MORDRED:
Model Of Resource Distribution and Resilient Economic Development.

Model Documentation 1.0

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1. Previous remarks

We have extended this documentation various times to make it as comprehensive as possible. It corresponds to the model version MORDRED 1.0 and allows to understand all other model versions and extensions. The development of different parts of the model and the corresponding scenario analyses is described in several working papers and articles. One module that is not strictly needed for MORDRED to run is the so-called 'Planetary Boundaries' module because the variables of this module do not feedback into other modules. We removed this module from MORDRED 1.0 and refrain from describing it here given that its structure, equation and data are described in detail in the corresponding article.

Since this is a system dynamics model it is not meant to be run backwards and historical analyses can only be done by adapting the parameters to the empirical context prior to 2019. MORDRED is built to explore a wide range of global socio-environmental scenarios that can deviate strongly from historical tendencies. Thus, while the model is a structural representation of the recent past (it is based on data ranging from 1995 – 2020) simulation outcomes critically depend on scenario assumptions that are independent from model assumptions.

Limitations:

1. The mathematical form chosen to model the majority of the changes in fertility rates, combined with the exclusion of cultural and political factors results in a tendency of the model to underestimate population growth in simulations without population policies which also implies an underestimation of environmental pressure.
2. The focus on the materiality of economic processes leads to scenarios with conservative abstract energy efficiency improvements (overestimation of environmental pressure) and low growth in consumption and GDP (underestimation of environmental pressure), i.e. the model does not focus on abstract economic production without a material basis.
3. Capital stock and land requirements corresponding to renewable energy technologies are subject to uncertainty. Projections could be improved if better data were available.
4. Damage estimates are not comprehensive and do not take into account structural disruptions (underestimation of economic impacts) but the severity of damage could be mitigated by adaptation which is not explicitly modeled (overestimation of economic impacts).

2. Model structure

Mordred is a system dynamics model programmed in Vensim and designed to represent the broad socio-economic dynamics at a global scale and their relationship with the environment. The model can be divided into several modules, each corresponding to a specific aspect of the system it aims to represent: demographics, economy, labor, energy, land use, climate and stressors.

The demographic module computes the evolution of the global population, divided into three world regions based on income levels: the core, semi-periphery, and periphery. This evolution depends on birth and death rates, which are themselves influenced by per capita consumption levels across different regions and social classes within the model (each region is divided into three social classes: the wealthiest 20%, the poorest 30%, and the remaining 50% in between). Additionally, birth and death rates are affected by per capita public spending on healthcare and education.

The demographic module also accounts for populations living in subsistence conditions, at the margins of the global economic system. For each region, migration between subsistence and the global economy is modeled as a function of the difference in living standards between the lowest-income class and subsistence conditions.

The economic module calculates the volume of goods and services produced in the global economy and their distribution across regions and social classes based on exogenously defined per capita consumption levels for each class and region. Government consumption is computed as a fixed percentage of individual consumption, while investment is determined endogenously by the quantity of capital goods required for production. However, the actual output of goods and services may not match demand, as it is constrained by the availability of energy, labor, and land. Additionally, production is affected by adverse climate change impacts and broader environmental degradation.

In the labor module the available workforce is computed and an upper limit on production capacity is imposed. Labor productivity trends are set exogenously through scenario assumptions. The maximum feasible labor input is also reduced by environmental deterioration. Similarly, labor productivity itself may suffer negative impacts from climate change.

The energy module calculates the total energy demanded by the system. First, it determines final energy consumption and then uses this variable to compute primary energy requirements. For fossil fuels, the module also accounts for the depletion of available resources and the increasing extraction difficulty as reserves are used up.

The land use module tracks land availability and its allocation among different uses. This allocation depends on predefined priorities for each land use according to scenario assumptions, and the land intensity of production processes and other land uses. As with labor, land productivity trends are set exogenously based on scenarios, although they can also be endogenously affected by environmental degradation damages.

The climate module is adapted from the climate submodule contained in WILIAM v1.3 (Lifi et al., 2023) and calculates changes in global average temperatures that are driven by different greenhouse gas emissions which are calculated in the stressors module. The latter quantifies the impact of human activity on the environment across multiple dimensions. Apart from greenhouse gas emissions, it also tracks human water usage, extraction of various materials, and water/air pollution from different contaminants.

The following sections describes each module with its key equations.

2.1. Demography

The demographic module simulates global population dynamics by dividing the world into three regions—center, semi-periphery, and periphery—and into 20 five-year age cohorts ranging from 0–4 to 95 and older. The population is further categorized into two groups: those integrated into the global economy and those engaged in subsistence activities.

To calculate the evolution of the population integrated into the global economy, the following factors are considered: the initial population stock (divided, as previously mentioned, by age and region), the flow of births, the flow of deaths, the flow of population transitioning from the global economy to subsistence, the flow of population moving from subsistence to the global economy, and the population shifting from one age group to another.

For the 0-4 age group the population stock is described as:

$$P_{r,c04}^{we} = \int_{\mathrm{t}_0}^{t} \left(B_r^{we} - D_{r,c04}^{we} + M_{r,c04}^{sub2we} - M_{r,c04}^{we2sub} - \frac{P_{r,c04}^{we}}{5} \right) dt + P_{r,c04}^{\mathrm{we}}(t_0);$$

for intermediate population stocks as:

$$P_{r,am}^{we} = \int_{\mathrm{t}_0}^{t} \left(\frac{P_{r,ay}^{we}}{5} - D_{r,am}^{we} + M_{r,am}^{sub2we} - M_{r,am}^{we2sub} - \frac{P_{r,am}^{we}}{5} \right) dt + P_{r,am}^{\mathrm{we}}(t_0) \text{ and}$$

for the population stock aged 95 or older:

$$P_{r,c95+}^{we} = \int_{\mathrm{t}_0}^{t} \left(\frac{P_{r,c9094}^{we}}{5} - D_{r,c95+}^{we} + M_{r,c95+}^{sub2we} - M_{r,c95+}^{we2sub} \right) dt + P_{r,c95+}^{\mathrm{we}}(t_0)$$

In addition, the population is divided into three social classes. However, the division into social classes is made apart from the previously established divisions and follows a different logic. The population stock only has the division into ages and regions and evolves from these with the equations that we are exposing. The division into three classes is established a posteriori: given a certain evolution of the population as a whole, in each time step each age cohort is divided into the richest 20%, the poorest 30% and the intermediate 50%.

The different components that determine population dynamics are calculated as follows. The birth flow is calculated using the population stock of age groups within the fertile range and the birth rate of each group. Birth rates are endogenously computed based on per capita consumption, divided into three social classes, and per capita public education spending, which is calculated in the economic module. Different functional forms have been used to estimate birth rates across age groups to achieve a better statistical fit.

Additionally, when per capita consumption falls below the monetized subsistence level (a fixed amount of 729 € at constant prices of 2019), a different function is applied to calculate the birth rate. This function is the same for all age cohorts, and its parameters are adjusted so that when per capita consumption is half the subsistence level, the birth rate drops to zero. The rates represent births every five years, so they must be divided by five to obtain annual figures.

If per capita consumption > subsistence consumption:

$$Br5y^{we}_{r,c1519} = \sum_{cl}\left(\left(yf^{Br5y}_{c1519} + (y0^{Br5y}_{c1519} - yf^{Br5y}_{c1519}) \cdot e^{-\alpha^{Br5y}_{c1519}\cdot\left(Cpc^{we,s}_{r,cl}+Edpc_r\right)}\right) \cdot clsh_{cl}\right)$$

$$Br5y^{we}_{r,c2024} = \sum_{cl}\left(\left(yf^{Br5y}_{c2024} + (y0^{Br5y}_{c2024} - yf^{Br5y}_{c2024}) \cdot e^{-\alpha^{Br5y}_{c2024}\cdot\left(Cpc^{we,s}_{r,cl}+Edpc_r\right)}\right) \cdot clsh_{cl}\right)$$

$$Br5y^{we}_{r,c2529} = \sum_{cl}\left(\left(yf^{Br5y}_{c2529} + (y0^{Br5y}_{c2529} - yf^{Br5y}_{c2529}) \cdot e^{-\alpha^{Br5y}_{c2529}\cdot\left(Cpc^{we,s}_{r,cl}+Edpc_r\right)}\right) \cdot clsh_{cl}\right)$$

$$Br5y^{we}_{r,c3034} = \sum_{cl}\left(\left(\beta1^{Br5y}_{c3034} + \beta2^{Br5y}_{c3034} \cdot ln\left(Cpc^{we,s}_{r,cl} + Edpc_r\right)\right) \cdot clsh_{cl}\right)$$

$$Br5y^{we}_{r,c3539} = \sum_{cl}\left(\left(\beta1^{Br5y}_{c3539} + \beta2^{Br5y}_{c3539} \cdot \left(Cpc^{we,s}_{r,cl} + Edpc_r\right)\right) \cdot clsh_{cl}\right)$$

$$Br5y^{we}_{r,c4044} = \sum_{cl}\left(\left(yf^{Br5y}_{c4044} + (y0^{Br5y}_{c4044} - yf^{Br5y}_{c4044}) \cdot e^{-\alpha^{Br5y}_{c4044}\cdot\left(Cpc^{we,s}_{r,cl}+Edpc_r\right)}\right) \cdot clsh_{cl}\right)$$

If per capita consumption < subsistence consumption:

$$Br5y^{we}_{r,a} = max\left(0, \sum_{cl}\left(\left(\beta0^{Br5y}_{a} + \beta1^{Br5y}_{a} \cdot Cpc^{we,s}_{r,cl}\right) \cdot clsh_{cl}\right)\right)$$

For age cohorts below 15 or above 44, the birth rate is always zero, regardless of whether consumption is above or below the subsistence threshold.

To obtain annual birth rates and births, we divide by five and multiply with the population size.

$$Br^{we}_{r,a} = \frac{Br5y^{we}_{r,a}}{5}$$

$$B^{we}_{r} = \sum_{a}\left(P^{we}_{r,a} \cdot Br^{we}_{r,a}\right)$$

Deaths are calculated using the population stock of different age groups and their respective mortality rates. These mortality rates depend on per capita consumption—divided into social classes—and per capita public healthcare spending. As with birth rates, death rates represent deaths every five years, so they must be divided by five to obtain annual figures. When per capita consumption is below subsistence consumption, a different equation is used which sets the mortality rate over five years to 5 when per capita consumption is reduced to half of subsistence consumption as physical survival becomes impossible at those low levels of consumption.

If per capita consumption > subsistence consumption:

$$Dr5y_{r,a}^{we} = \sum_{cl}\left(\left(yf_a^{Dr5y} + (y0_a^{Dr5y} - yf_a^{Dr5y}) \cdot e^{-\alpha_a^{Dr5y} \cdot (Cpc_{r,cl}^{we,s} + Hpc_r)}\right) \cdot clsh_{cl}\right)$$

If per capita consumption < subsistence consumption:

$$Dr5y_{r,a}^{we} = min\left(5, \sum_{cl}\left((\beta 0_a^{Dr5y} + \beta 1_a^{Dr5y} \cdot Cpc_{r,cl}^{we,s}) \cdot clsh_{cl}\right)\right)$$

To obtain annual mortality rates and deaths we divide by five and multiply with the population size.

$$Dr_{r,a}^{we} = \frac{Dr5y_{r,a}^{we}}{5}$$

$$D_{r,a}^{we} = P_{r,a}^{we} \cdot Dr_{r,a}^{we}$$

To calculate the population flow from the global economy to the subsistence economy, first, the ratio of the population that wishes to move to the subsistence sector is calculated for each region and social class. This ratio is then used to determine the flow. The ratio is calculated based on per capita consumption[1] and always ranges between 0 and 0.1. The flow is constrained by the availability of land for subsistence agriculture, which is calculated in the land use module:

$$Mr_{r,cl}^{we2sub} = \max\left(0, min\left(0.1, ß0 - ß1 \cdot Cpc_{r,cl}^{we,s}(ts-1)\right)\right)$$

$$MaxP^{sub} = Lnd_s \cdot Int_{sub\_lnd}^{Lnd}$$

$$M_{r,a}^{we2sub} = \max\left(0; \min\left(1; \frac{MaxP^{sub} - P^{sub}}{\sum\left(Mr_{r,cl}^{we2sub} \cdot P_{r,a}^{we} \cdot clsh_{cl}\right)}\right)\right) \cdot \sum_{cl}\left(Mr_{r,cl}^{we2sub} \cdot P_{r,a}^{we} \cdot clsh_{cl}\right)$$

On the other hand, the flow from the subsistence economy to the global economy is calculated using a ratio and the stock of population living in subsistence conditions. The ratio is determined based on the per capita consumption in the lowest classes of the

[1] In this case, as in some others, the value of the variable in the previous time step is used to avoid simultaneous equations.

different regions within the global economy and the fixed per capita consumption in subsistence.

Additionally, if there is insufficient land to sustain the subsistence population, forced integration into the global economy occurs. This process is independent of the previously mentioned ratio and serves as an adjustment mechanism when subsistence conditions cannot support the existing population.

$$Mr_r^{sub2we} = max\left(0, min\left(0.1; ß1 \cdot \left(Cpc_{r,low}^{we,s} - Cpc^{sub}\right)\right)\right)$$

$$M_{r,a}^{sub2we} = max\left(Mr_r^{sub2we} \cdot P_{r,a}^{sub}\,; \left(\frac{max(0; P^{sub} - MaxP^{sub})}{P^{sub}}\right) \cdot P_{r,a}^{sub}\right)$$

The same equations used for the population integrated into the global economy are applied to the population belonging to the subsistence sector, with only two differences. The first difference is that, instead of using the per capita consumption of the corresponding region and social class plus per capita public spending on health or education to calculate birth and death rates, the per capita subsistence consumption is used—which, as previously mentioned, is a constant. The second difference lies in the equations used to calculate population changes, where migration terms have reversed signs. This is because migrations from the global economy to subsistence represent an inflow for the subsistence population but an outflow for the global economy's population stock. Conversely, migrations from subsistence back to the global economy constitute an outflow for the subsistence population and an inflow for the global economy.

2.2. Economy

The economic module follows an input-output structure where production is determined by final demand and a series of other factors (technological changes, environmental degradation damages, resource scarcity, etc.) that we will examine below.

We begin by explaining the calculation of demand components before moving on to the calculation of production and the physical constraints that can limit production.

Final demand, like production, is calculated at a global scale and divided into sectors. Furthermore, final demand consists of three components: private consumption, public consumption, and investment.

Private consumption is calculated using exogenous per capita consumption trajectories. This approach allows for the direct simulation of different inequality scenarios in a straightforward manner. However, the mechanisms leading to inequality are not explicitly represented—only the final outcome is reflected, namely that per capita consumption differs across the three classes in the three represented regions.

