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*The Roads Towards Raw Materials Sustainability: a French Case Study*

by

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# The Roads Towards Raw Materials Sustainability : a French Case Study

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## Abstract

Circular Economy (CE) has become increasingly influential in policy-making over the past fifteen years. Governments and institutions have viewed CE as a way to achieve high levels of sustainability while maintaining GDP growth. Through the design of several policy scenarios (Business-As-Usual, Techno-Efficiency, Cradle-to-Cradle, Circular Degrowth, Circular Growth, and Optimistic Circular Growth), this paper assesses the efficacy of different Circular Economy policies in delivering a decrease in Raw Materials Extraction and CO<sub>2</sub> emissions in France from 2014 to 2050. It explains how waste generation and raw material use were modelled in the dynamic Environmentally-Extended Input-Output tables of the EUROGREEN model. It also describes how Material Flow Analysis (MFA) was used to model key CE mechanisms such as Residual Waste Management, Closing Supply-Chains, Waste Efficiency, and Eco-design.

**Keywords:** Circular Economy, Degrowth, Raw Materials, Recycling, Sustainability, Ecological Economics, Input-Output Analysis, Waste Management

## 1 Introduction :

The Circular Economy (CE) narrative has become mainstream in France since the 2010s. From prolonged heatwaves to severe droughts in large parts of the country, the effects of climate change have put populations and institutions under strain. As the ecological

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emergency is becoming more visible, the Circular Economy (CE) framework is increasingly seen by key public stakeholder as a possible way out of the impasse. For instance, conservative columnist and former Minister of Education Luc Ferry has publicly advocated for it in the media <sup>1</sup>. He defines CE as “positive” environmentalism, which could conciliate economic growth and climate action. In his opinion, a Circular Economy is one in which “everything can be recycled indefinitely, so if we take it as a model, we can not only reduce costs and make profits by not wasting useful materials, but also build an ecological future that, by integrating itself into the economy, will promote growth and consumption instead of reducing them to a trickle”. The private sector is also gradually becoming interested in the Circular Economy framework as a way to improve efficiency and increase profits <sup>2</sup>.

This vision of the Circular Economy as a possible driver of “green growth” is also gaining momentum in French <sup>3</sup>and European <sup>4</sup> policy-making. In 2015, the Law on the Energy Transition for Green Growth <sup>5</sup> first introduced the concept of Circular Economy in French legislation. This statute set important Circular Economy targets, namely “achieving a 65% recycling rate for non-hazardous non-inert waste by 2025” and “a 30% increase by 2030 in the ratio between GDP and the domestic consumption of materials”. As part of Emmanuel Macron’s *#MakeOurPlanetGreatAgain* initiative - by which he intended to put France at the forefront of the fight against climate change – two French ministries released a Roadmap for the Circular Economy <sup>6</sup> which listed “50 measures for a 100% circular economy”. Key members of the Ellen MacArthur Foundation, a think tank advocating for the implementation of Circular Economy in public spheres, actively contributed to this initiative. This roadmap became the basis for the 2020 Anti-waste Law for a Circular Economy. These policies promote the implementation of CE measures to “decouple growth from material consumption” <sup>7</sup> as part of an effort to make the economy “green”, in a sustainability thinking framework which deems “green” growth as a positive and attainable policy goal. The European Union has also drafted a Circular Economy Action Plan as part of the European Green Deal. The latter describes the

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<sup>1</sup>Luc Ferry et l’économie circulaire.

<sup>2</sup>McKinsey Circular Economy Report

<sup>3</sup>Loi anti-gapillage et économie circulaire.

<sup>4</sup>Circular Economy Action Plan

<sup>5</sup>Loi pour une transition énergétique

<sup>6</sup>Feuille de route

<sup>7</sup>Définition de l’économie circulaire

transition to a Circular Economy as a way to "reduce pressure on natural resources and (...) create sustainable growth and jobs".

As expectations are high regarding the Circular Economy policy framework, it seems interesting to investigate whether Circular Economy policy interventions can practically deliver what they promise to achieve. Can Circular Economy policies enable us to reach important sustainability thresholds i.e., a constant and absolute reduction in environmental pressures caused by the French economy? Moreover, is it possible to achieve a "100% circular economy", in which all waste would indefinitely replace Primary Raw Materials from "cradle to cradle" (Braungart and McDonough, 2009)? As they claim, is it thus possible to "eliminate the concept of waste" ? In a broader perspective, what are the potential effects of CE interventions on a macroeconomic and macro-ecological scale?

This paper aims to provide answers to these questions through the use of Ecological Macroeconomics. In the following sections, we will describe how waste generation and raw material use were modelled in the Environmentally-Extended Input-Output tables of the EUROGREEN model. We will explain how Material Flow Analysis (MFA) was used to model Residual Waste Management, Closing Supply-Chains, Waste Efficiency and Material Efficiency in the French version of EUROGREEN. Through the design of several policy scenarios (Business-As-Usual, Techno-Efficiency, Cradle-to-Cradle, Circular Growth, Optimistic Circular Growth and Circular Degrowth), this paper also assesses the efficacy of different Circular Economy policies in delivering a decrease in Raw Materials Extraction and CO<sub>2</sub> emissions in France from 2014 to 2050.

## **2 Literature Review :**

According to the Ellen MacArthur Foundation, Circular Economy is "a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution". It "is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. It is underpinned by a transition to renewable energy and materials. Transitioning to a circular economy entails decoupling economic activity from the consumption of finite

resources”<sup>8</sup>. Research has therefore focused on trying to assess the efficacy and impacts of CE policy interventions (Kagawa et al., 2006; Geng et al., 2016; Luzzati et al., 2022).

Leontief’s Input-Output (I-O) analysis has been frequently used in this endeavor (Koning, 2018). Input-Output tables enable us to determine the volume of inputs which need to be provided by each sector of the economy to satisfy a certain level of final demand (Leontief, 1936). Leontief’s approach has been extended to represent physical entities embedded in each sector’s value chain. Environmentally Extended Input Output (EEIO) tables (Duchin, 1990) have been particularly used to model the waste and carbon footprints of the different sectors of the economy (Nakamura and Kondo, 2002; Towa et al., 2020).

