alone, but it instead presents them across the entire value chain and all economic stakeholders, no longer describing the damage from climate change as a global risk, but as a set of specific events that impact on various stakeholders or sectors, on both the supply and the demand sides. The damage is then reflected through exogenous macroeconomic shocks, namely: the productivity of production factors and the rates of depreciation of capital, as well as the behaviour of demand for energy and for tourism services.

To that end, researchers used multi-sector models, adapted to identify shocks occurring on a sector by sector basis. In 2006, one of the first assessments was based on the static GTAP-EF model and assessed the long-term macroeconomic effects of the IPCC "B1" scenario on highly targeted consequences of climate change: tourism flows and sea-level rise. While the estimated macroeconomic effects remain limited, studies have highlighted interaction effects related to the simultaneous occurrence of multiple events and concluded that the cost of the damage should be assessed using a general equilibrium approach, so as to avoid restricting the analysis to direct costs only (Bigano *et al.*, 2006). Subsequently, Eboli *et al.* (2009) and Bosello (2012) extend this approach to dynamic multi-sector models and assessed the overall underlying damage in the IPCC scenarios, allowing for an assessment of the rise in macroeconomic costs over the century and the taking into account of closed model and feedback effects. The macroeconomic impacts of global warming estimated in the above-mentioned studies remain very low, or even positive for some European countries. Indeed, some European countries will benefit from the increase in tourist flows, as well as from the fact that some forms of damage harm foreign economies more and improve their competitiveness in terms of export prices (this is particularly the case with regard to falls in agricultural yields).

The European Commission has also adopted a similar approach in its GEM-E3 model, estimating damage for all EU countries based on a harmonised methodology and a broad climate and economic database. Its results still tended to underestimate the cost of climate change (a loss of 1.1 percentage points of GDP mainly related to labour productivity, sea level and agricultural yields). The primary difficulty, which was linked to the European-centred economic structure, was failing to take into account the indirect cost of damage occurring in the rest of the world and impacting on foreign trade (Ciscar Martinez *et al.,* 2014).

However, the researchers appear to believe that the "bottom-up" modelling approach (the main results of which, for Europe, are set out in the annexe) allows us to track, with precision and over time, how the effects of climate change would impact the economy, while taking into account feedback effects and second-round effects, such as changes in relative prices (Roson & Sartori, 2016). Finally, with new constraints on economic and financial stakeholders, some financial institutions have continued this work in order to anticipate the risks to their activity. Moody's rating agency has, for example, incorporated the cost of climate damage into its own macroeconomic model, but also underestimates the costs of climate change in northern countries, which would benefit from smaller falls in productivity, higher tourism flows and lower oil prices (Lafakis *et al.*, 2019).

After taking into account supply constraints in the "ThreeME" model (Section 1), the "bottom-up" damage functions are estimated using the data collected in the literature (Section 2). Once those functions are linked to the model (Section 3) and the aggregate cost of damage is estimated (Section 4), the macroeconomic consequences of a scenario of inaction are assessed in comparison with the consequences of an orderly transition (Section 5).

1. Modification of the "ThreeME" Macroeconomic Model

The "ThreeME" model (Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy policy[2]) is the tool used by ADEME to assess the cost of climate damage. It is a calculable general equilibrium model inspired by Keynesian economic theory (Reynès *et al.*, 2021). Unlike so-called "Walrasian" models, its prices are not adjusted instantly to balance supply and demand in markets, which reflects the existence of macroeconomic imbalances and the possibility of Keynesian multiplier effects. In the "ThreeME" model, the supply of currency depends on the monetary policy which sets the interest rate, unlike in the Walrasian framework in which it is determined by the balance between the supply of and demand for capital. Thus, investments are financed by creating currency, without this necessarily leading to an increase in the interest rate, which would lead to a total wipeout of demand for investment from other sectors of the economy.

It includes 33 productive sectors (producing 28 commodities). In particular, the model is based on French national accounts data and aggregates sectors in accordance with existing classifications, specifically setting out 13 distinct energy sectors and four production factors, namely labour, capital, intermediate goods and energy. The "generalised CES" production function allows companies to minimise their costs by performing trade-offs between these factors, as well as between the different energies used and between domestic and imported products. Finally, the model calculates the energy requirements by means of a granular representation of the capital stock of households, which changes in accordance with transport and heating needs and the energy performance of the supply of property and vehicles.

The model has been used for a number of forecasting exercises. The French Ministry for the Ecological Transition used it to create macroeconomic scenarios for the SNBC (Callonnec & Cancé, 2022). Like the Mésange model (Bardaji *et al.*, 2017), it also makes it possible to measure the macroeconomic impact of fiscal and budgetary policies (Callonnec *et al.*, 2016) or to assess the impact of specific climate measures, such as hypotheses regarding the development of the electricity mix in France (ADEME, 2016). More recently, the model has been used in the estimation of the macroeconomic effects of a delayed transition scenario (Boitier *et al.*, 2023).

New financial and economic regulations (taxonomy, non-financial reporting and new requirements of supervisory authorities) and new institutional needs for climate scenarios, particularly in the financial sector (TCFD, 2017; NGFS, 2021; ECB, 2022), are driving the development of macroeconomic modelling to extend the applications of climate scenarios and to better measure all the "climate risks" that may arise during the transition period (Carney, 2015). These scenarios include transition risks, defined as potentially adverse consequences of decarbonising the economy (Boitier *et al.*, 2023), but do not generally include physical risks, the assessment of which remains subject to too many uncertainties and is still affected by the application of damage functions aggregated at global level (NGFS, 2021). The article proposes the application of "bottom-up" functions, in accordance with the literature mentioned in the introduction, together with an upstream change to the theoretical structure of the model to assess the cost of climate damage in France.

Several significant changes have been made to the model. At the outset, the model is based on a "neo-Keynesian" framework in which activity stems from the behaviour of economic stakeholders in terms of demand: consumption, investment and exports in particular. In order for the accounting framework to remain consistent, the model ensures that supply (production and imports) is adjusted to aggregate demand in each period: this is the "resources-uses" balance, which then makes it possible to reconstruct the main aggregates of the national accounts. This theoretical framework is similar to that of the Mésange model, co-developed by INSEE and the French Treasury (Bardaji *et al.*, 2017), but it is not suitable for assessing the damage due to climate change because it has the following weaknesses:

- physical constraints on production: in the original version of ThreeME, the variation in production results solely from the change in domestic or external demand and possible exogenous shocks affecting production costs (prices of intermediate consumables, tax increases, etc.). Unlike neoclassical general equilibrium models, in which the quantities produced depend on the availability of production factors, neo-Keynesian models do

2. *There is an overview of the model on the website: www.threeme.org*

not adequately take into account the recessive effects that could result from a contraction in the quantity of production factors available. In addition, not all "real" factors of production are incorporated; for example, in the case of agriculture, the "land use" factor is not taken into account, although it is a factor that limits production;

- The determining factors of inflation: in ThreeME, inflation is mainly influenced by the prices of the factors ("cost-push inflation"), while on some markets, such as commodity or energy markets, inflation reacts and adjusts rapidly to direct imbalances in supply and demand ("demand-pull inflation").

The assumption that supply adjusts to demand within a relatively rigid price framework does not simulate the full impact of climate change. Physical risks would essentially come in two forms: direct damage to physical assets (through, for example, an increase in capital depreciation) and a disruption to the factors of production (through a decrease in the productivity of labour and capital). When either occurs, Keynesian models show two phenomena:

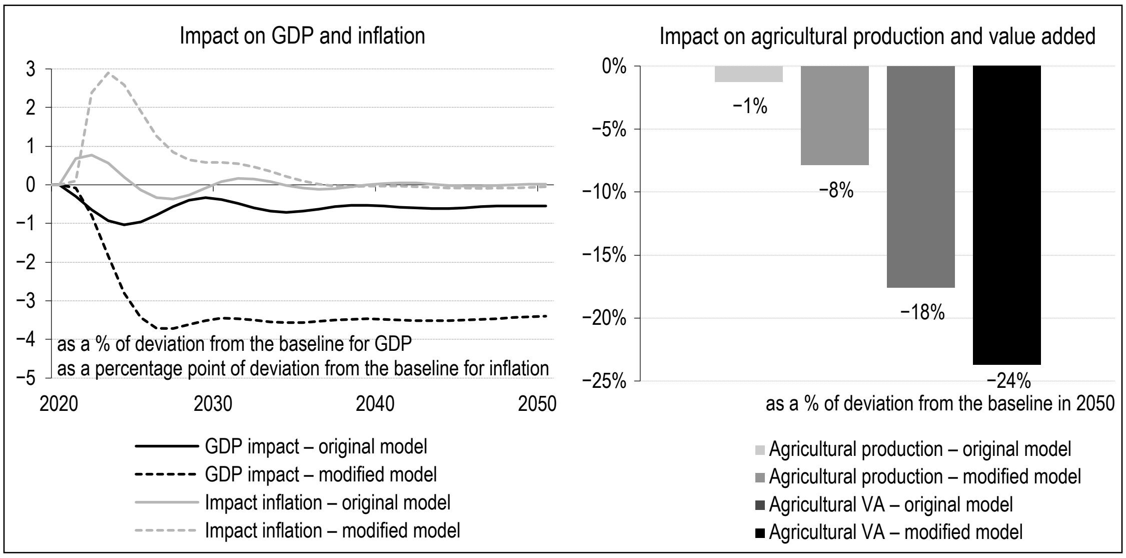
- first, unit costs of production are increasing and with the use of the factor itself having become more expensive, companies gradually pass on this increase to their sales prices (under the assumption that there is no long-term profit margin behaviour);
- second, demand for an "efficient" factor increases in order to compensate for the lower productivity of the factors already used and to satisfy demand. Increased investment and employment can have positive knock-on effects on activity, which may at least partially offset the direct recessionary effects of the shock to supply.

The latter effect is of little relevance in the agricultural sector (limited arable land) and the power generation sector (time needed for the installation of new capacities and dependence on certain climatic factors). It would be fanciful to think that additional investment or hiring could maintain the previous level of production.

As the simulations (Figure I) demonstrate, the traditional aggregated supply and demand framework ("original model") tends to minimise the costs of climate damage, not only because it allows for short-term adjustment of production (through job creation and additional investment), but also because price increases are smoothed due to adjustment times and nominal rigidities (the time it takes for the agricultural sector to incorporate the increase in production costs into its sales prices). This is why the modification of the agricultural sector is justified (cf. Box 1), which allows for production modelling that is correlated with actual yields and more realistic inflation in line with what is happening in the real economy ("modified model"), for example during summer drought periods.