To implement these trajectories in the model, initial per capita consumption is specified for each class and region, along with a growth rate for each consumption level. Additionally, as will be shown later, not all consumption demand may necessarily be met, since various production constraints can arise.

$$Cpc_{r,cl}^{we,d} = \int_{t_0}^{t} \left(Cpc_{r,cl}^{we,d} \cdot Cpc\_gr_{r,cl}^{we} - Cpc\_nc_{r,cl}^{we}\right)dt + Cpc_{r,cl}^{we,d}(t_0)$$

The sectoral distribution of per capita consumption is calculated using final consumption data from EXIOBASE3 (Stadler et al., 2018) that is aggregated to approximate the three MORDRED world regions. Thus, we obtain three sectoral distributions that belong to three per capita consumption levels (cf. section 3.2.3.5). The minimum consumption level corresponds to average household consumption in those Exiobase3 countries and regions that were matched with the MORDRED region 'periphery'. The maximum consumption level corresponds to average household consumption in those Exiobase3 countries that were matched with the MORDRED region 'center'. The medium value corresponds to the average household consumption in those Exiobase3 countries and regions that were matched with the MORDRED region 'semiperiphery'.

For per capita consumption levels below the approximated average 'periphery' consumption level the sectoral distribution corresponding to this minimum level is maintained. For levels above the average 'center' consumption, the sectoral distribution corresponding to this maximum level is maintained. For intermediate levels, an interpolation is established using the three available data points.

$$Cpc_{r,cl,i}^{we,d} = Cpc_{r,cl}^{we,d} \cdot Cpc\_ssh_{r,cl,i}$$

Once per capita consumption by sector is determined, it is multiplied by the population of each class and region to obtain total consumption per class and region. By aggregating across all classes and regions, we derive global private consumption by sector.

$$C_{r,cl,i}^{d} = Cpc_{r,cl,i}^{we,d} \cdot P_r^{we} \cdot clsh_{cl}$$

$$C_{r,i}^{d} = \sum_{cl} C_{r,cl,i}^{d}$$

$$C_{i}^{d} = \sum_{r} C_{r,i}^{d}$$

Public consumption is calculated based on private consumption, maintaining a constant ratio between the two (though future scenarios could potentially be designed where this ratio evolves over time). Next, a sectoral distribution is applied for each region, remaining constant throughout the simulation period. To obtain global public consumption by sector, we aggregate the public consumption across all three regions.

$$G_r^d = C_r^d \cdot G2Cr_r$$

$$G_{r,i}^d = G_r^d \cdot G\_ssh_{r,i}$$

$$G_i^d = \sum_r G_{r,i}^d$$

Last, investment is calculated by sector and directly at the global level, aiming to maintain a specific 'capital stock to production' ratio for each sector, depending on the capital intensity of the sector. Therefore, to calculate investment, both the capital intensity and the sector's production are taken into account, as well as the depreciation rate of the sector's capital stock.

Both capital intensity and the depreciation rate have an endogenous and an exogenous component. The exogenous component either evolves according to the technological changes assumed in the scenario or remains constant. The endogenous component depends on various changes occurring in the natural environment.

In the case of capital intensity, the exogenous part evolves according to technological changes, while the endogenous part is affected by two distinct factors. In the fossil fuel production sectors (sector 3 and 8), it is affected by the increasing difficulty of extraction as recoverable fossil resources become increasingly depleted. In agriculture (contained in sector 1), it is influenced by the damages caused by climate change on this sector. While damages in agriculture have been represented as an output loss ratio, extraction difficulty has been modeled as a factor that multiplies the factors of production required to extract fossil resources.

$$Int_1^k = \frac{Int_1^{k,bd}}{(1 - X\_loss_1)}$$

$$Int_{3,8}^k = Int_{3,8}^k \cdot Edf$$

For the rest of the sectors:

$$Int_i^k = Int_i^{k,bd}$$

The global mean temperature appears in most damage functions and enters the model as the difference between the global mean temperature at time t and in 1850.

$$\Delta Temp = Temp(t) - Temp(1850)$$

The function determining extraction difficulty is described in the energy section, while the corresponding output loss in the agricultural sector is modeled as:

$$X\_loss_1 = \beta^{X\_loss} \cdot \left(\frac{\Delta Temp - 1}{3}\right)$$

For the depreciation rate, the exogenous component remains constant, while the endogenous component depends on both temperature rise and sea level rise. Ultimately, sea level rise also depends on temperature, but the damage function is modeled differently in each case. When the damage is related to temperature increases, the function is continuous and affects the depreciation rate unevenly across different sectors. In contrast, when the damage depends on sea level rise, it is applied after certain temperature thresholds are exceeded (2°C, 3°C, and 4°C), following a Gaussian function and affecting all sectors' depreciation rates equally. In other words, the damage is assumed to affect the capital stock as a whole without sectoral differentiation.

Damage caused directly by temperature:

$$\delta_i^{temp} = \beta_i^{\delta\_temp} \cdot \left(\frac{(\Delta Temp - 1)^2}{9}\right)$$

Damage caused by sea level rise:

$$\delta_i^{slr} = \beta 0^{2℃\_slr} \cdot e^{-\left(\frac{\left(t-10-t^{2℃}\right)^2}{\beta 1^{2℃\_slr}}\right)} + \beta 0^{3℃\_slr} \cdot e^{-\left(\frac{\left(t-10-t^{3℃}\right)^2}{\beta 1^{3℃\_slr}}\right)} + \beta 0^{4℃\_slr} \cdot e^{-\left(\frac{\left(t-10-t^{4℃}\right)^2}{\beta 1^{4℃\_slr}}\right)}$$

Calculation of depreciation by sector:

$$\delta_i = \delta_i^{bd} + \delta_i^{temp} + \delta_i^{slr}$$

Once capital intensity and depreciation are known, sectoral investment can be calculated using the sector's output in the previous time step, its capital stock, and an adjustment parameter that regulates the investment speed. This ensures the investment isn't concentrated in a single period.

$$Inv_i^d = max\left(0;\ \beta^{Inv} \cdot \left(X_i^s(ts-1) \cdot Int_i^k - K_i\right) + \delta_i \cdot K_i\right)$$

The capital stock simply increases with investment and decreases with depreciation.

$$K_i = \int_{t_0}^{t} (Inv_i^s - \delta_i \cdot K_i)dt + K_i(t_0)$$

The sum of investment across all sectors yields total investment. Subsequently, to calculate gross fixed capital formation as a demand component, total investment is multiplied by a vector indicating which portion of the total investment goods each sector is responsible for producing. Additionally, there is supplementary gross fixed capital formation that becomes necessary when the temperature increase exceeds 2°C above pre-industrial levels due to assumed increased hard coastal protection. This additional investment is applied for 40 years once this temperature threshold is reached.

$$GFCF_i^d = GFCF\_ssh_i \cdot \sum_i \left(Inv_i^d\right) + Extra\_GFCF^{slr}$$

The sum of the three demand components yields final demand.

$$FD_i^d = C_i^d + G_i^d + GFCF_i^d$$

To calculate the output required to meet this final demand, using the input-output table is essential. Like capital intensity, the input-output table has both an exogenous component—which evolves according to hypothesized technological changes—and an endogenous component that depends on increasing fossil resource extraction difficulty and food sector damages.

Damage to the food sector is modeled as a factor that increases intermediate consumption of this sector. If temperature < 1.4 ºC:

$$Adf^{io} = 1$$

If temperature >1.4 ºC:

$$Adf^{io} = \beta 0^{Adf\_io} + \beta 1^{Adf\_io} \cdot \Delta Temp + \beta 2^{Adf\_io} \cdot \Delta Temp^2$$

Column 1 (food sector) of the input-output matrix:

$$a_{i,1} = a_{i,1}^{bd} \cdot Adf^{io}$$

Column 3 and 8 (fossil fuels) of the input-output matrix:

$$a_{i,3,8} = a_{i,3,8}^{bd} \cdot Edf$$

For the remaining sectors contained in the input-output matrix:

$$a_{i,j} = a_{i,j}^{bd}$$

Using final demand and the input-output table, the output vector required to satisfy final demand can be calculated through the Leontief inverse.

$$\bar{X}^d = (Id - A)^{-1} \cdot \overline{FD}^d$$

In this way, it is possible to determine the land, fossil resources, and labor required for the desired overall production. This calculation is performed in the respective modules (land use, energy, and labor). Since the production function used in the model is a Leontief production function, if there is scarcity in any of these resources, production is reduced proportionally to adjust to the resource's availability. In other words, there is no substitutability between the different production factors.

To represent this, a scarcity factor ranging from 0 to 1 is calculated in each of the corresponding modules. The smallest of these scarcity factors is then multiplied by the demanded output to determine the actual output produced. By convention, we will refer to this output as the supplied output (X^s).

$$Sf = \min\,(Sf^{Lb};\ Sf^{ff};\ Sf^{Lnd})$$

$$X_i^s = X_i^d \cdot Sf$$

This same scarcity factor is also applied to final demand to calculate the actual satisfied final demand, as well as to the productive factors to determine the resources that have actually been used.

$$FD_i^s = FD_i^d \cdot Sf$$

Regarding the application of scarcity within final demand—that is, to its different components—there are two possible methods. Either the scarcity factor is applied uniformly to all components, or an allocation function is used to prioritize certain components over others.

Vensim offers several allocation-type functions, and the one used in this model is the ALLOCATE AVAILABLE function. This function distributes a limited quantity (in this case, the total final demand that can be satisfied with the available production factors) among multiple claimants (the different demand components) based on a set of parameters. These parameters determine each claimant's priority, establishing who receives resources first and at what threshold of satisfied demand the allocation shifts to the next claimant. While the mechanics of this function are complex, they are thoroughly documented in Vensim's help section.[2]

Once the demand components are calculated, the per capita consumption for each class and region can be derived by dividing the consumption allocated to the corresponding group by the population that constitutes it.

$$Cpc_{r,cl}^{we,s} = \frac{\sum_i \left(C_{r,cl,i}^{s}\right)}{\sum_a \left(P_{r,a}^{we}\right) \cdot clsh_{cl}}$$

The per capita consumption not covered, which appears in the per capita consumption demand calculation equation, is computed as the difference between the demanded per capita consumption and the supplied per capita consumption.

$$Cpc\_nc_{r,cl}^{we} = Cpc_{r,cl}^{we,d} - Cpc_{r,cl}^{we,s}$$

2.3. Labor

The function of the labor module is to account for labor demand, the available workforce, the number of hours that can contribute to production, and the production limit imposed by this factor.

Labor demand is determined by the desired sectoral production and the labor intensity of different sectors. As with capital intensity, labor intensity also has an exogenous component, which varies depending on technological advancements in the proposed scenarios, and an endogenous component, which represents the damage caused by environmental degradation on labor productivity. Additional endogenous components have been introduced in extended MORDRED versions that are not described here.

The endogenous component is divided into three types of damage: damage to the food sector, the increased difficulty of fossil fuel extraction—both of which have been mentioned previously—and the damage caused by extreme heat on labor productivity. The first is modeled in the same way as for capital intensity, i.e. as a loss of output. In fact, the same variable is used (X_loss_1). The second is calculated in the energy module, as previously mentioned.

The third damage type is unique to this module and applies to all sectors, though with different strengths for each sector. It is modeled as a reduction in sectoral labor productivity.

$$HD_i^{Lb\_prod} = \beta_i^{HB\_Lb\_prod} \cdot \left(\frac{(\Delta Temp - 1)^2}{4}\right)$$

[2] https://www.vensim.com/documentation/fn_allocations.html

Taking into account the endogenous and exogenous components, the labor intensity can be calculated.

For sector 1:

$$Int_1^{Lb} = \frac{Int_1^{Lb,bd}}{\left(1 - X\_loss_1 - HD_1^{Lb\_prod}\right)}$$

For sector 3 and 8:

$$Int_{3,8}^{Lb} = \frac{Int_{3,8}^{Lb,bd}}{\left(1 - HD_{3,8}^{Lb\_prod}\right)} \cdot Edf$$

For the remaining sectors:

$$Int_i^{Lb} = \frac{Int_i^{Lb,bd}}{\left(1 - HD_i^{Lb\_prod}\right)}$$

Based on the output demanded by sector and the respective intensities, the sectoral labor demand and the total labor demand are computed:

$$Lb_i^d = X_i^d \cdot Int_i^{Lb}$$

$$Lb^d = \sum_i Lb_i^d$$

On the other hand, the maximum labor supply is calculated based on the population integrated into the global economy aged 15 – 64, a maximum participation rate, and a maximum number of working hours per worker. Additionally, when determining the maximum labor supply, a factor representing losses in labor supply due to rising temperatures is also applied.

$$HD^{Max\_Lb} = \beta^{HB\_Max\_Lb} \cdot \left(\frac{(\Delta Temp - 1)^2}{9}\right)$$

$$Max\_Lb = \sum_{r,[1519,\ldots,6064]} \left(P_{r,[1519,\ldots,6064]}^{we}\right) \cdot Prt\_r \cdot Max\_h \cdot \left(1 - HD^{Max\_Lb}\right)$$

From the total labor demand and the maximum labor supply, the labor scarcity factor is calculated. This factor indicates whether there is a labor shortage and, if so, its extent in meeting the demanded production.

$$Sf^{Lb} = min\left(1; \frac{Max\_Lb}{Lb^d}\right)$$

2.4. Energy

The energy module calculates energy consumption, including both final energy and primary energy. It also accounts for the amount of remaining extractable non-renewable energy resources and estimates extraction difficulty, allowing the corresponding modules to adjust extraction costs i.e. required intermediate inputs, labor hours, and capital needed per extracted unit.

To calculate final energy demand, the module multiplies the unadjusted desired sectoral output by conversion factors that convert monetary units into energy units.[3] On the one hand, the energy use of goods constituting final energy is computed, and on the other, non-energy use is determined. By adding up the two variables, the final energy demand is obtained.

$$FE_{i,en}^{d,eu} = X_i^d \cdot Cf_{i,en}^{eu}$$

$$FE_{i,en}^{d,neu} = X_i^d \cdot Cf_{i,en}^{neu}$$

$$FE_{i,en}^{d} = FE_{i,en}^{d,eu} + FE_{i,en}^{d,neu}$$

Subsequently, using the final energy demand, the module calculates the primary energy demand for fossil resources (oil, natural gas, and coal).[4] Fossil fuel consumption is later used to update the remaining amount of extractable resources.

$$PE_{ff}^{d} = \sum_i \left(FE_{i,ff}^{d}\right) \cdot FE2PE_{ff}$$

The model allows for rationing the extraction of non-renewable resources by imposing an annual maximum extraction ratio relative to the total extractable resource. Using both the demand for non-renewable resources and the maximum extractable amount, the energy scarcity factor is calculated. This factor ranges from 0 to 1 and indicates the fraction of the demanded output that can actually be produced. The extractable fossil fuel resource is derived by aggregating all types of fossil fuels.

$$Max\_ff = Max\_Er \cdot Rsc\_ff$$

$$Sf^{ff} = \frac{Max\_ff}{\sum_{ff}\left(PE_{ff}^{d}\right)}$$

The model calculates the actual energy production quantities by using both the general scarcity factor (which accounts for various production limits) and the demanded energy amounts. This approach ensures that output adjustments properly reflect all constrained resources across the economic system.

$$FE_{i,en}^{s} = FE_{i,en}^{d} \cdot Sf$$

$$PE_{ff}^{s} = PE_{ff}^{d} \cdot Sf$$

[3] Only the output of the energy sectors is used, thus, the conversion factor takes the value 0 when the sectors are not energy sectors.

[4] The final energy types cover oil, natural gas, coal, electricity, biofuels and waste, and other final energy. However, only oil, natural gas and coal are computed as primary energies. In the programming structure, final energies constitute the energy vector (en). Additionally, a subset of this vector - the fossil fuels subvector (ff) - is used for calculating primary energies.