Furthermore, EEIO analysis has been frequently used to model the effects of Circular Economy policy interventions on a macroeconomic scale (McCarthy et al., 2018; Aguilar-Hernandez et al., 2018). In this context, Closing Supply Chains (CSC) has often been described as a key mechanism of the Circular Economy framework. CSC policies (Donati et al., 2020) aim to create a waste treatment system enabling waste created during the production process to be reused in the form of new inputs in a circular pattern (Nakamura, 2023; Chen and Ma, 2015). Closing Supply Chains and Residual Waste Management (RWM), (e.g., waste collection and treatment systems) are closely intertwined. Waste, here considered as a secondary product (Merciai and Schmidt, 2018), is intended to serve as a substitute input for Primary Raw Materials (Beylot et al., 2016). This replacement of newly extracted inputs with recycled ones can limit the extraction of raw materials, as well as the emission of greenhouse gases (GHG) into the atmosphere. Instead of creating a new sector related to waste treatment in I-O tables, some researchers managed to integrate Secondary Raw Materials (SRM) into EEIO. In line with other researchers Beylot et al. (2016); Lenzen and Reynolds (2014); Zeller et al. (2019); Towa et al. (2020) stressed that, with an aggregated recycling rate of treated waste, it is possible to model Closing Supply Chain scenarios through the substitution of Primary Raw Materials by Secondary Raw Materials (or ”PRM/SRM substitution”). The latter are then regarded as new inputs in the economy.

Another main mechanism of the Circular Economy framework is Material and Waste

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<sup>8</sup>Introduction to the Circular Economy Framework

Efficiency (Aguilar-Hernandez et al., 2018). Material Efficiency is usually linked to the role of technology and technological innovation in the production process. It has been modelled through a technology-driven reduction in waste generation as well as a decrease in material use under the assumption of a lack of rebound effect. Design improvements<sup>9</sup> are also considered to be driving increases in efficiency (Donati et al., 2020).

## 3 The Model

### 3.1 Scenarios

This extension of the EUROGREEN model enables us to visualize the effects of five additional policy scenarios applied to the French economy from 2014 to 2050. The “Business as usual” (BAU) scenario describes the continuation of already observable trends in the French economy. The Techno-Efficiency (TE) scenario represents a situation in which innovation drives a sharp increase in material/waste efficiency in all sectors of the economy. In the “Cradle-to-Cradle” (C2C) scenario, the recycling and backfilling rate of treated waste gradually increases to 100% in 2050. In this case, the eco-design policy and the full substitution of Primary materials with Secondary materials lead to changes in the volume and structure of the output. The Circular Growth (CG) scenario combines the effects of increased recycling and material efficiency with a baseline PRM/SRM substitution rate, as the maximization of the output and GDP growth are prioritized over sobriety measures. Due to a lack of reliable data, this baseline PRM/SRM substitution coefficient lacks accuracy. We hence modelled an alternative, more Optimistic Circular Growth scenario (OCG). This scenario is identical to the CG scenario, except that we added a hypothesis of full PRM/SRM substitution. The Circular Degrowth (CD) scenario measures the potential effects of combined degrowth and cradle-to-cradle policy interventions.

### 3.2 Calibration

All the scenarios and mechanisms listed in 3.1 are activated in 2024.

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<sup>9</sup>Principles of a Circular Economy

## 4 Results

### 4.1 GDP growth

Figure 1: GDP growth real

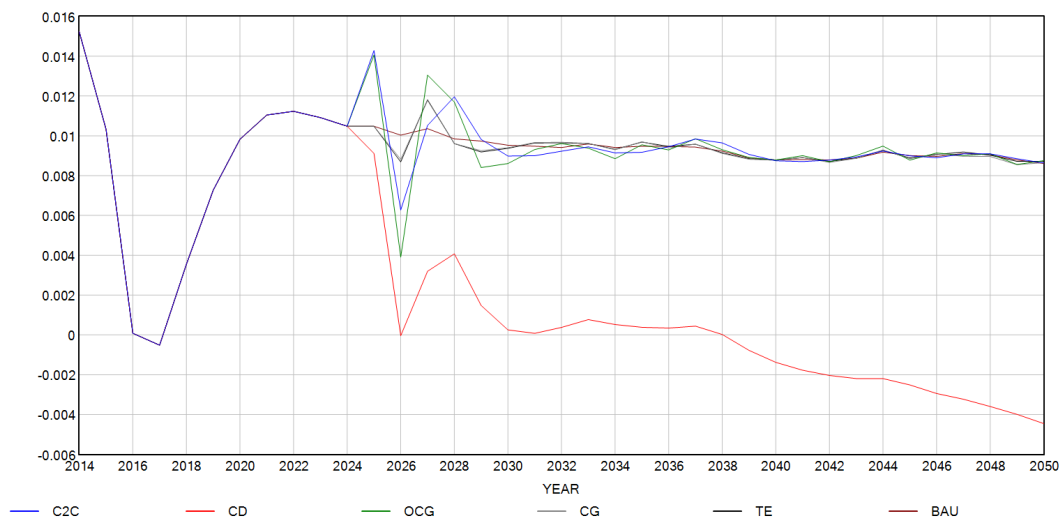


Figure 1 displays the evolution of France’s real GDP (0.01 = 1% GDP growth) from 2014 to 2050. In the BAU, C2C, TE, CG and OCG scenarios, the French economy sustains a real GDP growth rate of approximately 0.8% per year. In the Circular Degrowth scenario, negative real GDP rates are attained from 2038 in our simulations. The real degrowth rate is increasing over time, reaching approximately 0.4% per year in 2050.