In order to correct for these limitations, the levels of agricultural and energy production have been constrained. It is now not supply

Figure I – **Macroeconomic impact of an instant fall in agricultural yields of 10%**



Reading note: In the "original" ThreeME model (compared with the modified model), a decrease in agricultural yields of 10% leads to a fall in agricultural production of 1% (compared with 8%) in the long-term (in 2050).
Sources: The ThreeME model, according to the standard model (agricultural sector supply and demand equilibrium by volumes) or the modified version (price equilibrium).

that adjusts to demand in the context of relatively rigid short-term prices, but demand that adjusts to supply through greater price flexibility (Box 2). In the event of a reduction in domestic production, imports increase to meet at least part of the short-term demand that can no longer be met by domestic producers. This limits the rise in market prices and the drop in consumption. Given that these products are considered to be essential, demand is rather inelastic. However, it is declining due to higher prices. Under the assumption of a sharp contraction of world agricultural production, we could find ourselves in a scenario in which per capita food consumption would not be sufficient to avoid malnutrition in part of the population. The impact of scarcity on population growth[3] and labour productivity would then need to be taken into account. This last feedback loop has not yet been introduced into the model.

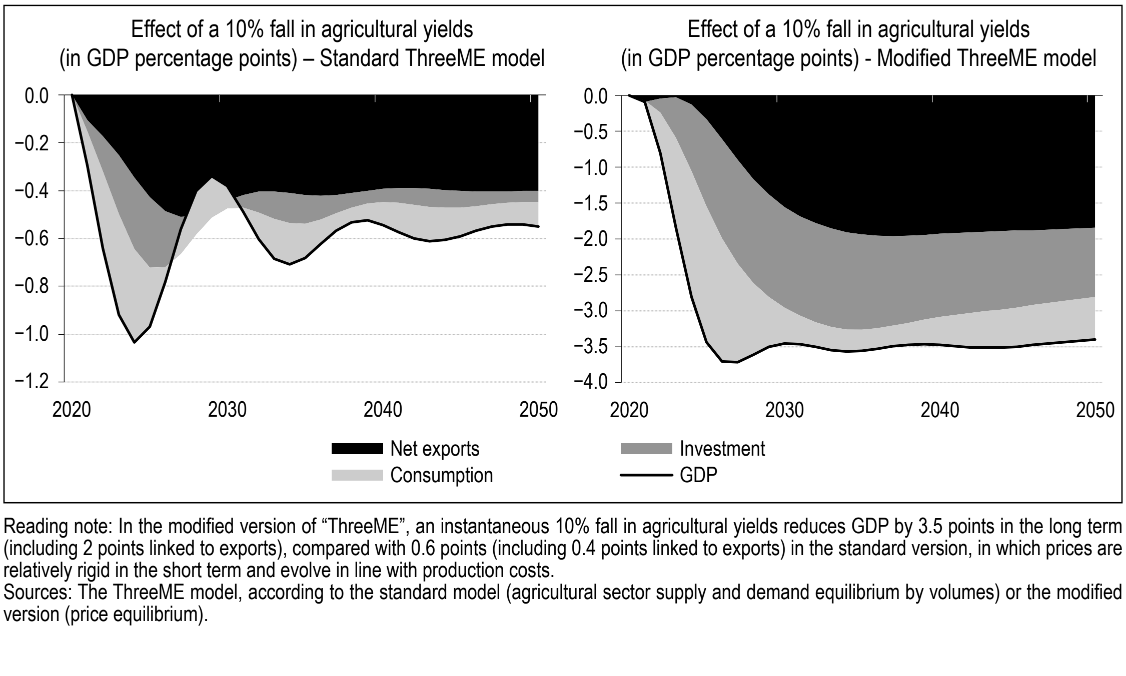
An instant and lasting fall in agricultural yields of 10% (i.e. a decrease in the productivity of each factor of production in the sector) is simulated and its effects are compared with the original model in order to confirm the new methodology (Figures I and II). Agricultural production falls instantly by 10% and the rise in the prices of agricultural products is sudden and abrupt. The overall inflationary effect is much higher in the new version of the model, as the adjustment is faster and is performed entirely through prices (and no longer through volumes). In the long term, declining activity and job losses limit wage growth and eventually reduce inflation. The rise in prices negatively impacts total consumption by stakeholders, who are forced to devote a larger share of their income to food at the expense of other goods and services. Ultimately, the drop in activity is much greater in the modified version. As also noted by Reilly *et al.* (2012) the macroeconomic effects are broader than the effects on agricultural production alone, as consumption is highly inelastic and requires factors of production to be partly reallocated to the agricultural sector in order to secure food demand first and foremost, at the expense of production in other sectors.

2. Estimation of a Damage Function in France

Using a "bottom-up" approach, ADEME economists have identified, both geographically and by sector, the costs of physical damage in France through an in-depth literature review, excluding at this stage non-monetary damage (impact on biodiversity), indirect effects of climate change (such as population displacement) and adaptation and reconstruction costs. The underlying monetary impacts in various global warming scenarios are extrapolated and sectoral damage functions are calibrated in accordance with traditional regressions. As for the assessment of acute risks, despite their unpredictability, they are extrapolated from historical inventories of natural disasters from the EM-DAT database (see below). Here we adopt a risk-based

3. In ThreeME, population growth is exogenous and is defined by using INSEE's estimate. It is around 0.4% per year. Food shortages could cause a rise in the mortality rate and a drop in the birth rate.

Figure II – **Effect of agricultural damage modelling on GDP**



Reading note: In the modified version of "ThreeME", an instantaneous 10% fall in agricultural yields reduces GDP by 3.5 points in the long term (including 2 points linked to exports), compared with 0.6 points (including 0.4 points linked to exports) in the standard version, in which prices are relatively rigid in the short term and evolve in line with production costs.
Sources: The ThreeME model, according to the standard model (agricultural sector supply and demand equilibrium by volumes) or the modified version (price equilibrium).

Box 2 – **The New Production and Inflation Dynamic in the Agricultural Sector**

In the usual Neo-Keynesian models, the production of the good Y_i adjusts to demand D_i and imports M_i, and the sale price is equal to a margin μ applied to the unit cost of production CU_i. People talk of "aggregate supply – aggregate demand" and "cost inflation" models:

$$Y_i + M_i = D_i$$
$$P_{Yi} = \mu\, CU_i = \mu\left(\alpha_{L,i}\, cl_{L,i} + \alpha_{K,i}\, ck_{K,i} + \alpha_{E,i}\, ce_{E,i} + \alpha_{mat,i}\, cmat_{mat,i}\right),$$

with $\alpha_{f,i}$: nominal remuneration of factor f in sector i and $cf_{f,i}$: unit cost of factor f in sector i.

This dynamic is changed for the agricultural sector. We introduce potential production Y_{pot} and potential imports M_{pot} of agricultural products that are in short supply and depend on the changes to the productivity of the factors, which is assumed to be exogenous:

$$\dot{Y}_{pot} = dlog\left(prog_{f_i}\right) + dlog\left(pop\right) \text{ and } \dot{M}_{pot} = dlog\left(prog_{f_i}\right) + dlog\left(pop\right).$$

The balance between supply and demand is no longer achieved by quantities but by prices. The equilibrium price $PY_{eq\,i}$ of domestically produced goods is equal to:

$$\boldsymbol{PY_{eq\,i}} Y_{pot_i} + Tax_i + Marg_i = PD_i.QD_i.$$

The equilibrium price $PM_{eq\,i}$ of imported goods is equal to:

$$\boldsymbol{PM_{eq\,i}} M_{pot_i} + Tax_i + Marg_i = PM_i.QM_i,$$

with QD as the demand for domestic products i (this is the sum of intermediate consumption and end consumption directed towards domestic producers), QM as the demand for products i directed towards the rest of the world, Tax as consumer taxes and $Marg$ as transport and trade margins.

The production price no longer depends on production costs but on the new equilibrium price:

$$P_{Yi} = \mu\, CU_i \text{ becomes: } \dot{P}_{Yi} = P\dot{Y}_{eqi}.$$

PM_i which was previously assumed to be exogenous becomes $P\dot{M}_i = P\dot{M}_{eqi}$.

End consumption CF is a function of population pop, income R and consumer prices P:

$$\dot{CF}_i = p\dot{o}p + \alpha\dot{R} - \beta\dot{P}_i \qquad (\alpha,\ \beta \text{ of the parameters}).$$

Intermediate consumption CI of agricultural products i by sectors j develops in the same way as the production of the sectors, but decreases relatively when their real prices $\left(\dot{P}_{ij} - \dot{P}_j\right)$ increase:

$$\dot{CI}_{ij} = \dot{Y}_j - \gamma\left(\dot{P}_{ij} - \dot{P}_j\right).$$

Imports M increase in the same way as demand D and decrease when their prices P_m rise faster than domestic prices P_i:

$$\dot{M}_i = \dot{D}_i + \gamma'\left(\dot{P}_i - \dot{P}_m\right).$$

Thus, demand adjusts to the level of potential supply through the increase in market prices. This specification simulates an effective decline in domestic agricultural production and yields, without an increase in sectoral investment and employment, and an increase in agricultural market prices, potentially exceeding the increase in unit production costs, which will have a crowding out effect on consumption of other products and a more negative effect on the trade balance.

approach and not a consequence-based one: it is nevertheless revealed that buildings and their occupants are exposed to a multiplicity of risks, as indicated by the forecasting studies carried out by ADEME (ADEME, 2022).

The main functions contributing to impacts are specified in Table 1. To our knowledge, this inventory takes into account most of the risks identified in international classifications (such as the European taxonomy) and makes a distinction between chronic risks and acute risks. Only the assessment of the acute risks remains incomplete. For example, forest fires, which are theoretically included in the history of natural disasters, are partially listed and their average cost (a few million euro) is likely underestimated,[4] especially

4. *ONERC (*Observatoire National sur les Effets du Réchauffement Climatique – *the French National Observatory on the Effects of Global Warming) (2009) estimates that the impact of climate change would be slightly positive for wood production until 2050, but would reverse by 2100 due to extreme events and the expansion of the Mediterranean forest.*

since non-monetary damage is not included in the assessment (adaptation to forest fires would cost France several billion euro per year). Other impacts related to natural disasters have also been investigated, though it has not been possible to obtain sufficiently detailed estimates to incorporate them into the damage, such as mountain risks and landslides; in theory, if all acute risks are taken into account in the inventory of natural disasters, the historical basis essentially reflects the monetary impacts of certain categories (floods, hurricanes, drought and periods of extreme temperatures). Moreover, it does not make it possible to model the future increase in the severity of such events. Finally, the effects of increased migration flows are not modelled.[5]

2.1. Chronic Risks

2.1.1. Productivity of Outdoor and Indoor Labour

It is estimated that labour productivity in some sectors will be significantly impacted, especially in outdoor working conditions (agriculture and construction) and in particular in southern European countries (Gosling *et al.*, 2018). In the absence of adaptation and under the worst impact models, outdoor labour productivity could decline by four percentage points by the end of the century in the case of high levels of global warming (two percentage points for indoor labour) (Figure III).