Fossil energy production is the only outflow from the stock of extractable non-renewable energy resources, so the evolution of the latter can be calculated using the former:

$$Rsc_{ff} = Rsc_{ff(t_0)} - \int_{\mathrm{t}_0}^{t} \sum_{ff} \left(PE_{ff}^{s}\right) dt$$

Finally, the stock of extractable resources is used to calculate the extraction difficulty factor, which increases the intensity of the productive factors needed to extract fossil energy.

$$Edf = max\left(1;\ \beta 0^{Edf} \cdot e^{\beta 1^{Edf} \cdot \left(1 - \frac{Rsc\_ff}{Rsc\_ff(t_0)}\right)}\right)$$

2.5. Land

The land module tracks available land for productive uses and its allocation. The available land can be divided into nine categories: built infrastructure, land used for renewable energy generation (energy land), land used for food generation by the global economy (food land), land used for food generation by the subsistence sector (subsistence land), forest that is used by productive sectors (forest land), primary forest with no productive use, secondary forest with no productive use, other productively used land (other land), and shrubland (this category describes land that is not a forest and not productively used).

Land demand depends on different variables and varying usage intensities. Firstly, for infrastructure land, consumption serves as a proxy variable along with land use intensity for infrastructure. Secondly, for land uses related to production, an intensity matrix is employed that links sectoral production with the land required to meet the demanded output. A comprehensive matrix including all sectors is used for programming convenience, though most cases show zero intensity. For instance, only the food sector requires food land, and only energy sectors demand energy land.

$$Lnd_{inf}^{d} = \sum_{r,cl,i} \left(C_{r,cl,i}^{d}\right) \cdot Int_{inf}^{Lnd}$$

$$Lnd_{prod\_Lnd}^{d} = \sum_{i} \left(X_i^d \cdot Int_{i,prod\_Lnd}^{Lnd}\right)$$

In the third place, the demand for subsistence land depends on the number of people living in subsistence, plus the inflow of those seeking to join the subsistence sector.

$$Lnd_{sub}^{d} = \sum_{r,a} \left(P_{r,a}^{sub} + M_{r,a}^{we2sub}\right) \cdot Int_{sub\_lnd}^{Lnd}$$

The usage intensities for productive land and subsistence land change exogenously according to different scenarios. Furthermore, for food land—both for the global economy and subsistence—there is also an exogenous component dependent on climate change. For the global economy, the damage has been modeled in the same way as for capital and labor, as an output loss. For subsistence, it has been modeled as an additional intensity that sums to the pre-damage intensity.

$$Ext\_Int_{sub\_lnd}^{Lnd} = \beta^{Ext\_Int\_Lnd\_sub} \cdot (\Delta Temp - 1)$$

$$Int_{sub\_lnd}^{Lnd} = Int_{sub\_lnd}^{Lnd,bd} + Ext\_Int_{sub\_lnd}^{Lnd}$$

$$Int_{foodland\_we}^{Lnd} = \frac{Int_{foodland\_we}^{Lnd,bd}}{(1 - X\_loss_1)}$$

The "demand" for primary forest always equals the amount of primary forest from the previous period, meaning it only disappears if subsequent land allocation assigns its space to other uses. A similar approach applies to secondary forest—its "demand" equals the previous period's secondary forest plus the productive-use forest, ensuring that abandoned productive forest is converted into secondary forest. Finally, the "demand" for shrubland equals all available land. This programming treats shrubland as residual land; during allocation, its "demand" is only fulfilled after other land demands are satisfied. However, if no other land types were demanded, all available land would turn into shrubland.

$$Lnd_{pfrst}^{d} = Lnd_{pfrst}^{s}(ts - 1)$$

$$Lnd_{sfrst}^{d} = Lnd_{sfrst}^{s}(ts - 1) + Lnd_{prod\_frst}^{s}(ts - 1)$$

$$Lnd_{shrub}^{d} = Dsp\_Lnd$$

The quantity of available land may decrease during the simulation due to environmental impacts that result in land losses.

Additionally, depending on the scenarios, there is an option to protect either a portion of primary forest or land used in the subsistence sector. If this option is activated, it comes at the expense of reducing the total land available for allocation.

$$Lnd\_loss = \beta^{Lnd\_loss} \cdot \left(\frac{(\Delta Temp - 1)^2}{9}\right)$$

$$Foodland\_loss = \beta^{Foodland\_loss} \cdot \left(\frac{(\Delta Temp - 1)^2}{9}\right)$$

$$Dsp\_Lnd = Dsp\_Lnd^{bd} - Lnd\_loss - Foodland\_loss - Prt\_Lnd_{sub\_lnd} - Prt\_Lnd_{pfrst}$$

The land allocation process begins after all land demands have been calculated. The system employs the ALLOCATE AVAILABLE function to determine land distribution, using the same methodology applied for allocating scarce production capacities among different demand components.

Following land allocation, the model calculates the land scarcity factor based on productive sectors' land demand versus available land supply. This factor reflects the tension between resource requirements and availability.

$$Sf^{Lnd} = \min\left(\frac{Lnd^{s}_{en\_lnd}}{Lnd^{d}_{en\_lnd}};\frac{Lnd^{s}_{foodland\_we}}{Lnd^{d}_{foodland\_we}};\frac{Lnd^{s}_{prod\_frst}}{Lnd^{d}_{prod\_frst}};\frac{Lnd^{s}_{oth\_lnd}}{Lnd^{d}_{oth\_lnd}}\right)$$

2.6. Stressors

The stressors module calculates human-generated emissions of various pollutants. Some impact other model components, while others serve solely as indicators.

The module tracks multiple stressor variables. The first group of variables is composed of different greenhouse gases: CO2, CH4, N2O, SF6, HFCs, and PFCs.

Emissions are derived from economic output and emission intensity factors. These intensity factors evolve exogenously based on technological change assumptions in each scenario. For the food sector, emission intensities are impacted by climate change damage effects.

Intensity in sector 1:

$$Int^{em}_{1,ghg} = \frac{Int^{em,bd}_{1,ghg}}{(1 - X\_loss_1)}$$

Intensity in the rest of sectors:

$$Int^{em}_{i,ghg} = Int^{em,bd}_{i,ghg}$$

Emissions:

$$Em_{ghg} = \sum_i \left(X^s_i \cdot Int^{em}_{i,ghg}\right)$$

The exception is CO2, where a distinction is made between emissions from fossil fuel combustion (calculated based on the primary fossil energy consumption), emissions from land-use changes, and emissions from non-combustion production processes. This differentiation allows for a more precise tracking of CO2 emission sources and their respective drivers within the model.

$$Em^{comb}_{CO2} = \sum_i \left(PE^s_{i,ff}\right) \cdot Int^{em}_{ff,CO2}$$

$$Em^{land}_{CO2} = Frst\_lnd\_rdct \cdot Int^{em,land}$$

$$Em^{other}_{CO2} = \sum_i \left(X^s_i \cdot Int^{em,other}_{i,CO2}\right)$$

$$Em_{CO2} = Em^{comb}_{CO2} + Em^{land}_{CO2} + Em^{other}_{CO2}$$

The second group consists of variables related to water consumption. A distinction is made between green water consumption and blue water consumption. Green water consumption is linked to food production and is therefore calculated using the sector's output along with a green water intensity factor. This intensity factor contains both an exogenous component and an endogenous component that reflects climate change impacts on the agricultural sector.

$$Int^{WC,green\_w} = \frac{Int^{\,WC,green\_w,bd}}{(1 - X\_loss_1)}$$

$$WC^{green} = X_1^s \cdot Int^{\,WC,green\_w}$$

Blue water consumption is divided into industrial water consumption, industrial water withdrawal, household water consumption, and household water withdrawal. The first two variables are calculated based on sectoral output and their respective blue water intensity factors. These intensity factors vary exogenously according to technological change assumptions. For the food sector, in addition to exogenous variations, they are also affected by climate change impacts.

Intensity for sector 1:

$$Int_1^{WC,blue\_w,prod} = \frac{Int_1^{WC,blue\_w,prod,bd}}{(1 - X\_loss_1)}$$

$$Int_1^{WW,blue\_w,prod} = \frac{Int_1^{WW,blue\_w,prod,bd}}{(1 - X\_loss_1)}$$

Intensity for the rest of the sectors:

$$Int_i^{WC,blue\_w,prod} = Int_i^{WC,blue\_w,prod,bd}$$

$$Int_i^{WW,blue\_w,prod} = Int_i^{WW,blue\_w,prod,bd}$$

Blue water consumption and withdrawal in production:

$$WC^{blue\_w,prod} = \sum_i \left(X_i^s \cdot Int_i^{WC,blue\_w,prod}\right)$$

$$WW^{blue\_w,prod} = \sum_i \left(X_i^s \cdot Int_i^{WW,blue\_w,prod}\right)$$

The second two are calculated from household consumption. The intensity of this water consumption varies exogenously.

$$WC^{blue\_w,hh} = \sum_i \left(C_{r,cl,i}^s\right) \cdot Int^{WC,blue\_w,hh}$$

$$WW^{blue\_w,hh} = \sum_i \left(C_{r,cl,i}^s\right) \cdot Int^{WW,blue\_w,hh}$$

The third group of stressors consists of extraction flows for 19 material types. The extraction is divided into used material extraction and unused material extraction. In both cases, the calculation is based on sectoral output and a specific extraction intensity for each material. These extraction intensities remain constant throughout the simulation.

$$Mat_{mat}^{used} = \sum_i \left(X_i^s \cdot Int_{i,mat}^{mat\_used}\right)$$

$$Mat_{mat}^{unused} = \sum_i \left(X_i^s \cdot Int_{i,mat}^{mat\_unused}\right)$$

$$Mat_{mat} = Mat_{mat}^{used} + Mat_{mat}^{unused}$$

Fourth, the model addresses phosphorus and nitrogen pollution. The pollution flow is calculated based on sectoral output[5] and intensity factors that evolve exogenously, with an additional endogenous component applied specifically to the food sector. Within the model, phosphorus and nitrogen pollution is categorized into three types: water pollution by nitrogen, water pollution by phosphorus, and soil pollution by phosphorus.

Intensity for sector 1:

$$Int_{1,P\&N} = \frac{Int_{1,P\&N}^{bd}}{(1 - X\_loss_1)}$$

Intensity for the rest of the sectors:

$$Int_{i,P\&N} = Int_{i,P\&N}^{bd}$$

Nitrogen and phosphorus contamination:

$$P\&N\_Poll_{P\&N} = \sum_i \left(X_i^s \cdot Int_{i,P\&N}\right)$$

Fifth, the model calculates air pollution. This is computed using sectoral output and exogenously evolving intensity factors, with an additional endogenous component for the food sector. The model classifies air pollution into three categories: NH3, PM2.5, and PM10.

Intensity for sector 1:

$$Int_{1,air\_poll} = \frac{Int_{1,air\_poll}^{bd}}{(1 - X\_loss_1)}$$

Intensity for all other sectors:

$$Int_{i,air\_poll} = Int_{i,air\_poll}^{bd}$$

Air pollution:

$$Air\_Poll_{air\_poll} = \sum_i \left(X_i^s \cdot Int_{i,air\_poll}\right)$$

[5] In practice, only sectors 1, 24, and 25 are used to calculate the generation of these pollutants. However, as in previous cases, the programming implementation calculates it across all sectors for convenience, with generation intensities set to 0 for the remaining sectors.

Finally, the consumption of industrial roundwood is calculated from the output of sector 2 and a conversion factor.

$$IRW = X_2^s \cdot Cf^{IRW}$$

3. Model data

3.1. Demography

3.1.1. Initial population

The raw data comes from the United Nations, Department of Economic and Social Affairs, Population Division (UN DESA, 2019c). The data for 2020 were taken because there are no data for 2019.

The data was matched to all the countries aggregated in Exiobase3.

There are 21 age categories in the raw data (from 0-4 years, 5-9 years, 10-14 years, …, 95-99 years, 100+years) whereas MORDRED has 20 age groups (from 0-4 years, 5-9, 10-14, etc., with the last category being people aged 95+). Thus, the last two age groups were aggregated. For every age group, the population of the respective countries was aggregated into the three MORDRED world regions (cf section 3.1.4).

Initial population in the formal and informal economy

The total initial population in the three world regions and in the 20 age groups were further sub-divided into population sustained by and working for the global economy, and population sustained by and working in a subsistence economy.

We estimate that in 2019 at least 800 million people lived not fully integrated or even apart from the global economy in different forms of subsistence regimes, focusing on the poorest population groups among the 380 to 510 million smallholder farms and the high intersection between subsistence farming and extreme poverty (Lowder et al., 2025; Samberg et al., 2016). For simplicity, we assume that (1) the share of people living in subsistence regimes does not vary by age group or gender, and (2) the vast majority of individuals living at the margins of the global economy reside in the periphery, with the remainder living in the semi-periphery. Due to the lack of precise data, we operationalized these qualitative assumptions by allocating 85% of the population in subsistence regimes to the periphery and 15% to the semi-periphery at the start of the simulations in 2019.

As mentioned in section 2.2, this 'subsistence class' is characterized by high but stable death and birth rates and very low but stable per capita consumption, which is only partially monetized. Fertility and mortality rates for the different age groups for the subsistence class are computed using the monetized per capita consumption of the subsistence class which we approximate by using the World Bank's extreme poverty line (World Bank, 2025) (2.15$ in 2017-PPP, converted to 1.997 (2019-)€ per day) which gives a per capita consumption of 729 € per year for 2019.

The remaining population in the center, semiperiphery and periphery lives within the formal economy and is matched to one of three classes within each MORDRED region.

3.1.2. Mortality and fertility parameters

The raw data for the calculation of birth and death parameters comes from UN DESA (2019b, 2019c, 2019a) and from Exiobase3 final demand data for 1995, 2000, 2005, 2010, 2015 and 2020 (Stadler et al., 2021).

The Exiobase3 data was converted to 2019-€ using the ECB deflator. All Exiobase sectors were aggregated into one single sector, apart from the 'Education (80)'and the 'Health and social work (85)' sector, which were matched to sector no. 22 (education) and sector no. 23 sectors, respectively (Table 3).

The original regional disaggregation of Exiobase with 44 countries and 5 (rest of the) world regions was preserved (cf.section 3.1.4).

The average government final demand for the education and health sector for all 49 Exiobase regions were calculated for the time periods 1995-2000, 2000-2005, 2005-2010, 2010-2015 and 2015-2020.

The average population size for every Exiobase region for the time periods 1995-2000, 2000-2005, 2005-2010, 2010-2015 and 2015-2020 was calculated by aggregating the 21 age groups and by aggregating country data into the 5 Exiobase world regions (WA, WL, WF, WE, WM).

By dividing government final demand by population size a series of different average per capita government expenditures for health and education were generated.

The average household consumption per capita for the time periods 1995-2000, 2000-2005, 2005-2010, 2010-2015 and 2015-2020 for the 49 Exiobase regions was calculated by 1) adding the Exiobase final demand categories of 'households' and 'non-profit organizations serving households' and summing over all sectors; 2) dividing the resulting final demand by the total population in the respective regions and time periods.