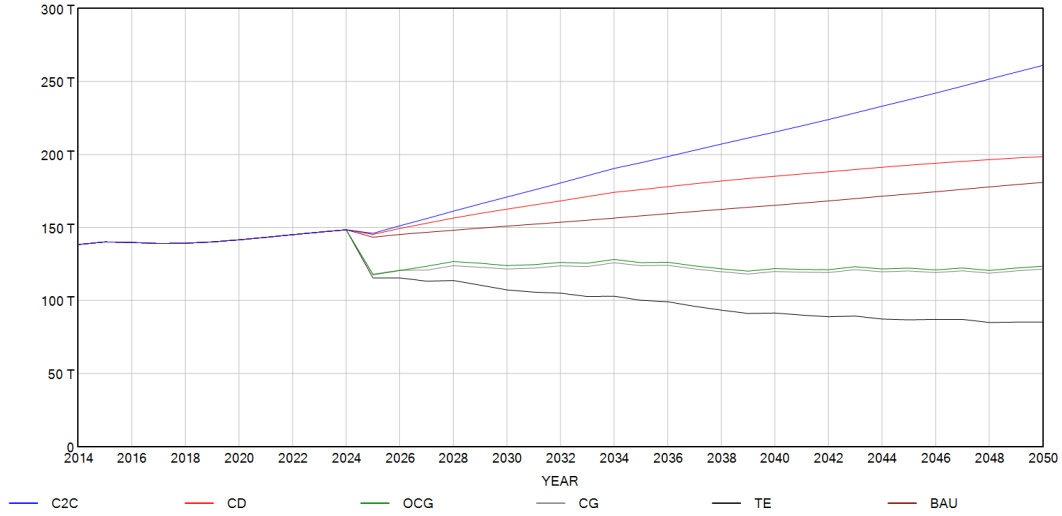
We can also observe in this graph that most of the curves follow an oscillatory behaviour. This oscillation is more pronounced in the OCG scenario than in the other curves. We will explain this phenomenon in the Discussion section of the paper.

### 4.2 Secondary Raw Materials :

Figure 2 shows the total amount of Secondary Raw Materials (or ”recycled materials”) produced in the French economy per year (expressed in 10,000 tons of Raw material equivalents). It varies greatly depending on the simulated policy scenario.

The scenario with the highest production of Secondary Raw Materials (SRM) is the C2C scenario. It sees an increase in SRM generation by a third compared to the

**Figure 2:** Production of Secondary Raw Materials



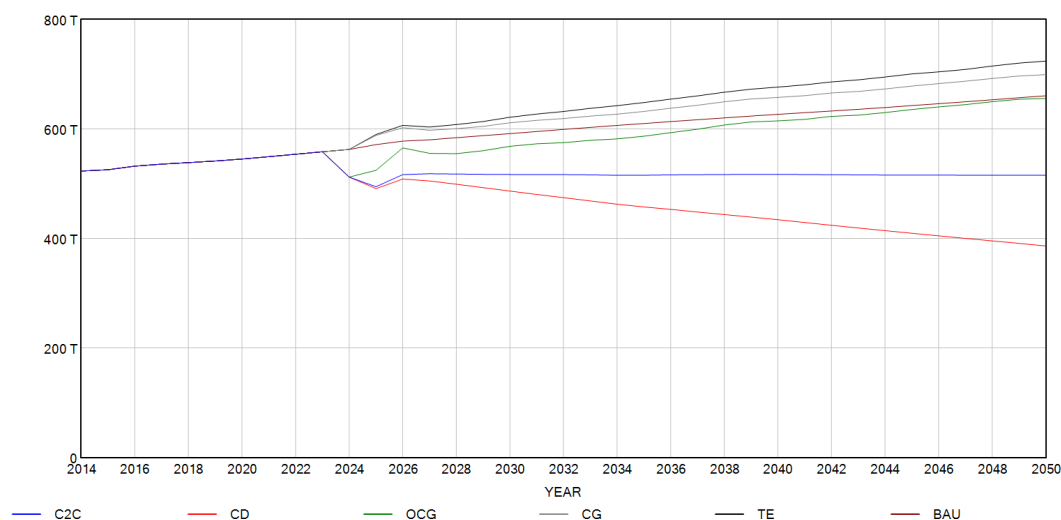
BAU scenario. The CD scenario ranks second in terms of SRM production. Circular Degrowth achieves this performance (+10% compared to BAU) despite reduced production and therefore waste generation. In the Circular Growth scenario, the amount of produced SRM is substantially lowered because of innovation-driven scrap diversion and thus reduction in waste production. The levels of SRM generation in the CG and OCG scenarios are, in 2050, way below the ones observed in the BAU scenario. In a TE scenario, the French economy would produce only a third of the secondary inputs generated in a C2C scenario.

### 4.3 Extraction Demand

Figure 3 describes the dynamics of the Primary Raw Materials Demand, expressed in thousands of tons of RME per year. This variable represents the amount of Primary Raw Materials which needs to be extracted to respond to the French aggregated demand.

The TE scenario stands out as being the one in which demand for Raw Materials is the highest. It is closely followed by the CG scenario, in which the French economy has a slightly reduced material footprint. The CG scenario and the TE scenarios carry approximately the same implications in terms of Raw Materials Extraction Demand. In our simulations, these two scenarios create a yearly extraction demand in 2050 which is substantially higher than in a BAU scenario. If the Optimistic Circular

**Figure 3:** Raw Materials Extraction Demand



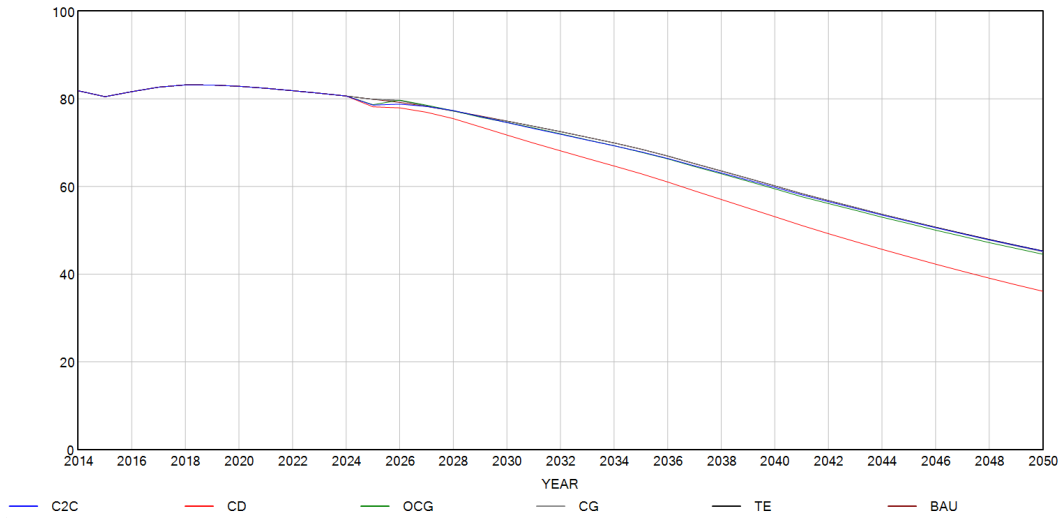
Growth scenario could help reduce the French Raw Materials Extraction Demand in the short term, it would create in fine an extraction demand which is similar to the one of the BAU scenario. It is noteworthy to observe that the four above-mentioned scenarios would equate in our simulations to a substantial increase in the extraction demand, and thus in the material footprint, of the French economy in 2050 compared to its 2014 levels.