2.1.2. Agricultural Yields

On the basis of several simulation and projection approaches, it is established that wheat and corn crop yields are expected to decrease significantly in the face of temperature rises, without taking into account the effects of precipitation (Zhao *et al.*, 2017). Only the effects on production costs and prices are taken into account here. If producers are encouraged to increase their capacity to meet demand, they will eventually be able to cope with a reduction in available space. If opportunities for additional investment are limited, that could contribute to increasing the economic cost of global warming. Due to a lack of expertise on the subject, the possibilities of replacing the current crops with varieties that are more resistant to heat and water stress were not taken into account (Figure IV).

2.1.3. Sea Level

The European Commission's projections on the impact of sea level and damage it causes along the coast (effects of tides, waves and storm surges and flooding caused by marine submersion) indicate that France would be one of the European countries most affected economically by rising seas (Vousdoukas *et al.*, 2019). It is

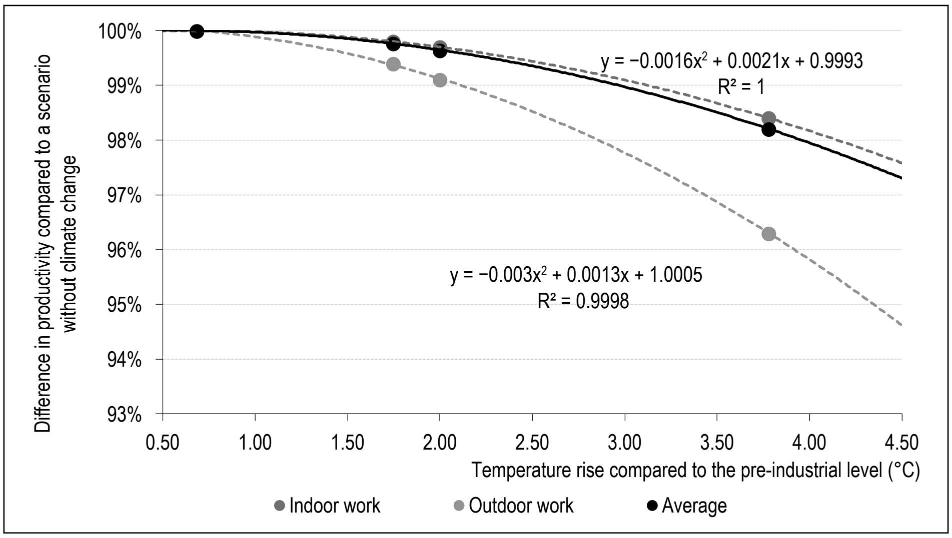
5. According to Missirian & Schlenker (2017), by the end of the century, the number of asylum applications would increase by 188% (66,000 additional applications per year) in the RCP 8.5 scenario.

Table 1 – **Selection of sectoral damage having a significant macroeconomic impact**

Sectoral damage functions	Macroeconomic shock	Sectors concerned
Hydroelectric generation capacities	Productivity of production factors	Power generation - hydraulic
Thermal generation capacities	Productivity of production factors	Power generation - thermal
Natural disasters	Depreciation rate	Residential and tertiary property
Supply chains	Global demand	The whole economy
Household energy demand	Energy consumption per m²	Household housing
Service energy demand	Company energy demand	The whole economy
Sea level rise	Depreciation rate	Residential and tertiary property
River flooding	Depreciation rate	Residential and tertiary property
Labour productivity - illnesses	Labour productivity	The whole economy
Productivity of outdoor work	Labour productivity	Agriculture, Forestry, Construction
Productivity of indoor work	Labour productivity	The whole economy (except outdoor work)
Agricultural and forestry yields	Productivity of production factors	Agriculture, Forestry
Wind turbine output	Productivity of production factors	Power generation - wind
Photovoltaic output	Productivity of production factors	Power generation - solar
Shrinkage and swelling of clay soils	Depreciation rate	Residential and tertiary property
Income from Tourism	Global demand	Private services

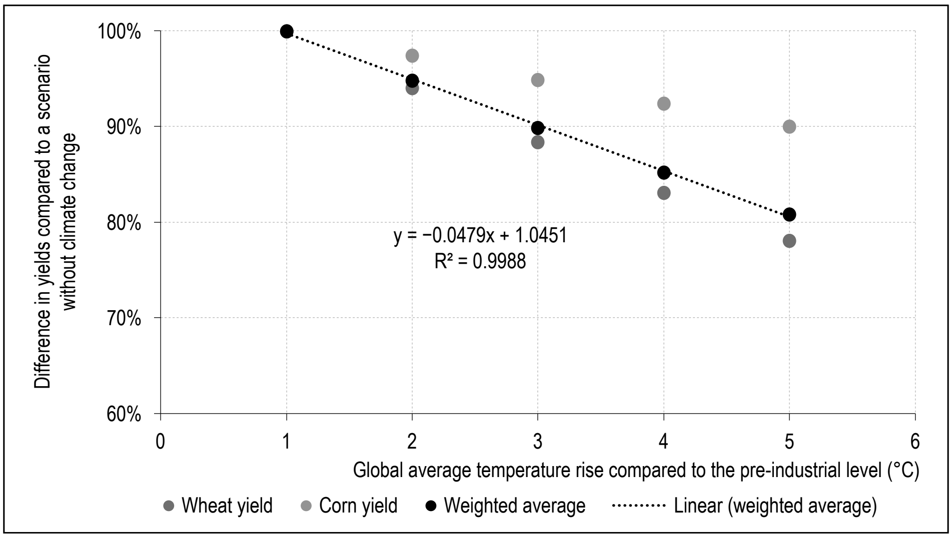
Reading note: Among the physical risks identified, sea level rise is assumed to influence, at the macroeconomic level, the rates of capital depreciation in the residential and tertiary property sector.
Sources: Jacquetin (2021).

Figure III – **Sectoral damage function – Labour productivity**



Sources: ADEME, based on Gosling *et al.* (2018).

Figure IV – **Sectoral damage function – Agricultural yields**



Sources: ADEME, based on Zhao *et al.* (2017).

thought that the annual damage caused would amount to between €5 billion and €10 billion by the end of the century according to the RCP 4.5 and RCP 8.5 scenarios (Figure V).

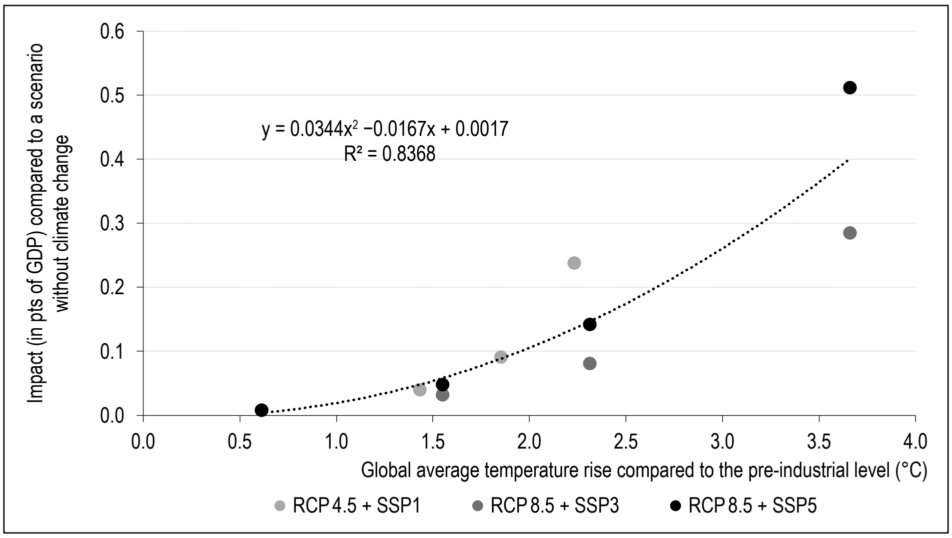
2.1.4. Changes in Heating and Air Conditioning Needs

Changes in temperature will have a major impact on the heating and air conditioning needs of the residential and tertiary sectors. Kitous & Després (2018) estimate the impact of temperature changes on residential demand for air conditioning and heating compared to a scenario where temperature does not increase after 2010. De Ciang & Sue Wing (2019) estimate the impact of temperature changes on other sectors. The impact on other sectors seems negligible in France, except for the impact on the commercial sector, which is estimated using a linear function. Using the relative weights of air conditioning and heating in residential demand for energy, and the share of residential and tertiary energy consumption, the average cost of the total demand for energy is estimated (Figure VI).

2.1.5. Power Generation

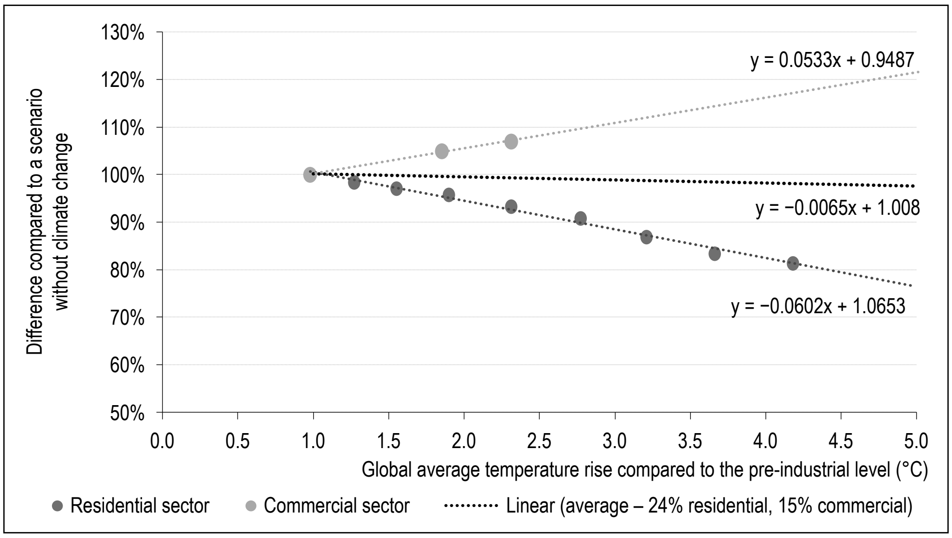
A function reflecting the change in output compared to the period 1971–2000 is estimated for four power generation technologies (solar, wind, hydroelectric and thermal) using Tobin *et al.* (2018). The impacts are more limited for

Figure V – **Sectoral damage function – Sea level**



Sources: ADEME, based on Vousdoukas *et al.* (2019).