Mortality and fertility rates over 5 years were derived by:

1.) calculating total deaths and births for every country over five years for the respective periods (1995-2000, 2000-2005, 2005-2010, 2010-2015 and 2015-2020) and respective age groups. This requires taking into account that the original data give births per 1000 women and per year.

2.) aggregating the death and births of the respective countries into deaths and births for the five Exiobase world regions (the rest of the countries can be incorporated without further changes).

3.) dividing the deaths and births by the total population in the respective age groups and regions. This gives mortality and fertility rates for every age group and for every Exiobase region (i.e. 44 countries and 5 world regions) which, multiplied by the respective population, indicate the number of deaths in the different age groups and the number of births coming from the different age groups that occur during 5 years.

With these results, we constructed a database containing 245 observations which we used to conduct a regression analysis. Each observation has 29 dimensions: the consumption of households per capita; the education expenses of governments per capita; the health expenses of governments per capita; the mortality rate for people aged 0-4; 5-9; 15-19; 20-24; 25-29; 30-34; 35-39; 40-44; 45-49; 50-54; 55-59; 60-64; 65-69; 70-74; 75-79; 80-84; 85-89; 90-94; 95+; the fertility rate for people aged 15-19; 20-24; 25-29; 30-34; 35-39; 40-44; 45-49.

We assume that mortality and fertility rates are fully determined by a range of variables, the most important of which being consumption per capita as well as health and education expenses. Thus, we do not assume the abstract variable 'time' to influence mortality and fertility rates and consequently do not factor 'time' into the regression analysis. This has a methodological-logical reason: Introducing a time-effect into the estimation of mortality and fertility rates can lead to serious distortions in a simulation-based dynamic model. For example, if time is found to decrease mortality, even in a context of extreme poverty and environmental impacts mortality would continue to decrease over time, which constitutes a contradiction. Apart from that, we use data spanning a period of only 25 years which we assume to be short enough to avoid 'correcting' for time.

The regression analysis links per capita consumption and government expenses for health and education to mortality and fertility rate of the different age groups.

In total, we construct 25 regression models covering all relevant age groups. Most of the age groups exhibit exponentially decaying, asymptotic patterns (Figure 1).

For all mortality rates, we used self-starting Nonlinear Least Squares Asymptotic Regression Models (cf. section the equation for $Dr5y_{r,a}^{we}$ in section 2.1) that were calculated in R via the NLS/SSasymp commands from the stats package because they provided better fits than logistic regressions. We made no further adjustments to the calculated automated best guess.

While the dependent variable is the mortality rate in the respective age group the independent variable is the sum of the per capita consumption and the per capita government expense for health.

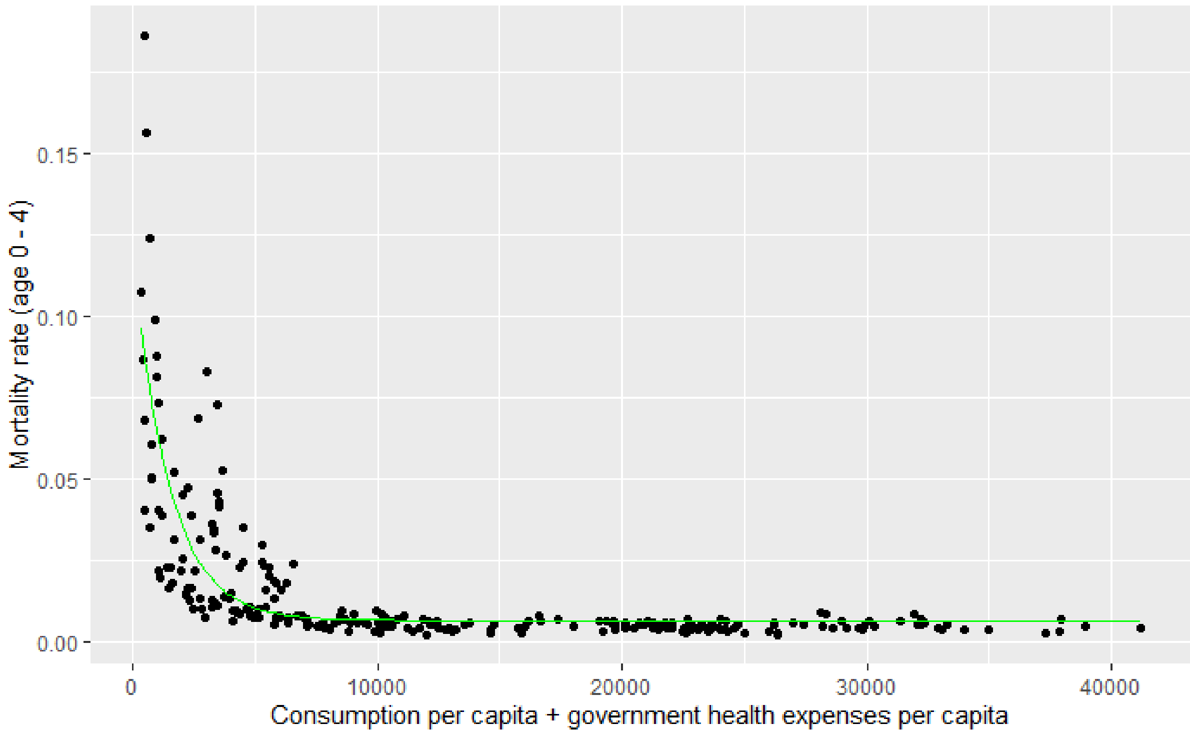

Figure 1: Mortality rates decrease with increasing consumption and health expenses. The green line is calculated from the parameters obtained from the NLS Asymptotic Regression Model.

For the birth rates the independent variable is the sum of the per capita consumption and the per capita government expense for education. For four age groups (15-19, 20-24, 25-29 and 40-44) we used the same function as for mortality rates whereas the birth rate of the age group 30-34 is best approximated through a logarithmic regression and the fertility rate of the age group 35-39 is best approximated through a linear regression.

To prevent illogical model outcomes in simulations where variables might take extreme values, in the model an upper bound of 1 for the mortality rate and a lower bound of 0 for the birth rate is applied. Since the model for the fertility of the age group 35-39 is a linear model, an upper bound of 0.25 is introduced which only begins to apply in the case of per capita consumption levels far above current levels (Figure 2).

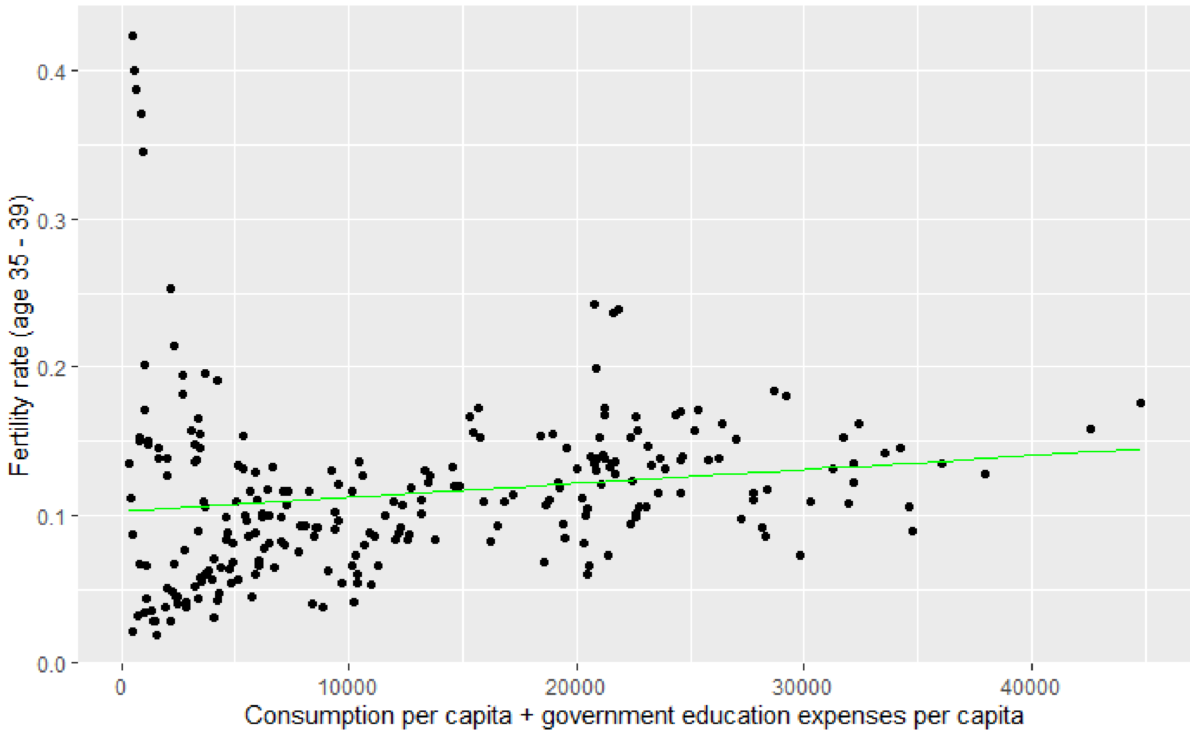

Figure 2: Fertility rates for the age group 35-39 increase with consumption and education expenses.

Fertility and mortality in the case of extremely low consumption values

The data that provide the basis for the regression analysis give mortality and fertility rates that are high but not excessively high for very low per capita consumption, which is due to the fact that these low per capita consumption values belong to the subsistence class and are based on the monetized consumption, thus, leaving out one part of the actual consumption. Thus, the regression functions are not suitable to describe death and birth rates at extremely low consumption of the classes that are sustained by the world economy because they do not have any other non-monetized consumption.

Thus, once the consumption per capita drops below the monetized subsistence level for a class that is sustained by the global economy linear functions that depend on per capita consumption ensure that mortality rates converge to 1 and birth rates to 0.

3.1.3. Migration between subsistence and world economy

The parameters regulating migration between the subsistence and the global economy reflect qualitative reasoning rather than any specific quantitative data sources and can be changes in different scenarios.

3.1.4. Aggregation of countries and EXIOBASE regions into MORDRED regions

The MORDRED regions *center*, *semiperiphery* and *periphery* are operationalized through the World Bank's income-based classification of countries for the year 2019 (World Bank, 2024d). For countries without a world bank classification, their GDP per capita was compared to countries with a world bank classification and comparable income per capita levels. In these cases, the value in the 'Worldbank classification' column of Table 1 is marked in *Italics*. Countries without UN population data are marked in *Italics* as well. Most of these countries have a very small population that is not significant at the global level, thus, their populations are set to zero.

Country number	Country Name	Worldbank classification	Exiobase3 Regions	MORDRED regions
1	Austria	H	AT	Center
2	Australia	H	AU	Center
3	Belgium	H	BE	Center
4	Bulgaria	UM	BG	Semiperiphery
5	Brazil	UM	BR	Semiperiphery
6	Canada	H	CA	Center
7	Switzerland	H	CH	Center
8	China	UM	CN	Semiperiphery
9	Cyprus	H	CY	Center
10	Czech Republic	H	CZ	Center
11	Germany	H	DE	Center
12	Denmark	H	DK	Center
13	Estonia	H	EE	Center
14	Spain	H	ES	Center
15	Finland	H	FI	Center
16	France	H	FR	Center
17	United Kingdom	H	GB	Center
18	Greece	H	GR	Center
19	Croatia	H	HR	Center
20	Hungary	H	HU	Center
21	Indonesia	UM	ID	Semiperiphery
22	Ireland	H	IE	Center
23	India	LM	IN	Periphery
24	Italy	H	IT	Center
25	Japan	H	JP	Center
26	South Korea	H	KR	Center
27	Lithuania	H	LT	Center
28	Luxembourg	H	LU	Center
29	Latvia	H	LV	Center
30	Malta	H	MT	Center
31	Mexico	UM	MX	Semiperiphery
32	Netherlands	H	NL	Center
33	Norway	H	NO	Center
34	Poland	H	PL	Center
35	Portugal	H	PT	Center
36	Romania	H	RO	Center

37	Russian Federation	UM	RU	Semiperiphery
38	Sweden	H	SE	Center
39	Slovenia	H	SI	Center
40	Slovak Republic	H	SK	Center
41	Türkiye	UM	TR	Semiperiphery
42	Taiwan, China	H	TW	Center
43	United States	H	US	Center
44	Afghanistan	L	WA	Periphery
45	Armenia	UM	WA	Semiperiphery
46	Azerbaijan	UM	WA	Semiperiphery
47	Bangladesh	LM	WA	Periphery
48	Bhutan	LM	WA	Periphery
49	Brunei Darussalam	H	WA	Center
50	Cambodia	LM	WA	Periphery
51	Hong Kong SAR, China	H	WA	Center
52	Macao SAR, China	H	WA	Center
53	Korea, Dem. Rep.	L	WA	Periphery
54	Fiji	UM	WA	Semiperiphery
55	French Polynesia	H	WA	Center
56	Georgia	UM	WA	Semiperiphery
57	Guam	H	WA	Center
58	Kazakhstan	UM	WA	Semiperiphery
59	Kiribati	LM	WA	Periphery
60	Kyrgyz Republic	LM	WA	Periphery
61	Lao PDR	LM	WA	Periphery
62	Malaysia	UM	WA	Semiperiphery
63	Maldives	UM	WA	Semiperiphery
64	Micronesia, Fed. Sts.	LM	WA	Periphery
65	Mongolia	LM	WA	Periphery
66	Myanmar	LM	WA	Periphery
67	Nepal	LM	WA	Periphery
68	New Caledonia	H	WA	Center
69	New Zealand	H	WA	Center
70	Pakistan	LM	WA	Periphery
71	Papua New Guinea	LM	WA	Periphery
72	Philippines	LM	WA	Periphery
73	Samoa	UM	WA	Semiperiphery
74	Singapore	H	WA	Center
75	Solomon Islands	LM	WA	Periphery
76	Sri Lanka	LM	WA	Periphery
77	Tajikistan	L	WA	Periphery
78	Thailand	UM	WA	Semiperiphery
79	Timor-Leste	LM	WA	Periphery
80	Tonga	UM	WA	Semiperiphery
81	Turkmenistan	UM	WA	Semiperiphery
82	Uzbekistan	LM	WA	Periphery
83	Vanuatu	LM	WA	Periphery
84	Vietnam	LM	WA	Periphery
85	*United States Minor Outlying Islands*	*L*	WA	Periphery