On the contrary, the C2C and the CD scenarios would enable a decrease in the Raw Materials Extraction Demand of the French economy by 2050. In the C2C scenario, France's material footprint stagnates near the unsustainable 2014 levels in 2050. The Circular Degrowth scenario reaches the highest decrease in Raw Materials Extraction among all tested policy scenarios. It achieves a reduction in yearly raw materials extraction of approximately 20% in 2050 compared to 2014.

#### 4.4 Reduction in CO<sub>2</sub> emissions :

Figure 4 plots the reduction in CO<sub>2</sub> emissions compared to 1990 levels (index 1990 = 100) of each policy scenario. On this graph, two dynamics can be clearly distinguished. Firstly, 5 curves closely follow each other (BAU, OCG, CG, C2C, TE). These scenarios would enable France to achieve a decrease in CO<sub>2</sub> emissions of approximately 55% in 2050 compared to 1990 levels. The Circular Degrowth scenario stands out once again

**Figure 4:** Reduction in CO<sub>2</sub> emissions compared to 1990 levels



by enabling the highest reduction in CO<sub>2</sub> emissions compared to 1990, with a combined decrease in emissions of more than 60%.

## 5 Discussion

The analysis of feedback loops, stocks, and flows in a system dynamics modelling framework can help to better understand the complexity of the relations between our socio-economic systems and the biosphere. Ecological Macroeconomics takes elements from both ecological economics and complexity theory to model and understand the various stresses our economic systems induce on planetary boundaries (Richardson et al., 2023). It uses both monetary and non-monetary metrics, with the underlying view that ordinal (prices) and cardinal (physical) values are incommensurable (Georgescu-Roegen, 1971). It therefore refuses the concept of weak sustainability, which hinges upon the assumption that all capitals (including a "natural" one) could be subsumed into a common stock, measured with the help of the same metric. Using Environmentally Extended Input Output tables in a demand-driven economy, Ecological Macroeconomics enables us to take into account the multidimensional features of our economy's throughput (Giampietro, 2019). Ecological Macroeconomics also paves the way for a comprehensive representation of the potential dynamics, trade-offs, and synergies between social and ecological targets, which can be assessed through the lens of the Doughnut Economics

model and its "safe and just space" for humanity (Raworth, 2012, 2018; O'Neill et al., 2018).

The EUROGREEN model (D'Alessandro et al., 2020), which adopts the methodological framework of Ecological Macroeconomics, is especially useful in its ability to compare the impacts of diverse sets of policy interventions and evaluate their effects on a range of ecological, social, and economic indicators. The results of the simulations suggest that Circular Economy policy tools cannot always deliver a reduction in environmental pressures caused by the French economy.

The simulation of different policy intervention scenarios firstly helps us to confirm the potential benefits of increased waste recycling. Indeed, in the Cradle-to-Cradle scenario, a higher recycling and backfilling waste treatment ratio drives a decrease in the demand for newly extracted Primary Raw Materials in 2050 compared to the baseline scenario. Yet, the extent of this reduction in the material footprint is limited in comparison with other policy simulations. This failure of the C2C scenario in attaining high levels of raw materials sustainability is mainly due to the oscillation of the Secondary Raw Materials production. This is partly due to the inclusion of an entropy coefficient, which accounts for the losses in waste quality and quantity which invariably occur along all economic and industrial processes (Georgescu-Roegen, 1971). I chose to model the impact of entropy on the degradation of waste with a new variable, the "Primary waste equivalent ratio". This ratio accounts for the role of entropy in decreasing the ability to recycle waste which was already recycled or reused many times. With this ratio, we apply the second law of thermodynamics as well as Georgescu-Roegen's proposed fourth law of thermodynamics to waste. As CSC is one of the main mechanisms of Circular Economy, we modelled the substitution of Extracted Primary Raw Materials for Secondary Raw Materials (or "PRM/SRM substitution"). Consequently, the waste coming from materials which were already processed many times (Secondary Materials) can be backfilled and recycled in different proportions due to the effect of entropy. The subsequent changes in the structure of waste, impact every year, in different proportions, the amount of Secondary Raw Materials produced within the French economy. This oscillation creates a yearly fluctuation (or change in slope angle) of the Raw Materials demand curve, which cannot persistently drop at the same pace if the output stays unchanged.

Secondly, this extension of the EUROGREEN model demonstrates the impossibility of achieving a perfectly Circular Economy “from cradle to cradle”. As research has previously shown, waste cannot disappear as it would contradict the laws of thermodynamics and the nature of our socioeconomic organisms (Giampietro, 2019).

Thirdly, the simulation of different sets of Circular Economy policies helped us better understand the potential counter-effects of technology-induced material efficiency. Indeed, the Techno-Efficiency scenario creates a slump in waste generation, which by itself drives a decrease in the production of Secondary Raw Materials. This mechanism induces an oscillatory behaviour, which can be observed in the case of the production of Secondary Raw Materials in Circular Growth, Optimistic Circular Growth, and Techno-efficiency scenarios (Graph 2). Each of the above-mentioned curves represents a policy scenario containing an increase in technology-driven material and waste efficiency. As material efficiency drastically decreases waste generation, there is less waste to be recycled in the year following the beginning of the implementation of technology-driven efficiency scenarios. The amount of Secondary Raw Materials produced by the economy decreases, driving an increase in the demand for newly extracted Raw Materials. As more Primary Raw Materials are used in the economy, more primary waste is generated and the amount of secondary materials increases. As the quantity of SRM increases, the quantity of waste consequently decreases the following year, leading yet again to an increase in the demand for raw materials. Thus, in our simulations, technological progress-driven material efficiency leads to larger environmental pressures.