Figure VI – **Sectoral damage function – Energy demand**



Sources: ADEME, based on Kitous & Desprès (2018) and Ciang & Sue Wing (2017).

the output of solar and wind power, which would be less than 10% in a scenario of inaction, while the output of hydroelectric and thermal power could decrease by 20% (Figure VII).

2.1.6. Income from Tourism

The effects of climate change on winter tourism (ski resorts) and then on summer tourism are estimated in order to obtain the overall impact on income from tourism. It is estimated that the fall in demand for winter tourism is linked to a reduction in the number of overnight stays (Jacob *et al.*, 2018) and the number of people heading up the slopes (Spandre *et al.*, 2019). The rise in summer tourism is taken from Jacob *et al.* (2018) (Figure VIII).

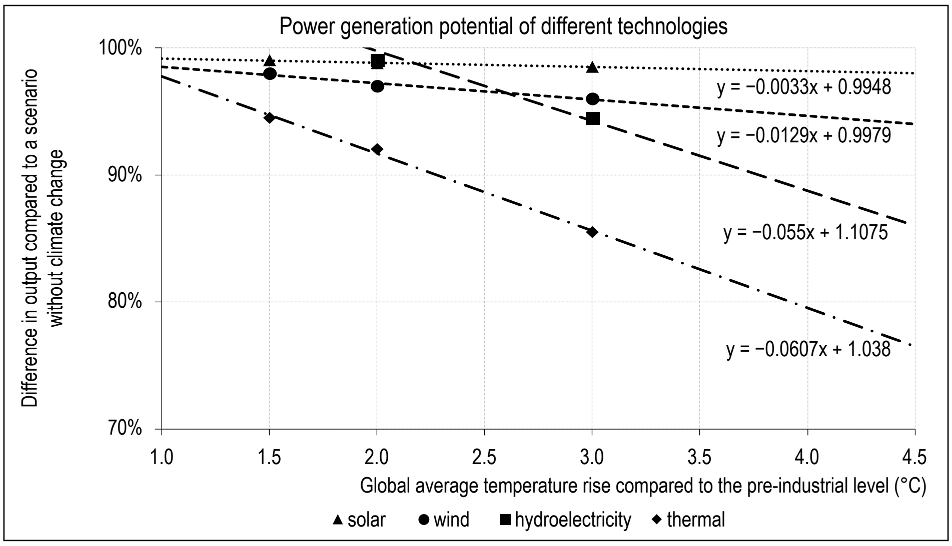
2.1.7. Shrinkage and Swelling of Clay Soils

Estimates of damage related to the shrinkage and swelling of clay soils are taken from Gourdier & Plat (2018). The increase in the cost of the damage depends first on the increase in the number of individual houses in risk areas and then on the increase in the scale and frequency of droughts (Figure IX).

2.1.8. Labour Productivity and Rise in Illnesses

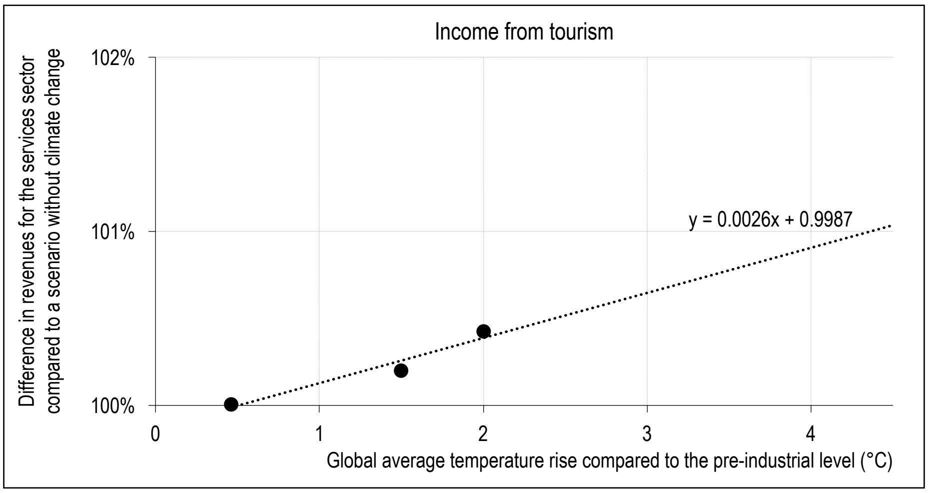
Paci (2014) assesses the impact of temperature rises on productivity at work in Europe (in terms of number of working days lost per capita) by assessing the relationship between

Figure VII – **Sectoral damage function – Power generation**



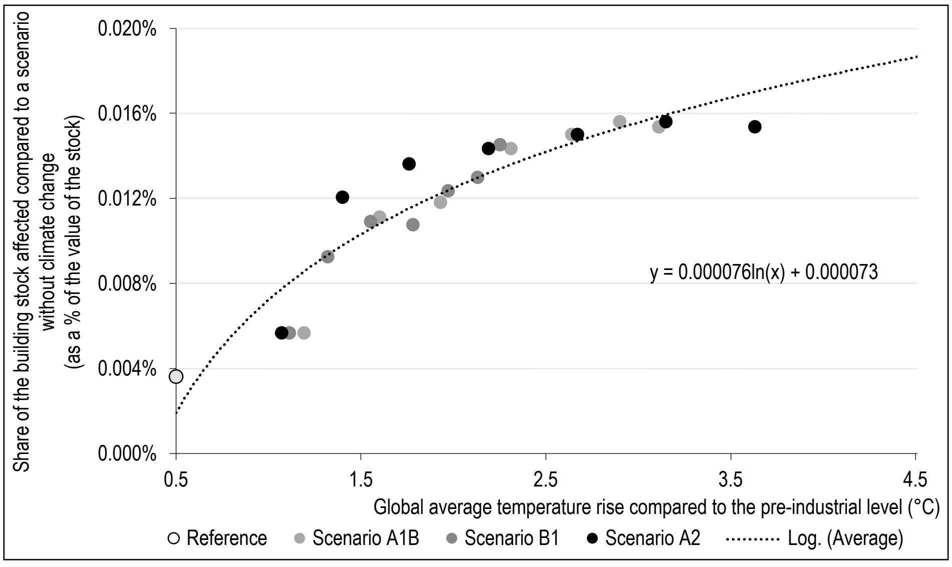
Sources: ADEME, based on Tobin *et al.* (2018).

Figure VIII – **Sectoral damage function – Tourism demand**



Sources: ADEME, based on Jacob *et al.* (2018) and Spandre *et al.* (2019).

Figure IX – **Sectoral damage function – Shrinkage and swelling of clay soils**



Sources: ADEME, based on Gourdier & Plat (2018).

temperature rises and number of working days lost through several phenomena: the increase in temperature-related morbidity and mortality (resurgence of cardiovascular and respiratory diseases), additional heat stress related to heat waves (mortality and morbidity) and the increase in food and water infections (salmonellosis and campylobacteriosis). It is assumed that the estimated per capita value for Europe is applicable to France as well (Figure X).

2.2. Acute Risks

2.2.1. Direct Costs in France

The International Disaster Database (EM-DAT) contains information on natural disasters and their economic costs (damage costs, insurance costs and reconstruction costs). Managed by the Centre for Research on the Epidemiology of Disasters (CRED, 2021) in Belgium, it is available for use in academic research and is one of the largest databases on extreme risks in the world. However, it displays information in a heterogeneous manner and remains subject to significant gaps (temporal and spatial coverage, missing indicators and estimates for certain categories of events, etc.).

It is thought that floods and hurricanes would have the most negative impact on the overall cost of extreme events in France (on average, \$1 billion per hurricane and \$0.8 billion per flood). Despite the increase in their intensity since 1990, there is still little detail on the cost of periods of extreme temperatures (only three events are recorded, including the heat wave of 2003 that cost \$6.5 billion and the period of freezing temperatures in 2021 in the Rhône region). When all categories are combined, the most costly event recorded was the case of the extratropical cyclones Lothar and Martin in 1999, costing nearly \$20 billion.

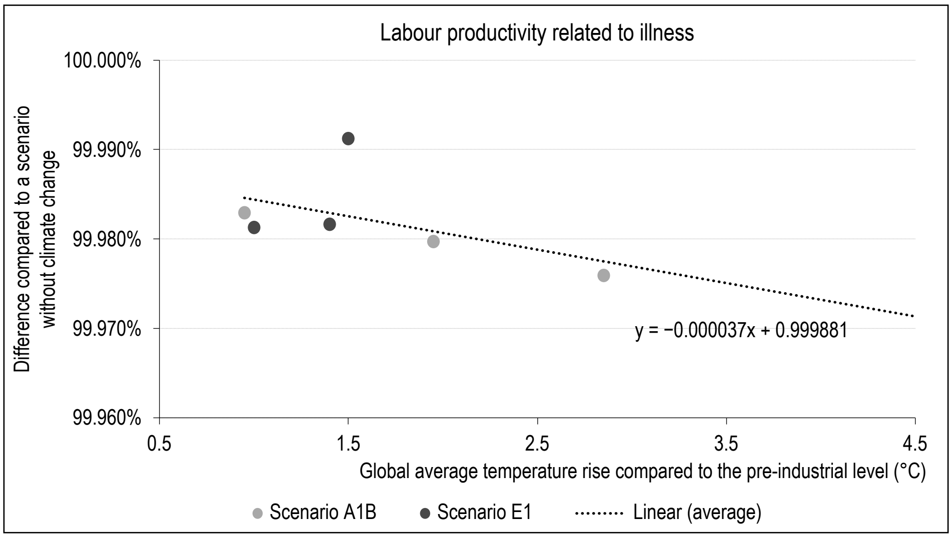
The available data make it possible to assess an upward trend in the number of natural disasters recorded and identified in the database as a function of changes in temperature (Figure XI). By imputing the average cost observed for these events (nearly €1 billion, Figure XI), it is possible to partially link the rise in temperatures since the pre-industrial era to the increase in the frequency of extreme physical risks.

This model remains very incomplete, as it does not account for the potential increase in severity of events in the future and does not examine the predominance of new categories of events to come, feedback loops or tipping points. Therefore, the long-term effects of natural disasters in a scenario of inaction would remain limited (around 1 percentage point of GDP per year in a scenario of inaction) and would represent only the average of the long-term cost.