86	*American Samoa*	UM	WA	Semiperiphery
87	*Antarctica*	*L*	WA	Periphery
88	*Bouvet Island*	*L*	WA	Periphery
89	*British Indian Ocean Territory*	*L*	WA	Periphery
90	*Wallis & Futuna*	*L*	WA	Periphery
91	*Christmas Island*	*L*	WA	Periphery
92	*Cocos Island*	*L*	WA	Periphery
93	*Cook Islands*	*L*	WA	Periphery
94	*Heard Island and McDonald Islands*	*L*	WA	Periphery
95	*Marshall Islands*	UM	WA	Semiperiphery
96	*Niue*	*L*	WA	Periphery
97	*Norfolk Island*	*L*	WA	Periphery
98	*Northern Mariana Islands*	H	WA	Center
99	*Nauru*	H	WA	Center
100	*Palau*	H	WA	Center
101	*South Georgia and the South Sandwich Islands*	*L*	WA	Periphery
102	*Pitcairn*	*L*	WA	Periphery
103	*Tokelau*	*L*	WA	Periphery
104	*Tuvalu*	UM	WA	Semiperiphery
105	Albania	UM	WE	Semiperiphery
106	Belarus	UM	WE	Semiperiphery
107	Bosnia and Herzegovina	UM	WE	Semiperiphery
108	Channel Islands (Gurenesey and Jersey)	H	WE	Center
109	Iceland	H	WE	Center
110	Montenegro	UM	WE	Semiperiphery
111	North Macedonia	UM	WE	Semiperiphery
112	Moldova	LM	WE	Periphery
113	Serbia	UM	WE	Semiperiphery
114	Ukraine	LM	WE	Periphery
115	*Aland Islands*	*H*	WE	Center
116	*Andorra*	H	WE	Center
117	*Vatican*	H	WE	Center
118	*Faeroe Islands*	H	WE	Center
119	*Gibraltar*	H	WE	Center
120	*Monaco*	H	WE	Center
121	*Isle of Man*	H	WE	Center
122	*Kosovo*	UM	WE	Semiperiphery
123	*Liechtenstein*	H	WE	Center
124	*San Marino*	H	WE	Center
125	*Svalbard*	*H*	WE	Center
126	Algeria	LM	WF	Periphery
127	Angola	LM	WF	Periphery
128	Benin	LM	WF	Periphery
129	Botswana	UM	WF	Semiperiphery
130	Burkina Faso	L	WF	Periphery
131	Burundi	L	WF	Periphery
132	Cabo Verde	LM	WF	Periphery
133	Cameroon	LM	WF	Periphery

134	Central African Republic	L	WF	Periphery
135	Chad	L	WF	Periphery
136	Comoros	LM	WF	Periphery
137	Congo, Rep.	LM	WF	Periphery
138	Côte d'Ivoire	LM	WF	Periphery
139	Congo, Dem. Rep.	L	WF	Periphery
140	Djibouti	LM	WF	Periphery
141	Equatorial Guinea	UM	WF	Semiperiphery
142	Eritrea	L	WF	Periphery
143	Eswatini	LM	WF	Periphery
144	Ethiopia	L	WF	Periphery
145	Gabon	UM	WF	Semiperiphery
146	Gambia, The	L	WF	Periphery
147	Ghana	LM	WF	Periphery
148	Guinea	L	WF	Periphery
149	Guinea-Bissau	L	WF	Periphery
150	Kenya	LM	WF	Periphery
151	Lesotho	LM	WF	Periphery
152	Liberia	L	WF	Periphery
153	Libya	UM	WF	Semiperiphery
154	Madagascar	L	WF	Periphery
155	Malawi	L	WF	Periphery
156	Mali	L	WF	Periphery
157	Mauritania	LM	WF	Periphery
158	Mauritius	H	WF	Center
159	Mayotte	*LM*	WF	Periphery
160	Morocco	LM	WF	Periphery
161	Mozambique	L	WF	Periphery
162	Namibia	UM	WF	Semiperiphery
163	Niger	L	WF	Periphery
164	Nigeria	LM	WF	Periphery
165	Rwanda	L	WF	Periphery
166	Reunion	H	WF	Center
167	São Tomé and Príncipe	LM	WF	Periphery
168	Senegal	LM	WF	Periphery
169	Seychelles	H	WF	Center
170	Sierra Leone	L	WF	Periphery
171	Somalia	L	WF	Periphery
172	South Sudan	L	WF	Periphery
173	Sudan	L	WF	Periphery
174	Togo	L	WF	Periphery
175	Tunisia	LM	WF	Periphery
176	Uganda	L	WF	Periphery
177	Tanzania	LM	WF	Periphery
178	Western Sahara	*LM*	WF	Periphery
179	Zambia	LM	WF	Periphery
180	Zimbabwe	LM	WF	Periphery
181	*French Southern Territories*	*L*	WF	Periphery
182	*Saint Helena*	*LM*	WF	Periphery

183	Antigua and Barbuda	H	WL	Center
184	Argentina	UM	WL	Semiperiphery
185	Aruba	H	WL	Center
186	Bahamas, The	H	WL	Center
187	Barbados	H	WL	Center
188	Belize	UM	WL	Semiperiphery
189	Bolivia	LM	WL	Periphery
190	Chile	H	WL	Center
191	Colombia	UM	WL	Semiperiphery
192	Costa Rica	UM	WL	Semiperiphery
193	Cuba	UM	WL	Semiperiphery
194	Curaçao	H	WL	Center
195	Dominican Republic	UM	WL	Semiperiphery
196	Ecuador	UM	WL	Semiperiphery
197	El Salvador	LM	WL	Periphery
198	French Guiana	UM	WL	Semiperiphery
199	Grenada	UM	WL	Semiperiphery
200	Guadeloupe	H	WL	Center
201	Guatemala	UM	WL	Semiperiphery
202	Guyana	UM	WL	Semiperiphery
203	Haiti	L	WL	Periphery
204	Honduras	LM	WL	Periphery
205	Jamaica	UM	WL	Semiperiphery
206	Martinique	*H*	WL	Center
207	Nicaragua	LM	WL	Periphery
208	Panama	H	WL	Center
209	Paraguay	UM	WL	Semiperiphery
210	Peru	UM	WL	Semiperiphery
211	Puerto Rico	H	WL	Center
212	St. Lucia	UM	WL	Semiperiphery
213	St. Vincent and the Grenadines	UM	WL	Semiperiphery
214	Suriname	UM	WL	Semiperiphery
215	Trinidad and Tobago	H	WL	Center
216	Virgin Islands (U.S.)	H	WL	Center
217	Uruguay	H	WL	Center
218	Venezuela, RB	UM	WL	Semiperiphery
219	*Bermuda*	H	WL	Center
220	*Bonaire, Saint Eustatius and Saba*	*H*	WL	Center
221	*British Virgin Islands*	H	WL	Center
222	*Cayman Islands*	H	WL	Center
224	*Falkland Islands*	H	WL	Center
225	*Greenland*	H	WL	Center
226	*Dominica*	UM	WL	Semiperiphery
227	*St. Kitts and Nevis*	H	WL	Center
228	*Montserrat*	*UM*	WL	Semiperiphery
229	*Sint Maarten (Dutch part)*	H	WL	Center
230	*Saint Barthelemy*	*H*	WL	Center
231	*Saint Pierre and Miquelon*	*H*	WL	Center
232	*St. Martin (French part)*	H	WL	Center

233	*Turks and Caicos Islands*	H	WL	Center
234	*Anguilla*	*H*	WL	Center
235	Bahrain	H	WM	Center
236	Egypt, Arab Rep.	LM	WM	Periphery
237	Iran, Islamic Rep.	UM	WM	Semiperiphery
238	Iraq	UM	WM	Semiperiphery
239	Israel	H	WM	Center
240	Jordan	UM	WM	Semiperiphery
241	Kuwait	H	WM	Center
242	Lebanon	UM	WM	Semiperiphery
243	Oman	H	WM	Center
244	Qatar	H	WM	Center
245	Saudi Arabia	H	WM	Center
246	West Bank and Gaza	LM	WM	Periphery
247	Syrian Arab Republic	L	WM	Periphery
248	United Arab Emirates	H	WM	Center
249	Yemen, Rep.	L	WM	Periphery
250	South Africa	UM	ZA	Semiperiphery

Table 1: Aggregation of population data into MORDRED regions. L = low-income, LM = lower-middle income; UM = upper-middle income, H = High income.

Economy

3.1.5. Production

The original data source for the economic module in MORDRED is Exiobase3 version 3.8.2 (Stadler et al., 2018, 2021) for the year 2019 in product by product format, downloadable as *IOT_2019_pxp.zip*. Includes data for the A matrix (A), sectoral output (x), final demand (Y) and inter-sectoral flows (Z) in million 2019-€. The data was processed with the pymrio python package (Stadler, 2021).

3.1.5.1. Data aggregation

The 200 sectoral categories in the Exiobase3 pxp data for 2019 were aggregated into 25 sectors while the 44 countries and 5 world regions in Exiobase were aggregated into one world region.

Original sectors aggregated to MORDRED sectors

Table 2 shows which Exiobase3 sectors were matched to which MORDRED sectors.

Exiobase3 Sector Number	Exiobase 3 Sector Name	Exiobase 3 Sector Abbreviation	MORDRED Sector Number
1	Paddy rice	AUT_Paddy rice	1
2	Wheat	AUT_Wheat	1
3	Cereal grains nec	AUT_Cereal grains nec	1
4	Vegetables, fruit, nuts	AUT_Vegetables, fruit, nuts	1
5	Oil seeds	AUT_Oil seeds	1
6	Sugar cane, sugar beet	AUT_Sugar cane, sugar beet	1
7	Plant-based fibers	AUT_Plant-based fibers	1
8	Crops nec	AUT_Crops nec	1
9	Cattle	AUT_Cattle	1
10	Pigs	AUT_Pigs	1
11	Poultry	AUT_Poultry	1
12	Meat animals nec	AUT_Meat animals nec	1
13	Animal products nec	AUT_Animal products nec	1
14	Raw milk	AUT_Raw milk	1
15	Wool, silk-worm cocoons	AUT_Wool, silk-worm cocoons	2
16	Manure (conventional treatment)	AUT_Manure (conventional treatment)	1
17	Manure (biogas treatment)	AUT_Manure (biogas treatment)	1
18	Products of forestry, logging and related services (02)	AUT_Products of forestry, logging and related services (02)	2
19	Fish and other fishing products; services incidental of fishing (05)	AUT_Fish and other fishing products; services incidental of fishing (05)	1
20	Anthracite	AUT_Anthracite	3
21	Coking Coal	AUT_Coking Coal	3

22	Other Bituminous Coal	AUT_Other Bituminous Coal	3
23	Sub-Bituminous Coal	AUT_Sub-Bituminous Coal	3
24	Patent Fuel	AUT_Patent Fuel	3
25	Lignite/Brown Coal	AUT_Lignite/Brown Coal	3
26	BKB/Peat Briquettes	AUT_BKB/Peat Briquettes	3
27	Peat	AUT_Peat	3
28	Crude petroleum and services related to crude oil extraction, excluding surveying	AUT_Crude petroleum and services related to crude oil extraction, excluding surveying	3
29	Natural gas and services related to natural gas extraction, excluding surveying	AUT_Natural gas and services related to natural gas extraction, excluding surveying	3
30	Natural Gas Liquids	AUT_Natural Gas Liquids	3
31	Other Hydrocarbons	AUT_Other Hydrocarbons	3
32	Uranium and thorium ores (12)	AUT_Uranium and thorium ores (12)	4
33	Iron ores	AUT_Iron ores	4
34	Copper ores and concentrates	AUT_Copper ores and concentrates	4
35	Nickel ores and concentrates	AUT_Nickel ores and concentrates	4
36	Aluminium ores and concentrates	AUT_Aluminium ores and concentrates	4
37	Precious metal ores and concentrates	AUT_Precious metal ores and concentrates	4
38	Lead, zinc and tin ores and concentrates	AUT_Lead, zinc and tin ores and concentrates	4
39	Other non-ferrous metal ores and concentrates	AUT_Other non-ferrous metal ores and concentrates	4
40	Stone	AUT_Stone	4
41	Sand and clay	AUT_Sand and clay	4
42	Chemical and fertilizer minerals, salt and other mining and quarrying products nec	AUT_Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	4
43	Products of meat cattle	AUT_Products of meat cattle	1
44	Products of meat pigs	AUT_Products of meat pigs	1
45	Products of meat poultry	AUT_Products of meat poultry	1
46	Meat products nec	AUT_Meat products nec	1
47	products of Vegetable oils and fats	AUT_products of Vegetable oils and fats	1
48	Dairy products	AUT_Dairy products	1
49	Processed rice	AUT_Processed rice	1
50	Sugar	AUT_Sugar	1
51	Food products nec	AUT_Food products nec	1
52	Beverages	AUT_Beverages	1
53	Fish products	AUT_Fish products	1
54	Tobacco products (16)	AUT_Tobacco products (16)	2
55	Textiles (17)	AUT_Textiles (17)	2

56	Wearing apparel; furs (18)	AUT_Wearing apparel; furs (18)	2
57	Leather and leather products (19)	AUT_Leather and leather products (19)	2
58	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	AUT_Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	5
59	Wood material for treatment, Re-processing of secondary wood material into new wood material	AUT_Wood material for treatment, Re-processing of secondary wood material into new wood material	6
60	Pulp	AUT_Pulp	5
61	Secondary paper for treatment, Re-processing of secondary paper into new pulp	AUT_Secondary paper for treatment, Re-processing of secondary paper into new pulp	6
62	Paper and paper products	AUT_Paper and paper products	2
63	Printed matter and recorded media (22)	AUT_Printed matter and recorded media (22)	7
64	Coke Oven Coke	AUT_Coke Oven Coke	3
65	Gas Coke	AUT_Gas Coke	3
66	Coal Tar	AUT_Coal Tar	8
67	Motor Gasoline	AUT_Motor Gasoline	3
68	Aviation Gasoline	AUT_Aviation Gasoline	3
69	Gasoline Type Jet Fuel	AUT_Gasoline Type Jet Fuel	3
70	Kerosene Type Jet Fuel	AUT_Kerosene Type Jet Fuel	3
71	Kerosene	AUT_Kerosene	3
72	Gas/Diesel Oil	AUT_Gas/Diesel Oil	3
73	Heavy Fuel Oil	AUT_Heavy Fuel Oil	3
74	Refinery Gas	AUT_Refinery Gas	3
75	Liquefied Petroleum Gases (LPG)	AUT_Liquefied Petroleum Gases (LPG)	3
76	Refinery Feedstocks	AUT_Refinery Feedstocks	8
77	Ethane	AUT_Ethane	8
78	Naphtha	AUT_Naphtha	8
79	White Spirit & SBP	AUT_White Spirit & SBP	8
80	Lubricants	AUT_Lubricants	8
81	Bitumen	AUT_Bitumen	8
82	Paraffin Waxes	AUT_Paraffin Waxes	8
83	Petroleum Coke	AUT_Petroleum Coke	3
84	Non-specified Petroleum Products	AUT_Non-specified Petroleum Products	8
85	Nuclear fuel	AUT_Nuclear fuel	4
86	Plastics, basic	AUT_Plastics, basic	5
87	Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	AUT_Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	6
88	N-fertiliser	AUT_N-fertiliser	9
89	P- and other fertiliser	AUT_P- and other fertiliser	9