Lastly, one of the overarching results of this study is that Circular Economy policy interventions do not prove to achieve any kind of “green growth”. Indeed, the Circular Growth and Techno-Efficiency scenarios, which both combine Circular Economy interventions and the prioritization of GDP growth maximization over sobriety measures, are lowly efficient in reaching high sustainability thresholds.

In our simulations, a combination of Circular Economy policy interventions with Degrowth (Circular Degrowth) is the most potent way to achieve raw materials sustainability. It is also the most efficient scenario to reduce France’s pressure on accounted planetary boundaries (here, material footprint and climate change). We should take

note that these encouraging results of Circular Degrowth might also prove beneficial to the preservation of other ecological aggregates. For instance, it has been demonstrated that both climate change and raw materials extraction (through changes in land use) are among the main drivers of biodiversity loss (IPBES, 2019).

If further research needs to be done to confirm these findings, we can cautiously state that Circular Economy mechanisms should not be implemented without questioning the current growth-centered paradigm. Implementing Circular Economy policies within a "green growth" framework may prove, on the contrary, either counter-effective or inefficient in achieving sustainability goals in the context of the ecological emergency. Still, 'Circular Growth'-inspired policy schemes might prove to be highly rewarding to the private sector. Companies could indeed substantially increase their economic performance through gains in material and waste efficiency <sup>10</sup>. Civil Society Organizations should therefore heighten their scrutiny over the potential adoption of such measures, which could prove beneficial to a minority of private actors without preventing the overshoot of planetary boundaries.

Instead, our findings suggest that a Circular Degrowth policy package could be the most effective way for the French economy to reduce both its intake of raw materials and its CO<sub>2</sub> emissions. The implementation of such a policy set would bring France one step closer to achieving its National Low-Carbon Strategy target to reduce territorial emissions by 75% compared to 1990 levels <sup>11</sup>.

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<sup>10</sup>Circular Economy of Cement

<sup>11</sup>Stratégie Nationale Bas-Carbone

## Appendix :

### A Data and definitions :

In our efforts to model flows of Secondary Raw Materials and waste in an Environmentally Extended Input Output (EEIO) framework, we extracted, assembled, and analysed data from an extensive number of databases. We will here provide a comprehensive list of the sources we mobilized for this work :

- Eurostat provides data on waste generation per sector <sup>12</sup> and waste treatment <sup>13</sup> for France in 2014. We also used the newly created “Eurostat RME country tool” database<sup>14</sup>, in which key figures about the material footprint <sup>15</sup> of the French economy are detailed.
- The NIOT database <sup>16</sup> also provided us with France’s input-output tables.
- The data and methodology of the EUROGREEN model (D’Alessandro et al., 2020) serve as a groundwork from which this paper tries to offer an extension. All the data that are not listed higher in this section were extracted from the EUROGREEN database.

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<sup>12</sup>Eurostat Waste Generation

<sup>13</sup>Eurostat Waste Treatment

<sup>14</sup>Eurostat RME country tool

<sup>15</sup>Eurostat Material Flows.

<sup>16</sup>NIOT Database

## B Methodology :

We will here describe the methodology used to model waste treatment and Secondary Raw Materials flows into the EUROGREEN model.

### Harmonization of data :

We reorganized the data provided in the “Eurostat RME Country tool - March 2023” to fit the taxonomy of sectors used in the EUROGREEN model. For clarity purposes, the sectors as classified in the “Eurostat Country RME tool - March 2023” (NACE rev.2) will be put in quotes (“Manufacturing” sector). The sectors as described in the EUROGREEN model are written beginning with a capital letter (Manufacturing sector).

We reformed the data from Eurostat to create EUROGREEN’s Fossil Fuels sector, which does not exist independently in Eurostat’s NACE V2 classification of economic activities. Indeed, in the Eurostat database, the economic activities we attributed to the Fossil Fuels sector are embedded in the NACE ”Manufacturing sector”. The details of these operations can be found in the “Supplementary information” of previous EUROGREEN papers <sup>17</sup>.

Firstly, we tried to estimate the amount of waste which is generated by the Fossil Fuels sector. For that purpose, we calculated ratios of raw material footprint (expressed in tons of Raw Materials Equivalents, or RME) per unit of output for both Fossil Fuels and Mining and Quarrying sectors. By dividing these two ratios, we found that in 2014, the Mining and Quarrying sector was using 39% less raw materials per unit of output than the Fossil Fuels sector. This latter percentage was then multiplied by the amount of waste generated by the Mining and Quarrying sector to find the approximate waste generated by the Fossil Fuels sector. The underlying assumption is that a difference in RME per output between two sectors would imply a proportional difference in the waste they generate.

$$Waste_{FF} = Waste_{MQ} * \frac{RME_{peroutputFF}}{RME_{peroutputMQ}} \quad (1)$$

In Eurostat’s NACE Rev.2 classification, the economic activities of the Fossil Fuels sector are attributed to the “Manufacturing” sector. We subtracted the waste generated

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<sup>17</sup>Supplementary Information

by the Fossil Fuels sector from the waste produced by the “Manufacturing” sector to get an accurate assessment of waste generation by these two sectors.

$$WasteMcorr = WasteM - WasteFF \quad (2)$$

Similarly, as described in the EUROGREEN sector taxonomy, we reaggregated Eurostat data on waste generation to find the waste released by the Non-financial and social economy sector as well as the Public sector. For instance, we aggregated the waste generated by Eurostat’s “Services (except wholesale of waste and scrap)” and “Wholesale of waste and scrap” sectors to form a new Non-financial and social economy sector. The waste produced by the “Water collection, treatment, and supply; sewerage; remediation activities and other waste management services” and “Waste collection, treatment and disposal activities; materials recovery” sectors were also added to constitute a newly created Public sector.

Due to gaps in data, the Financial and Other sectors were given the value of 0.

With this reassembled set of data, we created a vector of waste generation per sector. We used these figures to create a vector of ratios, which represent the material waste generated per million euros of output per sector.