2.2.2. Acute Risks in the Rest of the World

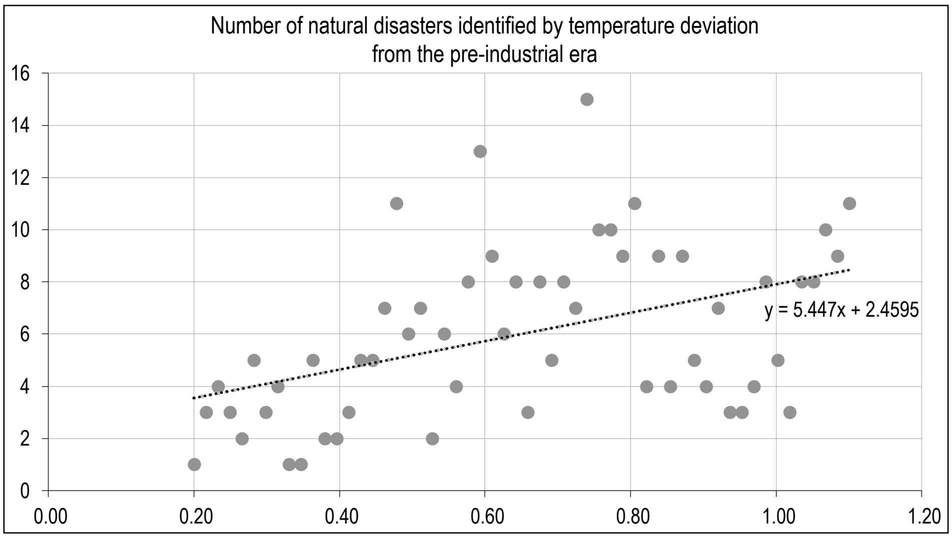
Climate risks will alter foreign economies and have a negative impact on their domestic demand (and therefore on demand for French goods and services) and their prices (and thus on inflation imported into France and relative price competitiveness). Finally, climate damage may also influence the financial environment (commodity prices, exchange rates and interest rates). The failure to take these effects into account has tended to minimise the costs of climate change, for example when the model is

Figure X – **Sectoral damage function – Illness**



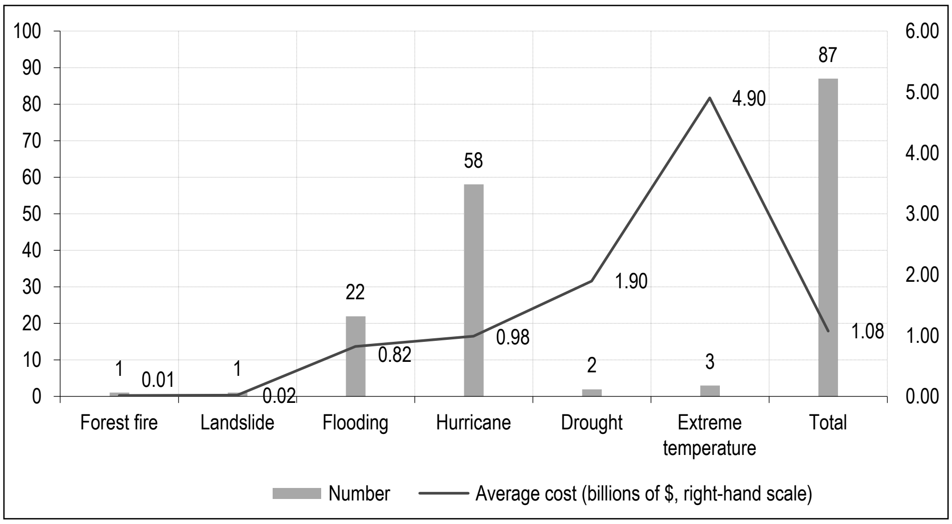
Sources: ADEME, based on Paci (2014).

Figure XI – **Sectoral damage function – Natural disasters in France**



Sources: EM-DAT (authors' calculations).

Figure XII – **Average cost of natural disasters in France by type of event**



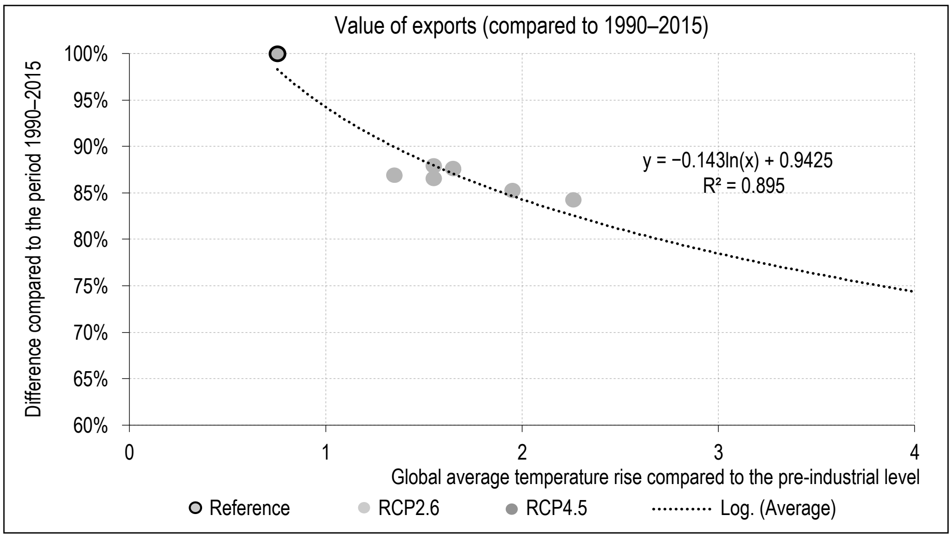
Sources: EM-DAT (authors' calculations).

centred on Europe (Ciscar Martinez *et al.*, 2014). However, some open-economy studies have been able to specifically assess future changes to regional trade flows linked to climate change. The OECD estimates, for example, that climate change combined with a scenario of inaction would have little impact on exports from the European Union and the United States up to 2060, but would have a greater negative impact on exports from Asian and African countries (Dellink *et al.*, 2017). In contrast, other studies examine potentially massive effects on the trade of EU countries. The latter hypothesis is the one that we favour in this study.

The effects on trade are estimated here on the basis of an econometric study linking the level of French exports to natural disaster indicators (Schleypen *et al.*, 2019). According to this model, the impact of extreme events on the supply chain would represent a major contribution to the cost of climate damage in France. They would correspond to the estimated economic consequences of disruptions to French supply chains caused by natural disasters abroad and the decline in external demand as a result of climate damage (Figure XIII). It underlines that the decline in exports observed is due to two mechanisms: the rising prices of resources for French companies – or the disruption of their supply – and falling demand for French companies when their customers are affected by natural disasters.

Aside from the clarity and rigour of their methodologies, the studies used were also selected

Figure XIII – **Sectoral damage function – Natural disasters worldwide**



Sources: ADEME, based on Schleypen *et al.* (2019).

because they assess the impact of risk by means of an economic indicator that can be used in a macroeconomic model and forecast the changes in that indicator in various temperature rise scenarios. However, it should be remembered that climate change impact studies can lead to highly heterogeneous results. While it is difficult to reconcile results over a wide range of fields, Table 2 compares our results (covering ten damage functions) with other recent estimates in the literature, most of which are identified by Delahais & Robinet (2023). France Assureurs (2021) estimated the cost, by 2050, of risks related to drought, floods, marine submersions and storms, and ONERC[6] (2009) forecast the costs associated with tourism, the shrinkage and swelling of clay soils, marine submersions and power generation.

3. Macroeconomic Modelling

3.1. Agricultural and Electrical Yields/ Labour Productivity

The fall in agricultural and forestry yields (cf. Figure IV) and electrical production (cf. Figure VII) is modelled as a fall in the productivity of all the factors of production $PROG_{f,s,t}$ (where f is either labour, capital, intermediate goods or energy) of the sector s concerned, in such a way as to reduce the total output of the sector by the same proportion. Falls in labour productivity linked, on the one hand, to the deterioration of working conditions both outdoors and indoors (cf. Figure III) and, on the other, to the increase in absenteeism related to health conditions (cf. Figure X), are modelled as shocks to the trend of labour productivity at the level of $PROG_{L,s,t}$ (but not to the other factors of production).

For the labour factor L in sector s and year t:

$$PROG_{L,s,t} = PROG\_CC_{L,s,t} \times PROG\_CC\_agri_{L,s,t} \times PROG\_CC\_elec_{L,s,t} \times PROG\_CC\_air_{L,s,t} \times PROG\_CC\_sickness_{L,s,t}$$

with

$$PROG\_CC\_agri_{L,s,t} = \begin{cases} \text{estimated function} & \text{if } s = agriculture \\ 1 & \text{if } s \neq agriculture \end{cases}$$

and

$$PROG\_CC\_elec_{L,s,t} = \begin{cases} \text{estimated function} & \text{if } s = power\ generation \\ 1 & \text{if } s \neq power\ generation. \end{cases}$$

$PROG\_CC\_air_{L,s,t}$ is the fall in labour productivity linked to indoor and outdoor working conditions,

$PROG\_CC\_sickness_{L,s,t}$ is the fall in labour productivity linked to the increase in absenteeism.

For the other factors f, $f \neq L$:

$$PROG_{f,s,t} = PROG\_CC_{f,s,t} \times PROG\_CC\_agri_{f,s,t} \times PROG\_CC\_elec_{f,s,t}$$

For all of the factors f:

$$PROG\_CC_{f,s,t} = PROG\_CC_{f,s,t-1} \times \left(1 + GR\_PROG_{f,s,t}\right)$$

where $GR\_PROG_{f,s,t}$ is the productivity gain for the factor f in sector s in year t.