90	Chemicals nec	AUT_Chemicals nec	9
91	Charcoal	AUT_Charcoal	3
92	Additives/Blending Components	AUT_Additives/Blending Components	9
93	Biogasoline	AUT_Biogasoline	10
94	Biodiesels	AUT_Biodiesels	10
95	Other Liquid Biofuels	AUT_Other Liquid Biofuels	10
96	Rubber and plastic products (25)	AUT_Rubber and plastic products (25)	9
97	Glass and glass products	AUT_Glass and glass products	5
98	Secondary glass for treatment, Re-processing of secondary glass into new glass	AUT_Secondary glass for treatment, Re-processing of secondary glass into new glass	6
99	Ceramic goods	AUT_Ceramic goods	11
100	Bricks, tiles and construction products, in baked clay	AUT_Bricks, tiles and construction products, in baked clay	11
101	Cement, lime and plaster	AUT_Cement, lime and plaster	5
102	Ash for treatment, Re-processing of ash into clinker	AUT_Ash for treatment, Re-processing of ash into clinker	6
103	Other non-metallic mineral products	AUT_Other non-metallic mineral products	11
104	Basic iron and steel and of ferro-alloys and first products thereof	AUT_Basic iron and steel and of ferro-alloys and first products thereof	5
105	Secondary steel for treatment, Re-processing of secondary steel into new steel	AUT_Secondary steel for treatment, Re-processing of secondary steel into new steel	6
106	Precious metals	AUT_Precious metals	5
107	Secondary precious metals for treatment, Re-processing of secondary precious metals into new precious metals	AUT_Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	6
108	Aluminium and aluminium products	AUT_Aluminium and aluminium products	5
109	Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	AUT_Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	6
110	Lead, zinc and tin and products thereof	AUT_Lead, zinc and tin and products thereof	5
111	Secondary lead for treatment, Re-processing of secondary lead into new lead	AUT_Secondary lead for treatment, Re-processing of secondary lead into new lead	6
112	Copper products	AUT_Copper products	5
113	Secondary copper for treatment, Re-processing of secondary copper into new copper	AUT_Secondary copper for treatment, Re-processing of secondary copper into new copper	6
114	Other non-ferrous metal products	AUT_Other non-ferrous metal products	5
115	Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	AUT_Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous	6

		metals into new other non-ferrous metals	
116	Foundry work services	AUT_Foundry work services	11
117	Fabricated metal products, except machinery and equipment (28)	AUT_Fabricated metal products, except machinery and equipment (28)	11
118	Machinery and equipment nec (29)	AUT_Machinery and equipment n.e.c. (29)	11
119	Office machinery and computers (30)	AUT_Office machinery and computers (30)	11
120	Electrical machinery and apparatus nec (31)	AUT_Electrical machinery and apparatus n.e.c. (31)	11
121	Radio, television and communication equipment and apparatus (32)	AUT_Radio, television and communication equipment and apparatus (32)	11
122	Medical, precision and optical instruments, watches and clocks (33)	AUT_Medical, precision and optical instruments, watches and clocks (33)	11
123	Motor vehicles, trailers and semi-trailers (34)	AUT_Motor vehicles, trailers and semi-trailers (34)	11
124	Other transport equipment (35)	AUT_Other transport equipment (35)	11
125	Furniture; other manufactured goods nec (36)	AUT_Furniture; other manufactured goods n.e.c. (36)	11
126	Secondary raw materials	AUT_Secondary raw materials	5
127	Bottles for treatment, Recycling of bottles by direct reuse	AUT_Bottles for treatment, Recycling of bottles by direct reuse	6
128	Electricity by coal	AUT_Electricity by coal	12
129	Electricity by gas	AUT_Electricity by gas	12
130	Electricity by nuclear	AUT_Electricity by nuclear	13
131	Electricity by hydro	AUT_Electricity by hydro	14
132	Electricity by wind	AUT_Electricity by wind	15
133	Electricity by petroleum and other oil derivatives	AUT_Electricity by petroleum and other oil derivatives	12
134	Electricity by biomass and waste	AUT_Electricity by biomass and waste	16
135	Electricity by solar photovoltaic	AUT_Electricity by solar photovoltaic	17
136	Electricity by solar thermal	AUT_Electricity by solar thermal	18
137	Electricity by tide, wave, ocean	AUT_Electricity by tide, wave, ocean	19
138	Electricity by Geothermal	AUT_Electricity by Geothermal	20
139	Electricity nec	AUT_Electricity nec	12
140	Transmission services of electricity	AUT_Transmission services of electricity	7
141	Distribution and trade services of electricity	AUT_Distribution and trade services of electricity	7
142	Coke oven gas	AUT_Coke oven gas	3
143	Blast Furnace Gas	AUT_Blast Furnace Gas	3
144	Oxygen Steel Furnace Gas	AUT_Oxygen Steel Furnace Gas	3

145	Gas Works Gas	AUT_Gas Works Gas	3
146	Biogas	AUT_Biogas	10
147	Distribution services of gaseous fuels through mains	AUT_Distribution services of gaseous fuels through mains	7
148	Steam and hot water supply services	AUT_Steam and hot water supply services	7
149	Collected and purified water, distribution services of water (41)	AUT_Collected and purified water, distribution services of water (41)	7
150	Construction work (45)	AUT_Construction work (45)	5
151	Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	AUT_Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	6
152	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	AUT_Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	7
153	Retail trade services of motor fuel	AUT_Retail trade services of motor fuel	7
154	Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	AUT_Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	7
155	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	AUT_Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	7
156	Hotel and restaurant services (55)	AUT_Hotel and restaurant services (55)	7
157	Railway transportation services	AUT_Railway transportation services	21
158	Other land transportation services	AUT_Other land transportation services	21
159	Transportation services via pipelines	AUT_Transportation services via pipelines	21
160	Sea and coastal water transportation services	AUT_Sea and coastal water transportation services	21
161	Inland water transportation services	AUT_Inland water transportation services	21
162	Air transport services (62)	AUT_Air transport services (62)	21
163	Supporting and auxiliary transport services; travel agency services (63)	AUT_Supporting and auxiliary transport services; travel agency services (63)	7
164	Post and telecommunication services (64)	AUT_Post and telecommunication services (64)	7
165	Financial intermediation services, except insurance and pension funding services (65)	AUT_Financial intermediation services, except insurance and pension funding services (65)	7
166	Insurance and pension funding services, except compulsory social security services (66)	AUT_Insurance and pension funding services, except compulsory social security services (66)	7
167	Services auxiliary to financial intermediation (67)	AUT_Services auxiliary to financial intermediation (67)	7

168	Real estate services (70)	AUT_Real estate services (70)	7
169	Renting services of machinery and equipment without operator and of personal and household goods (71)	AUT_Renting services of machinery and equipment without operator and of personal and household goods (71)	7
170	Computer and related services (72)	AUT_Computer and related services (72)	7
171	Research and development services (73)	AUT_Research and development services (73)	7
172	Other business services (74)	AUT_Other business services (74)	7
173	Public administration and defence services; compulsory social security services (75)	AUT_Public administration and defence services; compulsory social security services (75)	7
174	Education services (80)	AUT_Education services (80)	22
175	Health and social work services (85)	AUT_Health and social work services (85)	23
176	Food waste for treatment: incineration	AUT_Food waste for treatment: incineration	24
177	Paper waste for treatment: incineration	AUT_Paper waste for treatment: incineration	24
178	Plastic waste for treatment: incineration	AUT_Plastic waste for treatment: incineration	24
179	Intert/metal waste for treatment: incineration	AUT_Intert/metal waste for treatment: incineration	24
180	Textiles waste for treatment: incineration	AUT_Textiles waste for treatment: incineration	24
181	Wood waste for treatment: incineration	AUT_Wood waste for treatment: incineration	24
182	Oil/hazardous waste for treatment: incineration	AUT_Oil/hazardous waste for treatment: incineration	24
183	Food waste for treatment: biogasification and land application	AUT_Food waste for treatment: biogasification and land application	25
184	Paper waste for treatment: biogasification and land application	AUT_Paper waste for treatment: biogasification and land application	25
185	Sewage sludge for treatment: biogasification and land application	AUT_Sewage sludge for treatment: biogasification and land application	25
186	Food waste for treatment: composting and land application	AUT_Food waste for treatment: composting and land application	25
187	Paper and wood waste for treatment: composting and land application	AUT_Paper and wood waste for treatment: composting and land application	25
188	Food waste for treatment: waste water treatment	AUT_Food waste for treatment: waste water treatment	24
189	Other waste for treatment: waste water treatment	AUT_Other waste for treatment: waste water treatment	24
190	Food waste for treatment: landfill	AUT_Food waste for treatment: landfill	24
191	Paper for treatment: landfill	AUT_Paper for treatment: landfill	24
192	Plastic waste for treatment: landfill	AUT_Plastic waste for treatment: landfill	24
193	Inert/metal/hazardous waste for treatment: landfill	AUT_Inert/metal/hazardous waste for treatment: landfill	24

194	Textiles waste for treatment: landfill	AUT_Textiles waste for treatment: landfill	24
195	Wood waste for treatment: landfill	AUT_Wood waste for treatment: landfill	24
196	Membership organisation services nec (91)	AUT_Membership organisation services n.e.c. (91)	7
197	Recreational, cultural and sporting services (92)	AUT_Recreational, cultural and sporting services (92)	7
198	Other services (93)	AUT_Other services (93)	7
199	Private households with employed persons (95)	AUT_Private households with employed persons (95)	7
200	Extra-territorial organizations and bodies	AUT_Extra-territorial organizations and bodies	7

Table 2: Aggregation of Exiobase sectors into MORDRED sectors.

From the aggregated Exiobase3 data for 2019 we derive a 25X25 A matrix, the initial output and the sectoral shares of total gross fixed capital formation on a global scale.

Table 3 shows the order of the sectors in the A matrix.

Sector number	**Sector description**
1	Agriculture, food, beverages
2	Non-energy use of biomass
3	Fossil fuels used for energy
4	Mining
5	Industry not elsewhere classified
6	Recycling industry
7	Services not elsewhere classified
8	Non-energy use of fossil fuels
9	Chemical industry
10	Biomass used for energy
11	Manufacturing
12	Fossil fuel-based electricity
13	Nuclear electricity
14	Hydroelectricity
15	Wind based electricity
16	Biomass and waste based electricity
17	Solar PV electricity
18	Solar thermal electricity
19	Tide, wave and ocean based electricity
20	Geothermal electricity
21	Transport
22	Education
23	Health
24	Waste industry
25	Waste ‚recycling‘ (biogasification & composting) industry

Table 3: Overview MORDRED sectors.

3.1.5.2. Data modification

In MORDRED, there is a separation between the production and consumption of the subsistence class and the production and consumption within the formal economy. Thus, the part of the subsistence economy that is included in Exiobase3 is excluded in MORDRED.

We assume that the monetized output of the subsistence sector is concentrated in sector 1, which includes agricultural products, and that no intermediary inputs from the global economy are needed to produce output. The monetized output equals the monetized subsistence per capita consumption per capita times the subsistence population size.

We assume that 70% of the subsistence class works and that half of the working day of the subsistence class, i.e. 4 hours, goes to the production of output, which enters the formal economy, and, thus, is monetized.

Therefore, we deduct the monetized output of the subsistence sector from the sectoral output of sector 1, and deduct the amount of hours worked from the hours worked in sector 1.

The A-Matrix is modified for the column containing the intermediary products sector 1 demands from the 25 sectors to reflect the change in output.

As a side effect, both the labor productivity and the input intensity of sector 1 increases, as the more labor-intensive and less input-reliant subsistence regime gets excluded from the IO structure.

This modification allows us to have two separate economic structures and different mortality and fertility patterns for the subsistence class and the rest of classes in the case of very low per capita consumption. It also allows us to better reflect the higher labor productivity in agriculture for industrialized agriculture.

3.1.6. Capital

3.1.6.1. Capital output ratios

In MORDRED, the capital stock is calculated via sector specific capital-output ratios.

To estimate the capital-output ratios for the different MORDRED sectors at the global level, we draw on different data sources: for the estimations of capital stock we use the EU KLEMS database (2023 release, which also includes data for Japan, the UK and the US) (Bontadini et al., 2023; LUISS, 2023), the IndiaKLEMS database (2024 release) (RBI, 2024)and the China CIP 4.0 database (2023 release) (RIETI, 2023).

The following steps were taken:

1. Extraction of all capital stock and output data for all available countries:

We extracted the net capital stock for all assets (K_GFCF) for the year 2019 from the Capital Accounts excel sheets as well as the gross output (GO_CP) for the year 2019 from the National Accounts for all the available countries in EUKLEMS (in current prices, millions of national currency): Japan, UK, US, Austria, Belgium, Czechia, Germany, Denmark, Estonia, Greece, Spain, Finland, France, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia. Subsequently, the national currencies were converted to 2019-€, using the official exchange rates for 2019 provided by the World Bank. As the capital stock estimates for Japan constitute an outlier with respect to the other countries and as the quality of those estimates were questionable, we excluded Japan from the sample.

We extracted the net capital stock (K) as well as the gross output (GO) for the year 2019-20 (in krore of 2019-rupees) from IndiaKLEMS.

In the case of China, the most actual data is for the year 2017. To obtain the real net capital stock for this year, the net capital stock in 2000 in the different sectors (CHINA_CIP_4.0_(2023)_2.2.xlsx) is multiplied by the real net capital stock growth index for 2017 in the different sectors (CIP_4.0_(2023)_4.xlsx) and a conversion factor is applied to convert the data from mio. of 2000-yuan to mio. of 2017-yuan. We extract the output for the year 2017 from the CIP_4.0 (2023)1.3.xlsx excel sheet which contains the gross value of output by industry in millions of current (2017-) yuan.

Due to a lack of data for other countries, the countries in EUKLEMS are treated as a representative sample of the center, China is treated as a representative sample of the semiperiphery, and India is treated a representative sample of the periphery.

2. Matching of sectors with MORDRED sectors

EUKLEMS contains 52 sector categories (Table 4).

Sector abbreviation	Sector description
A	Agriculture, forestry and fishing
B	Mining and quarrying
C	Manufacturing
C10-C12	Manufacture of food products; beverages and tobacco products
C13-C15	Manufacture of textiles, wearing apparel, leather and related products
C16-C18	Manufacture of wood, paper, printing and reproduction
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C20-C21	Chemicals; basic pharmaceutical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22-C23	Manufacture of rubber and plastic products and other non-metallic mineral products
C24-C25	Manufacture of basic metals and fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C26-C27	Computer, electronic, optical products; electrical equipment
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.

C29-C30	Manufacture of motor vehicles, trailers, semi-trailers and of other transport equipment
C31-C33	Manufacture of furniture; jewellery, musical instruments, toys; repair and installation of machinery and equipment
D	Electricity, gas, steam and air conditioning supply
D-E	Electricity, gas, steam; water supply, sewerage, waste management
E	Water supply; sewerage, waste management and remediation activities
F	Construction
G	Wholesale and retail trade; repair of motor vehicles and motorcycles
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H	Transportation and storage
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J	Information and communication
J58-J60	Publishing, motion picture, video, television programme production; sound recording, programming and broadcasting activities
J61	Telecommunications
J62-J63	Computer programming, consultancy, and information service activities
K	Financial and insurance activities
L	Real estate activities
L68A	Imputed rents of owner-occupied dwellings
M	Professional, scientific and technical activities
M-N	Professional, scientific and technical activities; administrative and support service activities
N	Administrative and support service activities
O	Public administration and defence; compulsory social security
O-Q	Public administration, defence, education, human health and social work activities
P	Education
Q	Human health and social work activities
Q86	Human health activities
Q87-Q88	Residential care activities and social work activities without accommodation
R	Arts, entertainment and recreation

R-S	Arts, entertainment, recreation; other services and service activities, etc.
S	Other service activities

Table 4: Sectors in EUKLEMS.