This ratio was calculated in the following way :

$$InitialWastecoeffperOutput_i = \frac{materialwastepersector_i}{realoutputpersector} \quad (3)$$

### **Extracted Raw Materials Consumption :**

We used the methods of Material Flows Analysis (MFA) to model waste treatment in a System Dynamics I/O framework. We chose here to differentiate Primary Raw Materials from Extracted Primary Raw Materials to represent the activities of waste treatment carried out in the ‘technosphere’. According to (Giampietro, 2019), waste management is different in the biosphere and the technosphere. In the biosphere, ecosystems process

degradable matter to form new organic nutrients which are then used by living organisms. Within the technosphere, waste is processed through industrial operations to be used as new inputs in the economy.

We will thus distinguish two sorts of Primary Raw Materials, which correspond to the two kinds of waste which are treated through these two different processes (biological and technical). The first kind of Primary Raw Material is biomass. We consider biomass to be a renewable Primary Raw Material. It can be infinitely produced and harvested due to an infinite source of energy (on a human time scale) : the sun. We are however conscious that nutrient balance is necessary for biomass production not to aggravate the degradation of the quality of the soils, and thus be sustainable (Bouwman et al., 2017). Waste generated by the Agricultural sector is also assumed to be mainly composed of biomass, which can be processed by ecosystems without human action. On the other hand, we describe "Extracted Primary Raw Materials" as inputs which contribute to the depletion of a stock of non-renewable resources. These raw materials are assumed to be nonrenewable on a human time scale. When these inputs become waste, they are processed through industrial operations within the technosphere. It would take too long for them to be biodegraded.

Three sectors and one sub-sector can be counted as sectors providing raw materials according to Eurostat : the Agricultural sector, the Mining sector, the Fossil Fuels sector, and the plastics production sub-sector (which is part of the Manufacturing sector). We will here concentrate our analysis on the "Extractive" industries producing Extracted Primary Raw Materials: the Mining and Quarrying industry, the Fossil Fuels industry, and the Plastics production industry.

To differentiate the Primary Raw Material Use from the Extractive Materials use, we create an "Extraction share" of the total Raw materials used in the economy.

$$Extractionshare = \frac{FFwaste + MQwaste + Plasticswaste}{Agriculturewaste + FFwaste + MQwaste + Plasticswaste} \quad (4)$$

The average waste generation between 2014 and 2020 is used as a proxy for the Raw Materials Footprint used by each of these sectors. To estimate the amount of waste generated due to the production of plastics (embedded in the manufacturing sector), we used data from France's NIOT tables. We converted the value of the output of the

“Manufacturing of Plastics and Rubber” economic activities from dollars into euros. We then calculated the share this sub-sector represents in the whole Manufacturing sector. For simplification purposes, we assume that this sub-sector’s output equals the plastics output of the French economy in 2014. We then assumed that, as the “Plastics manufacturing” activities represent 3.54% of the Manufacturing sector’s output, Plastics production would also account for 3.54% of its waste. We eventually found that the Extraction share was of 0.6924 in 2014. This ratio will be assumed to stay constant over time.

### **Waste efficiency :**

Waste and material efficiency are important elements of the Circular Economy narrative. We therefore decided to represent the impact of technological change on waste generation. To account for technology-induced efficiency gains, we assumed that the “Energy conversion efficiency” ( $\eta$ ) of a sector would be an accurate proxy for waste efficiency. We figured that a sector equipped with energy-saving hardware would also be more efficient with the materials it uses. An increased “Energy conversion efficiency” for a sector would therefore induce a reduced waste generation per unit of output.

We multiplied the initial waste per output coefficient vector by this proxy for resource efficiency to model the impact of technological change on waste generation.

$$Wastecoeff_i = \eta_{coef} per_{industry} * InitialWastecoeff_{perOutput_i} \quad (5)$$

To assess the potential impacts of technological change and increased resource efficiency on waste production through for instance scrap diversion, we created an increased resource efficiency scenario. We calibrated this resource efficiency scenario to come into effect in 2024 to represent the potential effects of Circular Economy efficiency policies if they were to be implemented. We defined waste generation by sector as the product between the waste coefficient vector and the output (in monetary terms) per industry vector.

$$Wastepersector_i = Wastecoeff_i * realoutputpersector_i \quad (6)$$

As mentioned earlier, non-biomass waste only can be treated within the technosphere and processed into Secondary Raw Materials. To calculate the amount of material waste

which can be re-manufactured, reused, and recycled, we multiply the sum of industrial waste by the Extraction share.

$$Wastetoti = \text{sum}(Wastepersectori) * \text{extractionshare} \quad (7)$$

We then need to add household waste to the waste generated per sector to obtain the total waste generation of the French economy. For that purpose, we calculated the ratio of household waste per unit of total household domestic consumption (“total cyv real”). We then calculated the generation of waste by households in France. We found that households created 27.76 tons of waste per million euros of total household domestic consumption in 2014. As this value was almost constant in the following years, we assumed that this value would stay unchanged over time. Then, we modelled household-generated waste by multiplying the monetary value of domestic household consumption by the household waste generation coefficient.

$$HHwaste = HHwastecoefficient * HHrealconsumption \quad (8)$$

We could then reaggregate the total amount of generated waste in the French economy by adding industry and household-generated waste.

$$Totwaste = \text{sum}(Wastepersectori) + HHwaste \quad (9)$$

### **Waste treatment :**

To obtain the yearly amount of treated waste in the French economy, we calculated a coefficient of global waste treatment from publicly available Eurostat data. We were able to assess that the gaps and leaks in the French waste collection system accounted for approximately 8% of the generated waste in 2014. The waste treatment coefficient being stable at 0.92, it was deemed to be constant over time.

We modelled total treated waste as the multiplication of this waste treatment coefficient by the total amount of generated waste.

$$Tottreatedwaste = wastetreatmentcoeff * totwaste \quad (10)$$

The global amount of treated waste is distributed along different waste treatment

techniques. With the help of statistics from Eurostat, we created a vector of waste treatment coefficients by technique. By dividing the amount of “Disposal - landfill and other (D1-D7, D12)” waste, “Disposal - incineration (D10)” waste, “Recovery - energy recovery (R1)” waste and “Recovery - recycling and backfilling (R2-R11)” waste by the total treated waste, we could obtain 4 coefficients representing the share of total treated waste by technique : the landfilling coefficient, the incineration coefficient, the energy recovery coefficient, and the recycling and backfilling coefficient.