6. Observatoire National sur les Effets du Réchauffement Climatique *(the French National Observatory on the Effects of Global Warming).*

Table 2 – **Comparison of the ten damage functions with other assessments**

Physical risks	Authors' assumption (+3.5°C)	Comparative impacts	Reference
Labour productivity	−2 percentage points of productivity	+0.96 of a percentage point of annual GDP lost in 2045–2055 +1.14 percentage points in 2060–2070	France Stratégie (2023) RCP 8.5 - 2050
Agricultural yields	−12% in global yields	−6.5 percentage points of grassland yields −3.2 percentage points of soft winter wheat yields −4.2 percentage points of winter barley yields	France Assureurs (2021) RCP 8.5 - 2050
Marine submersion	−0.3 of a percentage point of GDP *(sea level)*	+€6.5 billion in 2020–2050 or €200 million per year €15 to €35 billion in Languedoc-Roussillon or €200 to €400 million per year	France Assureurs (2021) RCP 8.5 - 2050 ONERC (2009) - 4°C
Energy demand	−2% energy demand	−8 TWh of heating energy demand in 2050 +8 TWh of air conditioning energy demand	RTE, France's Transmission System Operator (2022) RCP 8.5 - 2050
Power generation	In France Hydroelectricity: −5% Wind: −5% Thermal (including nuclear): −20% Solar: −2%	In Europe Hydroelectricity: +3% Wind: -0.2% Nuclear: −2% Thermal: +0.2% Solar: stable In France: Hydroelectricity: −15%	Tobin *et al.* (2018) RCP 8.5 - 2050 ONERC (2009) - 2050
Tourism (skiing)	−11% income from skiing (+2°C)	20 operable resorts in the Alps (out of 143) 55 operable resorts in the Alps	WWF France (2021) / +4°C ONERC (2009) / +4°C
Health	In Europe 7.6 million working days lost per year (2085)	In Europe +60,000 deaths per year +15,000 victims of respiratory illnesses	IPCC (2023) +3°C
Shrinkage and Swelling of Clay Soils	0.016% of clay soils	+€17.2 billion or €500 million per year +€1.3 billion per year	France Assureurs (2021) RCP 8.5 – 2050 ONERC (2021) / +4°C
River flooding	−0.15 of a percentage point of GDP *(domestic natural disasters)*	+€3.1 billion per year or €100 million per year	France Assureurs (2021) RCP 8.5 - 2050
Global demand	Directed towards France: −20%	Directed towards the EU: stable	Dellink *et al.* (2017) RCP 8.5 - 2060

Notes: The estimates are presented for specific years (e.g.: 2050) or for a given level of global warming (e.g.: +4°C). The effects of floods (France Assureurs) are compared with the cost of domestic natural disasters, while those of marine submersions (France Assureurs) are compared with the cost of rising sea levels. The RCP 8.5 scenario (Representative Concentration Pathway 8.5) is a scenario involving a change to the concentration of GHGs in the atmosphere, leading to an increase in radiative forcing to 8.5 W/m^2 in 2100.

3.2. Damage to Physical Assets

Damage from rising sea levels (cf. Figure V), the shrinkage and swelling of clay soils (cf. Figure IX) and natural disasters (cf. Figure XII) are modelled as an additional increase in the rate of depreciation of sectoral capital $K_{s,t}$, distributed across residential property $\delta'_{BUIL,k\ t}$ (for 69%, which is the proportion of French residential capital estimated by Eurostat) and tertiary property $\delta'_{s,t}$ (31%). Finally, the effect is deducted from permanent household income to take into account wealth losses and long-term Ricardian equivalence effects and will have a negative impact on current consumption C_t.

$$K_{s,t} = \left(1-\delta'_{s,t}\right)K_{s,t-1} + I_{s,t}$$

$$\delta'_{s,t} = \delta_{t,s} + 0.31\times\left(\delta_{t,sea} + \delta_{t,RGA} + \delta_{t,extreme}\right)$$

$$\delta'_{BUIL\,k,t} = \delta_{BUIL\,k,t} + 0.69\times\left(\delta_{t,sea} + \delta_{t,RGA} + \delta_{t,extreme}\right)$$

$$C_t = c\times Revenue_t - 0.69\times\left(\delta_{t,sea} + \delta_{t,RGA} + \delta_{t,extreme}\right) \times BUIL_t \times P_{BUIL}$$

3.3. Energy Demand

The change in energy demand (cf. Figure VI) is modelled as a variation in the energy need per m² $ENERperM^2{}'$, which varies according to a coefficient $ENERperM^2\_CC$ which in turn depends on the variation in temperatures.

$$ENERperM^2{}' = ENERperM^2 \times ENERperM^2\_CC$$

A shock is introduced to the function of energy demand in the service sector $F_{E,spri}$:

$$d(\log\left(F'_{E,spri}\right) = d\left(\log\left(Y_{spri}\right)\right) - d\left(\log\left(PROG_{E,spri}\right)\right) + d\left(SUBST_{E,spri}\right)$$

$$F'_{E,spri} = F_{E,spri} \times ENER\_services\_CC$$

3.4. Global Trade

The effect of natural disasters in the rest of the world (cf. Figure XIII) and changes in tourist flows (cf. Figure VIII) are modelled as corrective factors for global demand for French goods and services $WD_t^{'}$.

For each commodity c exported:

$$WD_{c,t}^{'} = WD_{c,t} \times WD\_supplychain_t \times WD\_tourism_{c,t}$$

Where:

$$WD\_tourism_{c,t} = \begin{cases} \text{estimated function} & \text{if } c = \textit{Private services} \\ 1 & \text{if } c \neq \textit{Private services} \end{cases}$$

$WD\_supplychain_t$ is the fall in global demand caused by value chains and applies to all commodities exported.

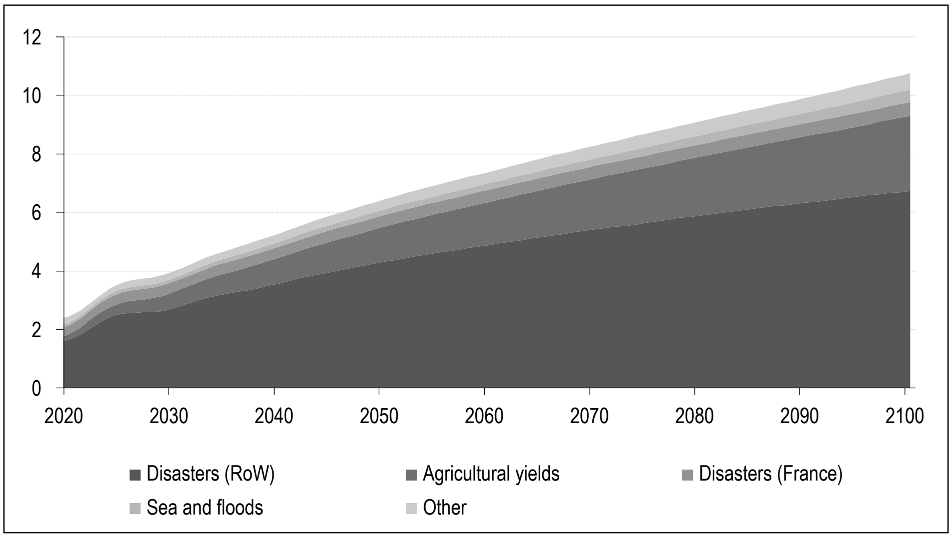
4. Assessment of the Cost of Macroeconomic Damage and Comparison with NGFS

By introducing these damage functions, calibrated for a warming scenario of +3.5°C by the end of the century (a scenario that is compatible with RCP 8.5[7]), it is possible to estimate the corresponding damage function at the aggregated level. If the temperature were to reach this level of warming, the damage of climate change could cost more than ten percentage points of annual activity compared to a scenario without climate change (Figure XIV). This counterfactual scenario is therefore fictitious, insofar as it does not include transition assumptions or costs of the damage. The contribution of the damage would be as follows:

- natural disasters occurring in the rest of the world (nearly six percentage points of activity);
- the fall in agricultural yields (three percentage points of activity);

7. The RCP 8.5 scenario (Representative Concentration Pathway 8.5) is a scenario involving a change to the concentration of GHGs in the atmosphere, leading to an increase in radiative forcing to 8.5 W/m² in 2100.

Figure XIV – **Macroeconomic damage function (as a % of GDP)**



Notes: Other risks include the shrinkage and swelling of clay soils, the change in energy output, the change in domestic energy demand, seasonal variations in tourism and the increase in absenteeism from work linked to the cost of illness.
Reading note: It is thought that global warming had already cost France nearly two percentage points of GDP in 2020 and would cost nearly ten percentage points of GDP in 2100 in a scenario of inaction, compared to a scenario without climate change.
Sources: ThreeME simulation combined with a global warming assumption of +3.5°C in 2100 compared to the pre-industrial era.

- direct costs of natural disasters in France (half a percentage point of activity);
- the rising sea level (half a percentage point of activity);
- finally, all other damage combined (half a percentage point of activity).

While this preponderance of trade effects is directly related to the estimate chosen outside the model and therefore remains subject to strong uncertainties, it is nevertheless consistent with the various estimates in the literature: most countries with a temperate climate could be significantly affected through trade and the risk of effects spreading (Lancesseur *et al.*, 2020).

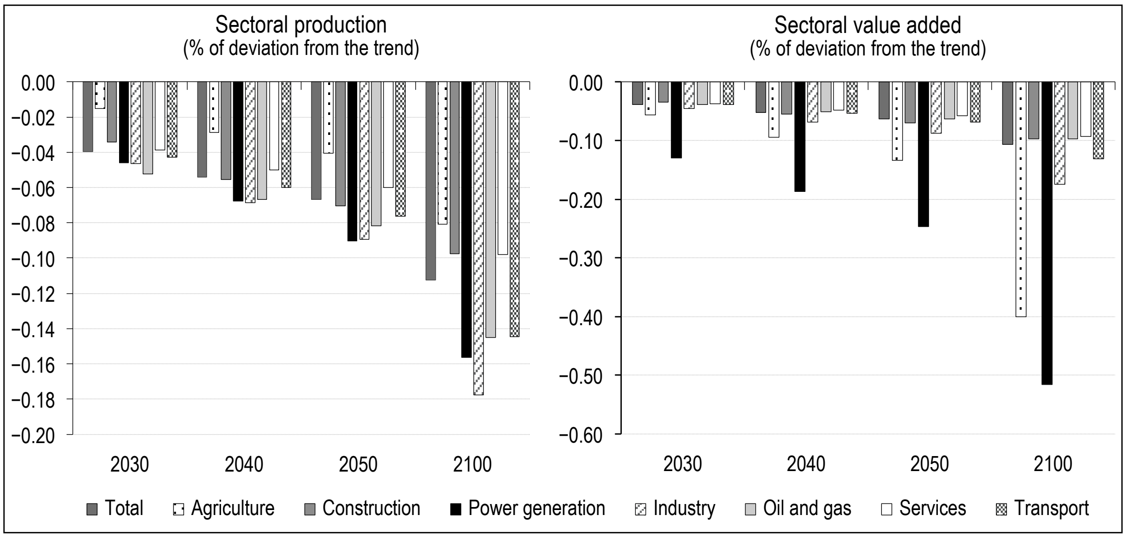
Looking at the details, activity in all economic sectors would be significantly affected (Figure XV), although the risks and effects are highly heterogeneous and have various causes. By their nature, the main sectors affected are primarily the exporting sectors (industry and services). In the absence of an adaptation policy, the agricultural sectors, as well as power generation and distribution, see their output fall at the same pace as technical performance. However, they are unable to pass on the full rise in production costs linked to inflation and therefore incur significant losses. For its part, construction is also impacted by economic decline, but benefits from the demand for repairs and reconstructions related to the damage caused to infrastructure by chronic risks and natural disasters. The fossil fuel distribution sector suffers due to the global fall in aggregate demand, and due to the reconstruction and development flows concerning old homes and buildings demolished and renovated to fit into less energy-intensive classes which, on paper, lowers the energy intensity of households.