The sectors contained in the country (cnt) data of EUKLEMS (except for Japan) were matched to the MORDRED sectors in the following way:

$$\frac{K}{X}_{center_1} = \frac{\sum_{cnt=1}^{26}(K_{A_{cnt}} + K_{C10-C12_{cnt}})}{\sum_{cnt=1}^{26}(X_{A_{cnt}} + X_{C10-12_{cnt}})}$$

$$\frac{K}{X}_{center_2} = \frac{\sum_{cnt=1}^{26}(K_{C13-C15_{cnt}} + K_{C16-C18_{cnt}})}{\sum_{cnt=1}^{26}(X_{C13-C15_{cnt}} + X_{C16-C18_{cnt}})}$$

$$\frac{K}{X}_{center_{3,8}} = \frac{\sum_{cnt=1}^{26} K_{C19_{cnt}}}{\sum_{cnt=1}^{26} X_{C19_{cnt}}}$$

(The same capital-output ratio is used for the sectors 3 and 8.)

$$\frac{K}{X}_{center_4} = \frac{\sum_{cnt=1}^{26} K_{B_{cnt}}}{\sum_{cnt=1}^{26} X_{B_{cnt}}}$$

$$\frac{K}{X}_{center_5} = \frac{\sum_{cnt=1}^{26}(K_{C24-C25_{cnt}} + K_{F_{cnt}})}{\sum_{cnt=1}^{26}(X_{C24-C25_{cnt}} + X_{F_{cnt}})}$$

$$\frac{K}{X}_{center_6} \; 0$$

$$\frac{K}{X}_{center_{7,10,12,13,14,15,16,17,18,19,20,24,25}} = \frac{\sum_{cnt=1}^{26}(K_{([D]+[D-E]+[E]+[G]+[G45]+[G46]+[G47]+[H52]+[H53]+[I]+[J]+[J58-J60]+[J61]+[J62-J63]+[K]+[L])_{cnt}})}{\sum_{cnt=1}^{26}(X_{([D]+[D-E]+[E]+[G]+[G45]+[G46]+[G47]+[H52]+[H53]+[I]+[J]+[J58-J60]+[J61]+[J62-J63]+[K]+[L])_{cnt}})}$$

(Due to a lack of desaggregation, the same capital-output ratio is used for the sectors no. 7, 10, 12 to 20 [12;20], 24 and 25.)

$$\frac{K}{X}_{center_9} = \frac{\sum_{cnt=1}^{26}(K_{C20_{cnt}} + K_{C20-C21_{cnt}} + K_{C21_{cnt}} + K_{C22-C23_{cnt}})}{\sum_{cnt=1}^{26}(X_{C20_{cnt}} + X_{C20-C21_{cnt}} + X_{C21_{cnt}} + X_{C22-C23_{cnt}})}$$

$$\frac{K}{X}_{center_{21}} = \frac{\sum_{cnt=1}^{26}(K_{([H]+[H49]+[H50]+[H51])_{cnt}})}{\sum_{cnt=1}^{26}(X_{([H]+[H49]+[H50]+[H51])_{cnt}}}$$

$$\frac{K}{X}_{center_{22}} = \frac{\sum_{cnt=1}^{26}(K_{P_{cnt}})}{\sum_{cnt=1}^{26}(X_{P_{cnt}})}$$

$$\frac{K}{X}_{center_{23}} = \frac{\sum_{cnt=1}^{26}\left(K_{Q_{cnt}}\right)}{\sum_{cnt=1}^{26}\left(X_{Q_{cnt}}\right)}$$

For this sector, the sub-categories Q86-Q88 were not included given that they are subsectors of Q and all countries had data estimates for Q but not for the subcategories.

The China CIP database contains 37 sectors that were matched with MORDRED sectors.

CIP sector number	CIP sector description	MORDRED sector
1	Agriculture, forestry, animal husbandry & fishery	1
2	Coal mining	3, 8
3	Oil & gas excavation	3, 8
4	Metal mining	4
5	Non-metallic minerals mining	4
6	Food and kindred products	1
7	Tobacco products	2
8	Textile mill products	2
9	Apparel and other textile products	2
10	Leather and leather products	2
11	Saw mill products, furniture, fixtures	11
12	Paper products, printing & publishing	2
13	Petroleum and coal products	3, 8
14	Chemicals and allied products	9
15	Rubber and plastics products	9
16	Stone, clay, and glass products	5
17	Primary & fabricated metal industries	5
18	Metal products (excluding rolling products)	5
19	Industrial machinery and equipment	11
20	Electric equipment	11
21	Electronic and telecommunication equipment	11
22	Instruments and office equipment	11
23	Motor vehicles & other transportation equipment	11
24	Miscellaneous manufacturing industries	11
25	Power, steam, gas and tap water supply	[12;20]
26	Construction	5
27	Wholesale and retail trades	7
28	Hotels and restaurants	7
29	Transport, storage & post services	21
30	Information & computer services	7
31	Financial Intermediations	7
32	Real estate services	7

33	Leasing, technical, science & business services	7
34	Government, public administration, and political and social organizations, etc.	7
35	Education	22
36	Healthcare and social security services	23
37	Cultural, sports, entertainment services; residential and other services	7

Table 5: CIP sectors matched to MORDRED sectors.

This gives the following capital-output ratios (all based on data for China):

$$\frac{K}{X}_{semiperiphy_1} = \frac{K_1 + K_6}{X_1 + X_6}$$

$$\frac{K}{X}_{semiperiphy_2} = \frac{K_7 + K_8 + K_9 + K_{10} + K_{12}}{X_7 + X_8 + X_9 + X_{10} + X_{12}}$$

$$\frac{K}{X}_{semiperiphy_{3,8}} = \frac{K_2 + K_3 + K_{13}}{X_2 + X_3 + X_{13}}$$

$$\frac{K}{X}_{semiperiphy_4} = \frac{K_4 + K_5}{X_4 + X_5}$$

$$\frac{K}{X}_{semiperiphy_5} = \frac{K_{16} + K_{17} + K_{18} + K_{26}}{X_{16} + X_{17} + X_{18} + X_{26}}$$

$$\frac{K}{X}_{semiperiphy_6} = 0$$

$$\frac{K}{X}_{semiperiphy_{7,10,12,13,14,15,16,17,18,19,20,24,25}} = \frac{K_{25} + K_{27} + K_{28} + K_{30} + K_{31} + K_{32} + K_{33} + K_{34} + K_{37}}{X_{25} + X_{27} + X_{28} + X_{30} + X_{31} + X_{32} + X_{33} + X_{34} + X_{37}}$$

$$\frac{K}{X}_{semiperiphy_9} = \frac{K_{14} + K_{15}}{X_{14} + X_{15}}$$

$$\frac{K}{X}_{semiperiphy_{11}} = \frac{K_{11} + K_{19} + K_{20} + K_{21} + K_{22} + K_{23} + K_{24}}{X_{11} + X_{19} + X_{20} + X_{21} + X_{22} + X_{23} + X_{24}}$$

$$\frac{K}{X}_{semiperiphy_{21}} = \frac{K_{29}}{X_{29}}$$

$$\frac{K}{X}_{semiperiphy_{22}} = \frac{K_{35}}{X_{35}}$$

$$\frac{K}{X}_{semiperiphy_{23}} = \frac{K_{36}}{X_{36}}$$

The INDIAKLEMS database contains 27 sectors that were matched with MORDRED sectors.

IndiaKlems sector number	IndiaKLEMS sector description	MORDRED sector
1	Agriculture,Hunting,Forestry and Fishing	1
2	Mining and Quarrying	4
3	Food Products,Beverages and Tobacco	1
4	Textiles, Textile Products, Leather and Footwear	2
5	Wood and Products of wood	2
6	Pulp, Paper,Paper products,Printing and Publishing	2
7	Coke, Refined Petroleum Products and Nuclear fuel	3, 8
8	Chemicals and Chemical Products	9
9	Rubber and Plastic Products	9
10	Other Non-Metallic Mineral Products	9
11	Basic Metals and Fabricated Metal Products	5
12	Machinery, nec.	11
13	Electrical and Optical Equipment	11
14	Transport Equipment	11
15	Manufacturing, nec; recycling	11
16	Electricity, Gas and Water Supply	[12; 20], 7, 10
17	Construction	5
18	Trade	7
19	Hotels and Restaurants	7
20	Transport and Storage	21
21	Post and Telecommunication	7
22	Financial Services	7
23	Business Service	7
24	Public Administration and Defense; Compulsory Social Security	7
25	Education	22
26	Health and Social Work	23
27	Other services	7, 24, 25

Table 6: IndiaKLEMS sectors matched to MORDRED sectors.

This gives the following capital-output ratios (all based on data for India):

$$\frac{K}{X}_{periphy_1} = \frac{K_1 + K_3}{X_1 + X_3}$$

$$\frac{K}{X}_{periphy_2} = \frac{K_4 + K_5 + K_6}{X_4 + X_5 + X_6}$$

$$\frac{K}{X}_{periphy_{3,8}} = \frac{K_7}{X_7}$$

$$\frac{K}{X}_{periphy_4} = \frac{K_2}{X_2}$$

$$\frac{K}{X}_{periphy_5} = \frac{K_{11} + K_{17}}{X_{11} + X_{17}}$$

$$\frac{K}{X}_{periphy_6} = 0$$

$$\frac{K}{X}_{periphy_{7,10,12,13,14,15,16,17,18,19,20,24,25}} = \frac{K_{16} + K_{18} + K_{19} + K_{21} + K_{22} + K_{23} + K_{24} + K_{27}}{X_{16} + X_{18} + X_{19} + X_{21} + X_{22} + X_{23} + X_{24} + X_{27}}$$

$$\frac{K}{X}_{semiperiphy_9} = \frac{K_8 + K_9 + K_{10}}{X_8 + X_9 + X_{10}}$$

$$\frac{K}{X}_{semiperiphy_{11}} = \frac{K_{12} + K_{13} + K_{14} + K_{15}}{X_{12} + X_{13} + X_{14} + X_{15}}$$

$$\frac{K}{X}_{semiperiphy_{21}} = \frac{K_{20}}{X_{20}}$$

$$\frac{K}{X}_{semiperiphy_{22}} = \frac{K_{25}}{X_{25}}$$

$$\frac{K}{X}_{semiperiphy_{23}} = \frac{K_{26}}{X_{26}}$$

In this way, we construct three 12-dimensional vectors containing the capital-output ratios for different MORDRED sectors for every MORDRED region: $\frac{K}{X}_{center}, \frac{K}{X}_{semiperiphery}, \frac{K}{X}_{periphery}$.

3. Global estimates

To obtain the capital-output ratios for the MORDRED sectors at the global scale, we draw a weighted average of the three capital-output ratio vectors. The weights are the shares of the respective regions in the total output generated by the EUKLEMS countries, China and India.

To obtain the shares of the output in total output, we use Exiobase3 country data for 2019 which we aggregate according to the sectors contained in the capital:output vectors: sector no. 1; 2; 3 + 8; 4; 5; 6; 7 + 10 + [12;20] + 24 + 25; 9; 11; 21; 22; 23.

The respective shares are:

$$share_{center} = \left(\frac{\sum_{cnt=1}^{26} X_{cnt_1}}{\sum_{cnt=1}^{26} X_{i_1} + X_{CN_1} + X_{IN_1}}, \frac{\sum_{cnt=1}^{26} X_{cnt_2}}{\sum_{cnt=1}^{26} X_{i_2} + X_{CN_2} + X_{IN_2}}, \dots, \frac{\sum_{cnt=1}^{26} X_{cnt_{12}}}{\sum_{cnt=1}^{26} X_{i_{12}} + X_{CN_{12}} + X_{IN_{12}}} \right)$$

cnt denotes the 27 countries of the center included in the EUKLEMS database (except for Japan).

$$share_{semiperiphery} = \left(\frac{X_{CN_1}}{\sum_{cnt=1}^{26} X_{cnt_1} + x_{CN_1} + x_{IN_1}}, \frac{X_{CN_2}}{\sum_{cnt=1}^{26} X_{i_2} + X_{CN_2} + X_{IN_2}}, \dots, \frac{X_{CN_{12}}}{\sum_{cnt=1}^{26} X_{i_{12}} + X_{CN_{12}} + X_{IN_{12}}}\right)$$

$$share_{periphery} = \left(\frac{X_{IN_1}}{\sum_{cnt=1}^{26} X_{i_1} + X_{CN_1} + X_{IN_1}}, \frac{X_{IN_2}}{\sum_{cnt=1}^{26} X_{i_2} + X_{CN_2} + X_{IN_2}}, \dots, \frac{X_{IN_{12}}}{\sum_{cnt=1}^{26} X_{i_{12}} + X_{CN_{12}} + X_{IN_{12}}}\right)$$

The global capital-output vector is:

$\frac{K}{X_{world_i}} = \sum_{r=1}^{3} \frac{K}{X_{i_r}} * share_{i_r}$ with r denoting the three regions.

This vector can be converted from a 12-dimensional vector into a 25-dimensional vector by disaggregating those sector categories that contain various MORDRED sectors, using the same value for all MORDRED sectors that belong to the respective category.

4. Correction factor

Last, we apply a correction factor $\alpha_{\frac{basic}{acquisiion}}$ to convert the acquisition prices of the capital stock into basic prices, given that the output in Exiobase is assumed to be given in basic prices.

$$\frac{K}{X_{world_{i_{basic\ prices}}}} = \frac{K_{i_{acquisition\ prices}}}{X_{i_{basic\ prices}}} * \alpha_{\frac{basic}{acquisiion}}$$

$\alpha_{\frac{basic}{acquisiion}}$ is obtained in the following way:

We draw on WIOD 2016 data (Timmer et al., 2015; WIOD, 2016) for the year 2014 for all countries used to estimate capital-output ratios at the global level. For all countries with available data in WIOD (i.e. all countries except from China and the US) we extract the GFCF data for total intermediate consumption in basic prices and information on taxes less subsidies on products and international transport margins. $\alpha_{\frac{basic}{acquisiion}}$ is calculated as:

$$\alpha_{\frac{basic}{acquisiion}} = \frac{\sum_{i=cnt}^{26} GFCF_{total\ intermediate\ consumption_{cnt}}}{\sum_{cnt=1}^{26} GFCF_{total\ intermediate\ consumption_{cnt}} + \sum_{cnt=1}^{26} taxes - subsidies_{cnt} + \sum_{cnt=1}^{26} Transport_{cnt}}$$

3.1.6.2. *Sectoral share of GFCF and capital depreciation*

Both the data for annual sector-specific Gross Fixed Capital Formation (GFCF) and capital depreciation come from Exiobase3. In MORDRED, GFCF is the sum of the final demand categories GFCF, changes in inventories and changes in valuables. The sectoral share in GFCF is obtained by dividing GFCF in the respective sector by total GFCF.

$$GFCF_{share} = \frac{GFCF_i + changes\ in\ inventories_i + changes\ in\ valuable_i}{\sum_{i=1}^{25}(GFCF_i + changes\ in\ inventories_i + changes\ in\ valuables_i)}$$

The capital depreciation in million € for the different sectors is contained in the Exiobase3 Extension F: Operating surplus: Consumption of fixed capital. Since it is assumed to be given in acquisition prices, the $\alpha_{\frac{basic}{acquisiion}}$ correction factor is applied to convert the data into basic prices.

3.1.7. Consumption side

In MORDRED, there are three world regions ('Center', 'Semiperiphery' and 'Periphery') and within each world region, there are four classes (Top20, Middle50, Bottom30 and Subsistence). The per capita consumption of an individual, thus, depends on the specific class and territory (cf. section 2.2).