The recycling and backfilling coefficient was calculated as follows :

$$Recyclingcoefficient = \frac{recycledwaste}{totalwastetreated} \quad (11)$$

We obtained 0.65 as the average recycling and backfilling coefficient between 2014 and 2020. This coefficient is assumed to stay constant in a baseline scenario. When multiplying this coefficient by the amount of treated waste, the model can endogenously determine the global amount of recycled waste each year.

$$Recycledwaste = recyclingcoefficient * treatedwaste \quad (12)$$

As the scientific literature finds it hard to determine a comprehensive average amount of energy recovered by tons of undifferentiated treated waste, we chose here not to model the new inputs (or Secondary Raw Materials) created through energy recovery in an input-output framework.

The second pillar of the Circular Economy framework is the idea that waste can be transformed into new inputs (or Secondary Raw Materials), replacing our linear system with a circular one “from cradle to cradle”. We created another scenario to test the macroeconomic and environmental effects of this part of the Circular Economy framework. We used two assumptions in this scenario, aiming to represent the Circular Economy’s main representation of “cradle to cradle” policies.

The first one is that all Secondary Raw Materials could replace Primary Raw Materials as similar inputs in the production process. This scenario’s assumption states that a circular economy would prioritize a diminution in primary raw material resources use over the maximization of the output. Instead of putting new products on the market

with these recycled materials (GDP growth), economic agents within the French economy would rather replace primary inputs with secondary ones. This would have as an effect to maintain the same approximate level of output, in a post-growth perspective. This kind of economic behaviour could be favored by the adoption of appropriate regulation. This assumption is purely theoretical and represents a “best-case scenario”, in which the Secondary Raw Materials would keep the same qualitative properties as the Primary Raw Materials, thus enabling them to fulfil the same tasks.

The second assumption is that an increased recycling and backfilling rate could enable an economy to become “circular” e.g., to enable a long-lasting and sufficient diminution of the economy’s intake of Primary Raw Materials (natural “resources”). The potential effects of a 100% waste recycling scenario will be developed further in the article. We are fully aware that these assumptions are at least partially unrealistic. They aim to test the potential efficacy of the Circular Economy policy framework in a “best-case scenario”.

### **Substitution of primary materials for recycled materials :**

We modelled the substitution of primary materials for secondary materials, as previously described, in a “best-case scenario”.

Secondary Raw Materials are modelled as waste, which is transformed into newly ready-for-use inputs through an industrial process. As an economic process, it is not exempt from entropy. Indeed, the second law of thermodynamics states that a body’s entropy invariably increases over time. Matter thus degrades both in quantity and quality as time goes on. The ability of a matter to be reused or recycled into a new input invariably consequently decreases with the number of times it is recycled. In an industrial process, waste from an already-recycled product can be less recycled than a ton of primary raw materials that are about to be recycled for the first time. The waste treatment process can therefore not be considered to be a closed loop (e.g. fully ”circular”), as some proponents of the CE framework state, as it would contradict the second law of thermodynamics.

To represent this in the EUROGREEN model, we chose to create a new concept : the tons of Raw Materials Waste equivalent (or eq-rmW). This kind of unit is already used in physics, with for instance CO<sub>2</sub> equivalents (eq-CO<sub>2</sub>). ”Eq-CO<sub>2</sub>” is a unit which describes the radiative forcing of other Greenhouse Gases. It can be understood as the

radiative forcing created by a gas which is equivalent to one ton of CO<sub>2</sub>.

In the waste treatment process, one unit of raw materials waste equivalent (eq-rmW) represents the amount of waste whose quantitative and qualitative features are equivalent to one unit of raw materials recycled for the first time. We take here as a reference for recycling the quantity and quality of a ton of primary raw materials waste. This new unit enables us to describe heterogeneous matter in a functionally homogeneous manner. We can thus account for the effects of entropy on waste recycling.

We put the entropy rate at 0.2, meaning that we expect waste to lose 20% of its qualitative/quantitative features at each cycle. More literature could help to put this entropy coefficient at an accurate and objective rate.

The “tons of eqRMW coefficient” is defined as follows:

$$TeqRMWcoefficient = \frac{(RM Ctot - SRM * (entropycoeff))}{RM Ctot} \quad (13)$$

The degradation of matter over time induces the generation of a lesser amount of waste, or the generation of waste with reduced quality, hence negatively impacting the production of Secondary Raw Materials. This phenomenon creates a gap, which is compensated by an increase in Raw Materials Extraction to meet the demand.

The equation for total waste treated, thus expressed in tons of eqRMW, is defined as such :

$$TotwasteeqRM = (totwaste * Wastetreatedcoeff) * TeqRMwastecoefficientdelay \quad (14)$$

### **Extracted Raw Materials Footprint :**

In line with the Eurostat RME Country tool database, we use Raw Material Equivalents (RME) as an indicator evaluating the amount of raw materials (in tons) embedded in a unit of output. To model the primary Raw material use in an input-output framework, we calculated the Raw Material Consumption per sector of the French economy. Raw Material Consumption is the quantity of resources (in tons of Raw Materials Equivalents) embedded in the goods and services consumed by a country’s domestic demand. It can be calculated in the following way, in which the domestic extraction (DE), the imports

(M), and the exports (X) are expressed in tons of Raw Material Equivalents.

$$RMC = DE + M - X \quad (15)$$

We used data from the Eurostat RMC Country Tool to model these variables in the EUROGREEN model. As our attempts to disaggregate the data on raw material footprint per sector proved to be unsatisfying, further research and data production may be needed to assess the exact amount of raw materials embedded in each sector's production. Despite this key data gap, we assessed France's Raw Material Consumption in an aggregated manner. We calculated average ratios for the period 2014 – 2020, which eventually enabled us to infer France's RMC. We used both France's Supply-Use tables and Eurostat data on aggregated Raw Material Consumption for that purpose.

Firstly, to endogenously model France's Domestic Extraction, we calculated a ratio of Domestic Extraction (in tons of RME) by unit of domestic demand (in euros). By calculating the average of these ratios from 2014 to 2020, we obtained a coefficient of 0.835 thousand tons of RME per million euros of French domestic demand. We found that the standard deviation of this average was low (0.04). We could thus model in a fairly accurate manner the French Domestic Extraction as the multiplication between this Domestic Extraction coefficient and the real French total domestic demand.

$$RMDE_{tot} = RMDE_{coef} * sum(Z_{dom}) \quad (16)$$

We used the same method to model the quantity of raw materials embedded in France's exports and imports. On average, for the same period, we calculated that one million euros of imports had a material footprint of 2.02 thousand tons of RME (standard deviation of 0,09).