Our estimate is currently in the high range of those in the literature. For example, the *Direction générale du Trésor* (French Treasury) identifies damage of between −2% and +5% of GDP in 2050 and between −6% and +10% in 2100 for a scenario of inaction (Lancesseur *et al.*, 2020), while macroeconomic modelling work shows very modest results (see Table A1 in the Appendix). By way of comparison, our estimate is related to damage functions that are referenced in the literature at global level and are applied in the first NGFS scenarios (NGFS, 2020). These functions are "top-down", polynomial and estimated at global level, unlike our function which is "bottom-up". The estimated impacts are among the highest identified by the NGFS (Figure XVI).

5. Application to a Scenario of Inaction

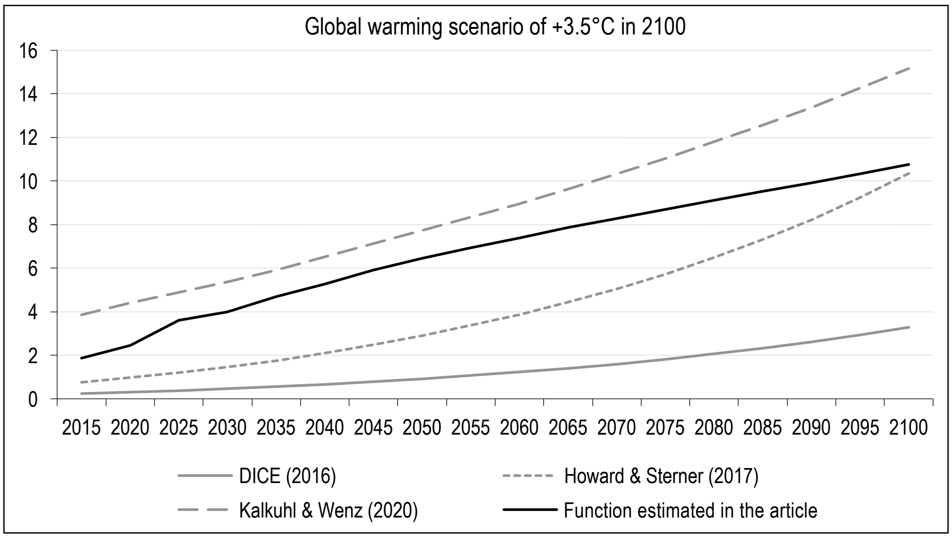
The sectoral specific damage functions proposed in Section 2 are now included in a traditional scenario analysis exercise. On this occasion, the simulation assesses the macroeconomic impact of a scenario of inaction compared to an orderly transition scenario, known as "Net Zero 2050" (NZ50). In order to construct these scenarios, conservative macroeconomic assumptions are applied from ADEME's work on transition risks (Boitier *et al.*, 2023) without, however, attempting to reproduce the granular nature of the climate policies assessed in the SNBC scenarios (Callonnec & Cancé, 2022).

Figure XV – **Sectoral impacts of climate change damage in a scenario of inaction**



Sources: ThreeME simulation combined with a global warming assumption of +3.5°C in 2100 compared to the pre-industrial era.

Figure XVI – **Comparison with other macroeconomic damage functions (as a % of GDP)**



Sources: NGFS database, Phase I (2020).

5.1. Shared Growth Path

Constant gains in productivity are assumed over the period, amounting to 1% per year in France and the rest of the world, which is the central assumption of the scenarios used by the *Conseil d'orientation des retraites* (2021) – French Pension Advisory Council. In the long-term, the national economy grows at the pace set by the Solow growth path (1956), which is defined by the sum of gains in productivity and changes in the labour force. Similarly, global demand grows at a similar pace, albeit slightly faster as a result of more dynamic population projections in the rest of the world.

5.2. Transition Assumptions

The assumptions adopted in the orderly transition scenario include:

- public action which translates into the linear and anticipated rise in real carbon prices up to $€_{2020}$/900/tCO_2 in 2050,[8] a level close to the shadow price of French carbon (France Stratégie, 2019),[9] with equitable income redistribution between companies and households (50/50);
- an energy mix that is consistent with NGFS assumptions and French climate strategies, anticipating a strong development of biofuel and biogas production, a phasing out of coal in power generation and a limited fall in the share of nuclear power in favour of renewable energies (wind and solar);
- the energy prices projected by the International Energy Agency (IEA, 2021), anticipating a modest rise in real fossil fuel prices (oil, natural gas and coal) linked with continued moderation of demand; a fall in demand for fossil fuels;
- foreign trade assumptions that are consistent with the NGFS scenarios, marked by a global phenomenon of relocation and a moderation of global demand toward France, as well as more dynamic inflation of foreign prices due to the lower carbon intensity of production in France.

5.3. Climate Assumptions

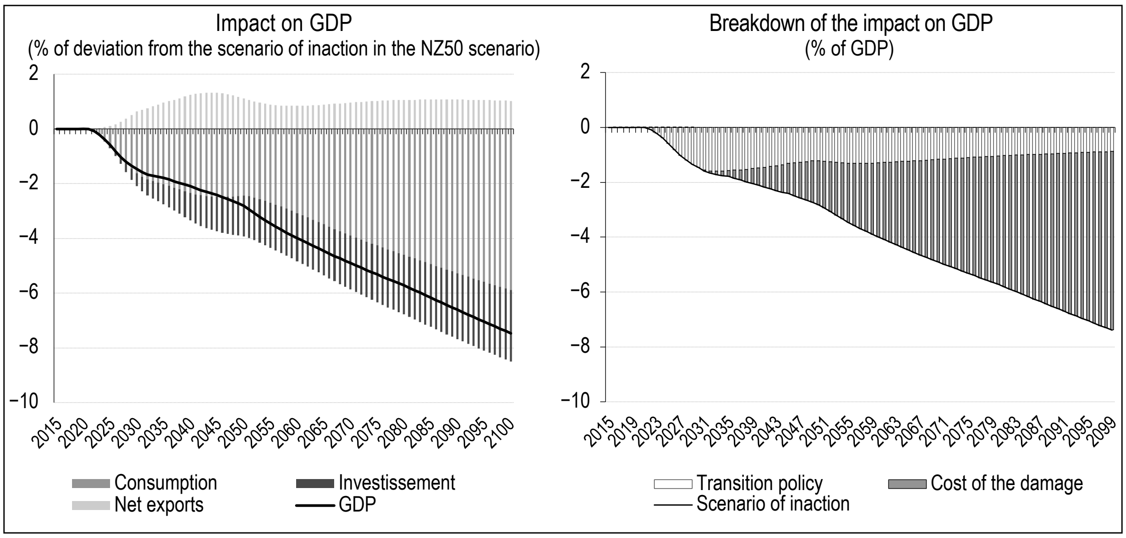
The temperature scenarios are derived from NGFS simulations based on the various integrated assessment models (in this case, the REMIND-MAgPIE model).[10] Since the ThreeME model is unable to produce climate scenarios itself, it remains dependent on the temperature trajectories associated with the NGFS narratives. These are therefore applied to the model "exogenously". The orderly transition scenario ensures that the temperature rise is limited to +1.5°C above its level in the pre-industrial era, while in the scenario of inaction, the global temperature rise is +3.5°C by the end of the century, as assumed by the NGFS "Hothouse World" scenario (NGFS, 2020).

8. In 2024, the carbon component (which is incorporated into domestic consumption taxes on fossil fuels and is proportional to their carbon content) was €44.6/tCO_2.

9. The shadow price of carbon represents the price per tonne of carbon equivalent (CO_2e) emitted and makes it possible to achieve the French targets in the fight against global warming. This value is used by the public authorities to guide public policy, particularly in the areas of investments, taxation and environmental regulation.

10. REMIND-MAgPIE is a so-called "IAM" that allows the assessment of the climate impact of policies aimed at fighting global warming on changes in temperatures (Luderer et al.*, 2015).*

Figure XVII – **Macroeconomic impact of the scenario of inaction**



Sources: Modified ThreeME model incorporating supply constraints and damage functions.

The scenario of inaction presupposes the absence of any new transition policy after 2022 and the energy mix being kept as it is today. The macroeconomic impact of political inaction is reflected in the absence of the benefits observed in the orderly transition scenario. However, the temperature trajectories diverge significantly from 2030 and the cost of the additional damage observed then gradually increases. By the end of the century, the scenario of inaction would cost nearly seven percentage points of GDP annually, of which one percentage point is linked to the freezing of transition policies and six percentage points are due to the costs of additional damage (Figure XVII and Figure XVIII).

Sectoral damage essentially follows the costs modelled in the creation of the damage function (Section 2) and represents nearly six percentage points of GDP. Due to its nature, the oil and gas sector broadly benefits and output in all other sectors falls (Figure XVII and Figure XVIII). The closed macroeconomic model allows for the modelling of negative spillover effects; for example, rising agricultural prices affect prices, wages, export competitiveness and employment, which has a negative impact on activity and income and affects other sectors. Moreover, since food is an unavoidable form of consumption, rising agricultural prices force household consumption away from other sectors.