Thus :

$$RM_{imptot} = RM_{Impcoef} * totalZ_{impreal} \quad (17)$$

To calculate the average raw material footprint per unit of exports, we divided the aggregated material footprint of exports (estimated by Eurostat) by the value of real exports for France. We obtained 0.85 as the average value for the 2014–2020 time span (standard deviation of 0,04). We could therefore, and with a certain accuracy, model the raw material footprint of French exports as the multiplication of the raw material

export coefficient by the real value of exports.

$$RMexptot = RMexpcoef * totalexpreal \quad (18)$$

For the calculation of these values, we always assume that the coefficients are constant because of their low standard derivations.

Once these values were estimated, we could assess the Raw Material Consumption of France as :

$$RMCtot = RMDEtot + RMimptot - RMexptot \quad (19)$$

To only account for the nonrenewable part of the Raw Material Consumption, we multiplied the Raw Material Consumption by the Extraction share to create the Extracted Raw Material Consumption.

$$ExtractedRMC = RMC * extractionshare \quad (20)$$

### **Domestic Extraction Demand :**

We modelled the Extraction Demand as the Extracted Raw Material Consumption from which is subtracted the amount of Secondary Raw Materials produced in a certain year. This variable is an indicator of an economy's intake of natural resources, and of the strain it creates on key sustainability indicators.

We chose to insert a substitution coefficient in this equation to model the impact of the increased substitution of Primary Materials for Secondary Materials. We assume that the substitution rate is at least partly exogenous depending on political actors' might to prioritize raw material sustainability over higher input and GDP growth. The substitution coefficient is exogenously determined depending on the adopted scenario. As the literature on this issue is still nascent, we assume that the baseline substitution scenario coefficient is 0.66. We acknowledge that further research needs to be done to better assess the scale of this mechanism. In an optimistic "best-case" scenario, the maximal substitution coefficient of 1 can be applied in the model.

$$ExtractionDemand = ERMC - (SecondaryRM * substitutioncoefficient) \quad (21)$$

This extraction demand can also be defined as an aggregated ratio of Extracted Materials

use per Total Material use :

$$ExtractedMaterialsUseratio = \frac{ExtractionDemand}{ERMtot} \quad (22)$$

As an additional indicator of ecological performance, we calculated the extracted Raw materials Extraction per unit of output.

It can be defined as :

$$Extractionperoutput = \frac{DomPrimaryRMDemand}{output} \quad (23)$$

### Materials substitution “from cradle to cradle” :

The Extracted Materials Use ratio represents the evolution of the demand for newly Extracted Raw Materials. We calculated the evolution rate of this indicator to provide an indication of the potential changes in extractive sectors’ output over time.

$$Extractionevolutionratio = \frac{ExtractedMaterialsUseratio}{ExtractedMaterialsUseratiodelay} \quad (24)$$

We created an extraction substitution coefficient to replicate the evolution of the demand on the extractive sector’s output. We assume that the extraction evolution ratio has the same effect on the output of all sectors. The Extraction substitution coefficient is a delayed version of the Extractive industry evolution coefficient. We created this delay in order to avoid a ‘close loop’ modelling error, which would prevent us from running the model. We were able to model the decrease in output of the extractive industries caused by Secondary Raw Materials substitution. We multiplied Fossil Fuels and Mining and Quarrying initial technological coefficient vectors (A coeff) by the newly created Extraction substitution coefficient with the aim of replicating the evolution of the demand on the output of extractive sectors.

$$AcoeffMQ = initialAcoeffMQ * Extractionsubstitutioncoefficient \quad (25)$$

$$AcoeffFF = initialAcoeffFF * Extractionsubstitutioncoefficient \quad (26)$$

We operated in the same way for the Plastics manufacturing sub-sector. Indeed, to create the Manufacturing sector substitution coefficient, we multiplied the plastics share of the manufacturing sector by the inverse of the extractive industry evolution coefficient.

### **Eco-design scenario :**

In 2020, the French anti-waste law for a circular economy set as a target the end of single-use plastics in 2040. This Circular Economy policy is strongly influenced by the Ellen MacArthur Foundation, which sets eco-design as one of the most important Circular Economy mechanisms. According to the latter, the best way to make an economy circular is to reduce waste generation "by design". We thus aimed to model the consequences of eco-design on the output of extractive industries.

The French administration stated in 2022 that 46% of the plastics in France were consumed as packaging. To provide a first assessment of the impacts of eco-design on the economy in a Circular Economy policy scenario, we assumed that the same proportion of the French plastics output is used in packaging. We also figured that this percentage of the Plastics manufacturing sub-sector would be targeted by this new law, as packages are most of the time only used once. We assessed the possible consequences of this law in a "sobriety" scenario, in which profits and GDP are not maximized through the attainment of optimal output levels. To assess the consequences of this scenario on the output, we created an indicator representing the share of single-use plastics (SUP) among the total plastics sub-sector output. This single-use plastics share is the inverse of the durable plastics share (54%).

$$SUPshare = 1 - DPshare \quad (27)$$

It enabled us to create a share of SUP production out of the manufacturing output. It helped us model the impact of decreased production of SUP on the manufacturing technological coefficient vector. We assumed that the whole production of single-use plastics could not fully disappear and that a small proportion of single-use plastics would still be produced in 2050.

$$SUPshareM = initialSUPshareM - 0.0254 * \frac{0.46 - SUPshare}{0.46} \quad (28)$$

Once the share of single-use plastics was calculated, we created a SUP substitution

rate. The initial SUP share of the manufacturing sector equals to 0,16284.

$$SUPsubratio = 1 - \frac{SUPshareM}{initialSUPsharemanuf} \quad (29)$$

This ratio was then replicated on the technical coefficient of the Manufacturing sector.

$$AcoefM = initialAcoefM * Extractionsbstcoef * SUPsubratio \quad (30)$$

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## **Competing interests :**

The author declares no competing interests.