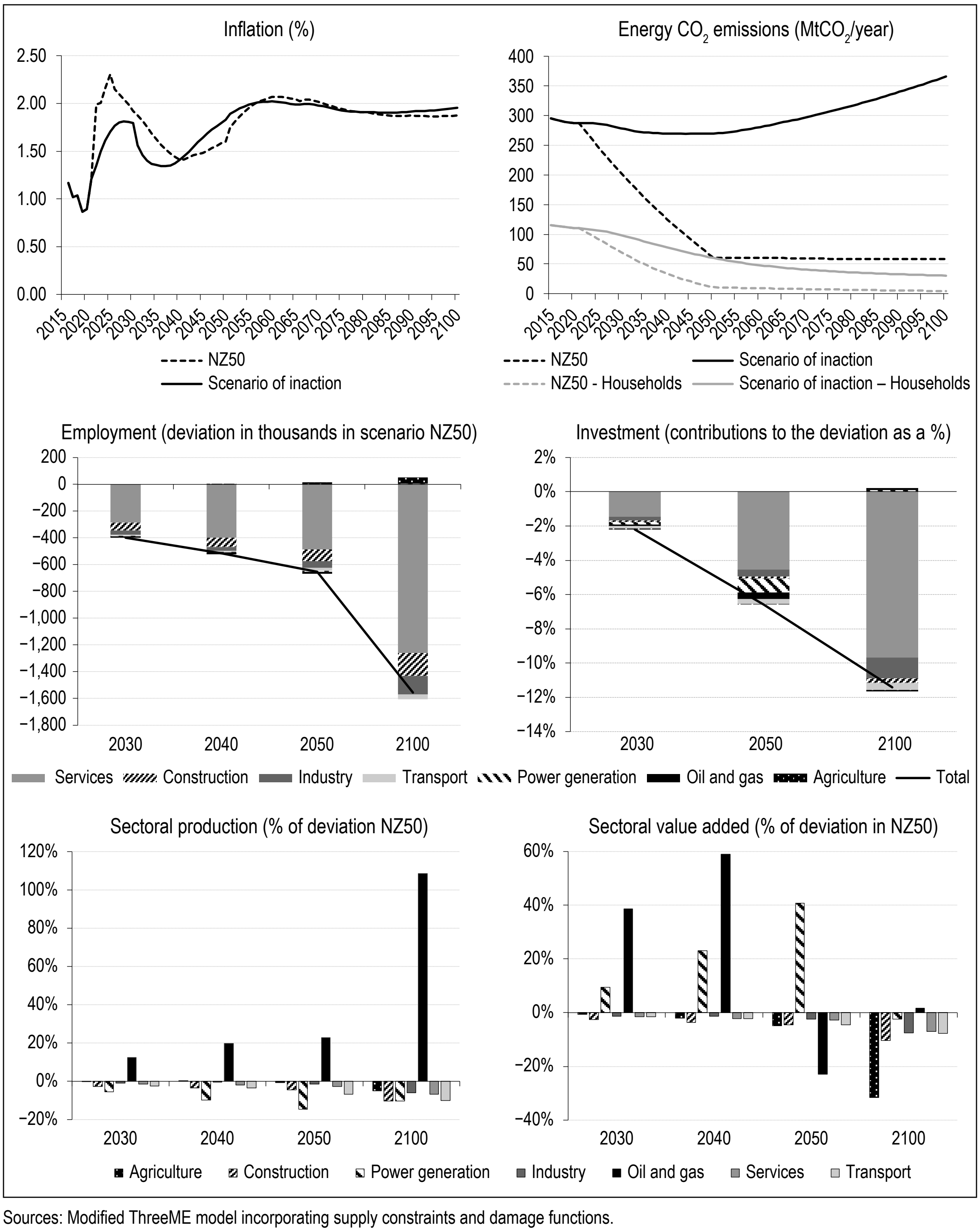
In the short-term, inflation is lower than in the transition scenario, but becomes higher once the main climate actions (of the transition scenario) are implemented. Job losses and falling investment are mainly concentrated in the services sector, although the latter is not directly exposed to most climate risks. On the one hand, the increase in the price of energy and food leads to the crowding out of purchases of services; on the other hand, any reduction in consumption or investment has a negative knock-on effect on the whole economy, including the tertiary sector, which accounts for nearly 80% of it.

* *
*

By creating sectoral damage functions, we assess and compare the monetary consequences of damage using the same economic indicator (GDP) and take into account the interaction effects and the dynamic effects of that damage. This work is not immune to certain limitations, which are largely related to the uncertainties regarding the extent of the damage: difficulty in modelling the medium- and long-term effects of natural disasters, in modelling the spread of physical risks in the rest of the world and in modelling the damage to assets and its consequences on stakeholders. The projections are still based on an assumption of exogenous growth and this is unrealistic in climate scenarios that see a disruption to the means of production.

Neo-Keynesian-inspired models also remain limited in terms of assessing the physical limits and concrete effects of a shortage, which would have the effect of rationing for stakeholders, for example, but which go beyond the scope of macroeconomic models (where the equilibrium is ultimately ensured by variations in quantity).

Figure XVIII – **Detailed sectoral impact of the scenario of inaction**



Sources: Modified ThreeME model incorporating supply constraints and damage functions.

Climate change is not only a threat to the performance of the factors and production costs. It can be accompanied by a sharp reduction in production in certain sectors or locations. That is why we have proposed changes to the ThreeME model. Simulations performed before and after modification of the agricultural and energy blocks of the model show significant differences in results. The impact of the damage on macroeconomic aggregates is significantly higher when a quantitative constraint with high price flexibility is introduced into the model. This is the first time, to our knowledge, that a macroeconomic model has tried to incorporate constraints on domestic production (with demand then having to be met by more expensive imports), to determine pricing methods by sector (by production costs or market balances) and to determine the nature of goods consumed according to household preferences (basic necessities or not).

Exporting sectors are the main victims of the effects of climate change in this instance, and damage in the agricultural and power generation sectors could also expose the entire economy to a systemic recessionary effect. Shortages would fuel higher market prices for food and electricity, increasing national dependence on imports (assuming there is no widespread global shortage). As such, these two sectors would be the main sources of a sustained increase in inflation in France; however, the activity of all sectors would also be negatively impacted by a fall in demand since it depends on disposable income "after unavoidable consumption". Other sectors could limit their losses in part by increasing their sale prices. This would be more difficult for sectors that are subject to strong competition and are price takers, because they cannot pass on inflation in their costs via their sale prices. This could cause widespread failures.

The introduction of damage functions into the models could make it possible to broaden the scope of the transition scenarios and better reflect the economic consequences of a lack of ambition in relation to transition actions at global level. Although the risks remain subject to very broad uncertainties and do not take into account extreme events and their consequences (tipping points and feedback loops), developing such tools is essential in the context of scenario analysis and new financial climate stress tests (Jacquetin, 2021). It would be a good thing for them to be re-assessed and clarified as the state of the art and modelling tools continue to develop.

The domestic impacts that we have estimated are currently based mainly on the damage that has an impact through foreign trade and they are surely underestimated, especially given that they do not take into account non-monetary costs (biodiversity) and the costs of adapting to climate change (management of heat waves or forest fires and management of migratory flows linked to climate change). Some potentially massive impacts linked to chronic risks in the rest of the world will also need to be clarified. Multi-region models would then be more relevant to "connect" trade flows with the consequences of damage estimated on a region by region basis, which would help to broaden the "national" scope of forecasting work to a wider field.

Furthermore, all shocks are introduced here in the form of gradual and linear changes during the transition period, following the example of the first "climate stress test" exercise carried out by the Banque de France (Allen *et al.*, 2020). While chronic risks should come to fruition in the long-term, intense episodes are already increasing and threatening the economy in the short-term (the summer drought in 2019 and the period of freezing temperatures in April 2021 in the Rhône-Alpes region). Anticipating the consequences of such disasters can go beyond the traditional macroeconomic framework, which continues to kick the can down the road in relation to climate risks until some far-off point in the future. □

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APPENDIX

Table A1 – **Review of the macroeconomic impacts of physical risks in europe taken from the "bottom-up" approach**

Study	Model	Scenario	Damage studied	Macroeconomic effects
Deke *et al.* (2001)	DART A global dynamic multi-region and multi-sector CGE model	Scenario B (IPCC II) "Back-to-Coal" Scenario	Agricultural yields Sea level	+0.5% of agricultural production −0.1% of other production 2 percentage points of GDP to be devoted to adaptation
Bosello *et al.* (2004b)	GTAP-EF A global static multi-region and multi-sector CGE model	Scenario B1 (IPCC II)	Vector-borne diseases	−0.7 of a percentage point of GDP
Bosello *et al.* (2004a)	GTAP-EF	Scenario B1 (IPCC II)	Sea level	−0.001 of a percentage point of GDP
Berrittella *et al.* (2004)	GTAP-EF	Scenario B1 (IPCC II)	Tourism	−0.1 of a percentage point of GDP
Bigano *et al.* (2006)	GTAP-EF	Scenario B1 (IPCC II)	Sea level Tourism	−0.1 of a percentage point of GDP
Eboli *et al.* (2009)	ICES A global dynamic multi-region and multi-sector CGE model	Scenarios A1B, A2, B1 (IPCC 2007)	Health and productivity Agricultural yields Tourism Energy demand Sea level	+0.2 of a percentage point of GDP
Roson & van der Mensbrugghe (2010)	ENVISAGE A global dynamic multi-region and multi-sector CGE model with a climate module	Endogenous global warming scenario (+4.8°C in 2100)	Sea level Agricultural yields Water availability Health Tourism Energy demand	+0.5 of a percentage point of GDP (2050) +1.2 of a percentage point of GDP (2100)
Ciscar *et al.* (2011)	GEM-E3 Europe	4 scenarios up to 2080 2.5°C 3.9°C 4.1°C 5.4°C	Agricultural yields Sea level Coastal flooding River flooding Tourism Health	< −1 percentage point of GDP in 2080 (from €20 billion (2.5°C) to €65 billion (5.4°C) in GDP losses)
Bosello *et al.* (2012)	ICES	Scenario A1B (IPCC)	Sea level Tourism Agricultural yields Energy demand River floods Labour productivity Forest productivity	−0.15 of a percentage point of GDP
Aaheim *et al.* (2012)	CGE model	Scenarios +2°C and +4°C	Extreme events Agricultural and forestry yields Power generation Energy demand Sea level Health Tourism	Up to −0.7 of a percentage point of GDP (2080)
Ciscar *et al.* (2014)	GEM-E3 A European dynamic multi-region and multi-sector CGE model	Scenario A1B (IPCC)	Agricultural yields Energy demand Forest fires Sea level Tourism Health	−1.1 percentage points of GDP
OCDE (2015)	ENV-Linkages A global dynamic multi-region and multi-sector CGE model	Scenario A1B (IPCC) and RCP 8.5	Extreme events Agricultural and forestry yields Sea level Health Energy demand Tourism	−0.5 of a percentage point of GDP (2060)

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Table A1 – *(contd.)*

Study	Model	Scenario	Damage studied	Macroeconomic effects
Roson & Sartori (2016)	Damage functions based on GTAP	Temperature rise of +3°C	Sea level Agricultural yields Labour productivity Health Tourism	France 0 percentage points of GDP +0.0002 of a percentage point of GDP 0 percentage points of GDP +0.0501 of a percentage point of GDP −0.3515 of a percentage point of GDP **−0.30 of a percentage point of GDP in total**
Kompas *et al.* (2018)	GTAP-INT Intertemporal global multi-region and multi-sector general equilibrium model	RCP scenarios 2.6/4.5/6.0/8.5	Agricultural yields Sea level Labour productivity Tourism Energy demand Water stress	From −0.139 of a percentage point of GDP (+1°C) to −0.662 of a percentage point of GDP (+4°C)
Lafakis (2019)	Moody's Analytics Global Macroeconomic Model Multi-regional structural model	RCP scenarios 2.6/4.5/6.0/8.5	Sea level Health Labour productivity Agricultural yields Tourism Energy demand	France +0.1 of a percentage point of GDP

Notes: Overall, impacts in the scenarios are assessed against a theoretical counterfactual scenario "without climate change". The macroeconomic impacts are presented for 2050 for Europe or similar groups (the EU, western Europe or southern Europe) including France. The assessments are sometimes more granular and extend until 2100 or are specifically for France.