3.1.7.1. *Initial inequality in consumption between world regions: Regional share in global final demand without GFCF*

Data on the global final demand of households is obtained by aggregating the Exiobase categories 'households' and 'non-profit organizations serving households, and data for final demand for GFCF by aggregating the Exiobase categories 'GFC', 'changes in inventories' and 'changes in valuables'. The government final demand can be directly taken from Exiobase.

We assume that final demand of households and governments is distributed unequally between regions. Although GFCF is also unequally distributed between regions, in MORDRED this does not affect consumption per capita and life expectancy, thus, there is no need for disaggregation.

The inequality in the regional share in the global final demand without GFCF is approximated based on World Bank data containing the 'Final consumption expenditure (%) of GDP' (World Bank, 2024a) and 'GDP (current US$)' (World Bank, 2024b) for the year 2019.

We included 249 countries that were matched to the MORDRED regions according to their World Bank classification as high (center), upper-middle (semiperiphery), lower-middle and low (periphery) income.

Using all the available data, we calculated the average final consumption expenditure as percentage of GDP for the center, semiperiphery and periphery. Countries that lacked data for final consumption expenditure as percentage of GDP were given the average value of their region. Countries without GDP data were left out of the analysis.

The total consumption for every region was derived by summing over the consumption of every country belonging to the region.

The regional share in global final demand without GFCF was calculated by dividing the final demand of the respective region by the sum of final demand of all regions

Given that the periphery had the most missing values for GDP (21 countries) and that the data was given in current rather than in PPP-USD, we multiplied the share of the periphery with a factor of 1.6 and deducted the increase in share of the periphery from the share of the center.

The resulting regional shares in global final demand without GFCF are: 0.6073 for the center, 0.2559 for the semiperiphery and 0.1367 for the periphery.

3.1.7.2. Household and government share in regional final demand without GFCF

To approximate differences in the shares of households and governments in final demand between MORDRED regions, we use Exiobase3 data on final demand for the year 2019 because this data has a relatively high regional disaggregation and differentiates between final demand from governments and from households (when we speak of household consumption or demand in the context of Exiobase3, we always refer to the Exiobase categories ‘households’ and ‘non-profit organizations serving households’ which are added into one MORDRED category ‘households (hh)’).

We use pymrio (Stadler, 2021)to aggregate Exiobase countries and regions in a way that they approximate the MORDRED regions (Table 7).

MORDRED	Exiobase countries/regions
Center	Austria, Belgium, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovak Republic, Great Britain, USA, Japan, Canada, South Korea, Australia, Switzerland, Taiwan, Norway
Semiperiphery	Bulgaria, China, Brazil, Mexico, Russia Federation, Türkiye, Indonesia, South Africa, Rest of the World Latin America (WL), Rest of the World Middle East (WM)
Periphery	India, Rest of the World Asia (WA), Rest of the World Europe (WE), Rest of the World Africa (WF)

Table 7: Matching Exiobase countries and regions to MORDRED regions.

To allocate the Rest of the World Exiobase regions to the MORDRED regions we calculated for every region the percentage of people living in countries classified as ‘center’, ‘semiperiphery’ and ‘periphery’, using the UN population data for 2020 (cf. section 3.1.1). WA, WL, WF and WE were matched to the MORDRED region where the highest share of population lived: In WA, 83.7% of the population lives in countries classified as ‘periphery; In WL, 74.63% of the population lives in countries classified as ‘semiperiphery’; in WF, 98.5% of the population lives in countries classified as ‘periphery’; in WE, 63.4% of the population lives in countries classified as ‘periphery’. In WM, 42.6% of the population lives in the periphery, 38.88% lives in the semiperiphery and 18.53% lives in the center. Thus, while less than half of the population lives in peripheral countries, more than half of the population lives in semiperipheral or central countries. Consequently, WM as a whole was matched to the semiperiphery.

For every region, the share of government consumption in total consumption is calculated by aggregating the sectoral final demand of the government and households.

$$G2Cr_r = \frac{\sum_{i=1}^{25} G_{r_i}}{\sum_{i=1}^{25} G_{r_i} + \sum_{i=1}^{25} C_{r_i}}$$

The resulting share of government consumption in the regional final demand without GFCF is 22.5% for the center, 25.5% for the semiperiphery and 16% for the periphery.

3.1.7.3. Inequality in consumption between classes within world regions

In MORDRED, within every region the population that does not live in subsistence is divided into three consumption classes: The richest 20%, the poorest 30% and the remaining half of the population constituting the middle class. In this way, the MORDRED reflects inequalities between as well as within world regions. Additionally, there is a subsistence class which consumes 729 € per capita independent from the world region.

To derive realistic per capita consumption of these classes we rely on the GCIP database which provides real monthly consumption estimates for every decile for the majority of the countries in the world and more than half a century (Lahoti et al., 2016).

We use only the data for 2014, which is the closest to the start of the simulation year in MORDRED and includes the most countries (159 observations). The data is given in 2011-PPP-USD. Since we are only interested in the consumption shares of the different percentiles, it is not necessary to convert the data into another currency.

The 159 countries for which data was available were matched to the MORDRED regions and the respective UN population estimates for 2020 was added for every country.

Missing data: The distribution of consumption among percentiles for countries with considerable population that were not included in the GCIP data was approximated by other countries in the same region (if possible, neighboring countries) with similar GDP per capita. For the comparison, data from the World Bank (2024c) on GDP per capita was taken for the year 2011. Countries not included in the World Bank dataset were left out of the analysis. If there were no countries with similar GDP per capita levels in the region, other regions were taken as reference. Table 8 shows the missing countries in the GCIP and how they were replaced.

Country	Consumption distribution approximated through
Guyana	Ecuador
Puerto Rico	Bahamas
Bahrain	USA
Iraq	Iran
Kuwait	Singapore
Lebanon	Iran
Oman	USA
Quatar	Luxembourg
United Arab Emirates	Singapore
Yemen	Egypt
Saudi Arabia	USA
Brunei Darussalam	Singapore
Equatorial Guinea	Gabon
Eritrea	Ethiopia
Eswatini	South Africa
Gambia	Chad
Libya	Gabon
Macao	Singapore
Solomon Islands	Papua-New-Guinea
South Sudan	Sudan
Vanuatu	Papua-New-Guinea
Zimbabwe	Zambia

Table 8: Approximation of countries missing in the GCIP dataset.

The remaining countries not included in the GPIC database either had no UN population data, very small population size (<200000 people) and/or no World Bank data, and, thus, were left out from the analysis.

For Myanmar the average mean consumption in 2011-PPP USD was corrected by multiplying it by 100 because the value was two orders of magnitude lower than all the other values in the countries constituting the periphery, indicating a mistaken position of the comma.

For the conversion of the country-level data into regional-level data we used the gpinter interpolation tool of the World Inequality Database that allows users to merge the income distribution of several countries into a single one. The population of the respective countries serves to assign different weights to the respective inequality distributions. To this end, we restructured the data to fit the required format (shares, average values and threshold values for every percentile as well as the population size of the respective country). Because everyone within one percentile consumes the same, the consumption of the percentile is the average consumption of the percentile, and the threshold value was set to be 1 USD below the consumption value.

The aggregation tool estimated a consumption distribution for every MORDRED region on a percentile basis. Thus, for every region, the consumption share of the poorest 30% was derived by summing over the share of the first 30 percentiles; the consumption share of the Middle50 was derived by summing over the share of the following 50 percentiles; and the consumption share of the richest 20% was derived by summing over the shares of the remaining percentiles.

3.1.7.4. Shares and Calculations

The consumption distribution for the Top20, Middle50 and Bottom30 includes the consumption of the people living in subsistence within the Bottom30 because the survey data used to calculate inequalities in consumption do not exclude people living in subsistence. However, in MORDRED, the population belonging to the Top20, Middle50 and Bottom30 in every region is calculated as 20%, 50% and 30% of the population living fully integrated in the global economy.

Thus, for the semiperiphery and periphery, we first calculate the overall consumption of the richest 20%, the middle50% and the 30% poorest percent by applying regional shares, household shares and class shares to global total consumption.

Dividing these values by 20%, 50% and 30% of the population gives three average per capita consumption values.

We subtract the population sustained by the subsistence sector from the total population in the two MORDRED regions and construct the actual Top20, Middle50 and Bottom30 classes which are smaller than the previous numbers. This leads to a re-classification of a part of the population: the poorest members of the population become the subsistence class ($n_{low \rightarrow Subsistence}$), some people belonging to the middle 50% are now part of the Bottom30 ($n_{middle \rightarrow low}$), and some people belonging to the richest 20% now become part of the Middle50 ($n_{high \rightarrow middle}$). The original number of people in every segment is written as n_{high_0}, n_{middle_0} and n_{low_0}.

We construct the overall consumption of the actual classes and their average per capita consumption. For the Top20 we multiply the population belonging to the actual Top20 with the per capita consumption of the richest 20% of the total population

$(n_{high} - n_{high \rightarrow middle}) * av\_T20_0$.

Thus, while the top class shrinks in number, its average per capita consumption remains unchanged and high: $av\_T20_1 = av\_T20_0$.

The new overall consumption of the actual Middle50 is the sum of the total consumption of the people that were previously classified as part of the richest 20% and the total consumption of the people that still belong to the Middle50:

$$C_{middle} = n_{high \rightarrow middle} * av\_T20_0 + (n_{middle} - n_{middle \rightarrow low}) * av\_M50_0$$

Dividing the overall consumption by the new population belong to the Middle50 gives the average per capita consumption for this class

$$av\_M50_1 = \frac{(n_{high \rightarrow middle} * av\_T20_0 + (n_{middle} - n_{middle \rightarrow low}) * av\_M50_0)}{n_{middle_0} + n_{high \rightarrow middle} - n_{middle \rightarrow low}} \text{ with } av\_M50_1 > av\_M50_0.$$

To obtain the new overall consumption of the actual Bottom30 class we subtract the consumption of the population that is now part of the subsistence class (this class has a fixed monetized per capita consumption of $C_{Subsistence} = 729$ € /year) from the total consumption of the original B30 class and add the overall consumption of the people that were previously classified as part of the middle 50% :

$$C_{low_1} = C_{low_0} + n_{middle \to low} * av\_M50_0 - n_{low \to Subsistence} * C_{Subsistence}$$

Dividing the overall consumption by the new population belonging to the Bottom30 gives the average per capita consumption for this class:

$$av\_B30_1 = \frac{(C_{low_1})}{n_{low_0} + n_{middle \to low} - n_{low \to Subsistence}} \text{ with } av\_B30_1 > av\_B30_0.$$

In this way, the inequality in consumption between classes is preserved and the consumption of the subsistence class is separated from the consumption of the rest of the classes.

3.1.7.5. Consumption vectors of households

The consumption vector of households that describes how the final demand of households (classes) is distributed among the MORDRED sectors, i.e. a 25-dimensional vector containing the sectoral shares for a given level of total consumption per capita (evidently, the sum of 25 shares equals 1).

The vector changes along two linear functions of per capita consumption. The first linear function contains the points 1,356 €/(person*year) and 3,838.5 €/(person*year). The second linear function contains the points 3,838.5 €/(person*year) and 24,672.6 €/(person*year). At consumption levels below 1,356 €/person or above 24,672.6 €/person the consumption vector stays at the distribution corresponding to these minimum and maximum values (cf. section 2.2). In this way, we are able to depict the most significant changes in consumption patterns as the population grows richer, namely, a reduction of the relative importance of the food sector (sector 1), and an increase in the relative importance of the service sector (sector 7).

The consumption vector for households is only calculated for the population belonging to the global economy given that the consumption of the subsistence class is completely separated from the IO structure.

To construct the function describing changes in the consumption vector we use Exiobase3 data for 2019 that was aggregated in two ways: the sectoral aggregation resulted in the 25 MORDRED sectors, while the regional aggregation approximated the Exiobase countries and regions to the MORDRED regions (Table 7).

For every approximated MORDRED region we calculated the average annual per capita household final demand and the corresponding shares of the 25 sectors in the final demand. Thus, the minimum value of 1,355.8 €/(person*year) and the corresponding consumption vector comes from the approximated ‘periphery’, the middle value of 3,838.5 €/(person*year) with the corresponding consumption vector comes from the approximated ‘semiperiphery’ and the maximum value and consumption vector from the Exiobase3 ‘center’.

Using the three consumption vectors corresponding to the three per capita consumption levels we calculated the sectoral consumption of every class in MORDRED, using their initial consumption per capita level. Aggregating the sectoral consumption of every class yielded a relatively accurate approximation of the actual total sectoral household final demand on the global level: the sectors with the highest overestimation of demand were sector 8 (1.27 times above the 'real' global household demand) and sector 1 (1.18 times above) while the sectors with the highest underestimation of demand were sector 18 (solar thermal based electricity) and sector 15 (wind power based electricity) with 84% and 86% of 'real' global sectoral household demand. More than half of the sectors had an aggregated demand of around 0.94 and 1.07 of the actual global demand. Thus, to achieve a complete equivalence between the aggregated and the global final demand in the initial moment of the simulation, the three original consumption vectors were divided by a 25-dimensional vector correcting for over- and underestimation of household demand in the different sectors.

3.1.7.6. Consumption vectors of governments

The consumption vector of governments describes how the final demand of governments in each MORDRED region is distributed among the MORDRED sectors, i.e. a 25-dimensional vector containing the sectoral shares (evidently, the sum of 25 shares equals 1).

Given that a preliminary analysis of government expenditures in the three approximated MORDRED regions of the 2019 Exiobase3 data did not yield significant differences in sectoral shares we assume that the share of each sector in government consumption is equal in the periphery, semiperiphery and center of MORDRED.

Thus, the sectoral shares on the regional level are the same as on the global level and the consumption vector of governments can be obtained by dividing the global government final demand of the respective sector by total global government final demand.

3.2. Labor

We obtain the data on labor intensity from the Exiobase3 extensions (.S) which gives data in million work hours per million euros for different employment categories.

To obtain the general labor intensity, we aggregate the employment categories 'Low-skilled male', 'Low-skilled female', 'Medium-skilled male', 'Medium-skilled female', 'High-skilled male' and 'High-skilled female'.

The labor intensity of sector no. 1 is derived by dividing the new hours worked in sector no. 1 (without the hours belonging to subsistence output) by the new output of sector no. 1 (without the subsistence output) (cf. section 3.2.1.2).

3.3. Energy

3.3.1. Electricity production

In MORDRED, different sectors are assumed to produce the electricity that is consumed in productive processes as is depicted in Table 9. The data on the quantity of the different types of final energy produced in the initial year (2019) of the simulation on the global level comes from the IEA and from OWD. The data for electricity production was converted into EJ and then scaled down to reflect electricity consumption (consumption < production) because the non-energy sectors demand electricity that can actually be consumed in their production processes from the energy sectors. The share of oil, gas and coal in the fossil electricity sector was calculated with data for the base year and is kept constant during the simulation.

Sector number	Biophysical output	Data source
12	electricity produced with fossil fuels (coal, gas, oil)	IEA (2021)
13	nuclear electricity	ibid.
14	hydroelectricity	ibid.
15	electricity from wind power plants	ibid.
16	electricity from bioenergy	OWD (2024)
17	electricity from solar	ibid.
18	estimated electricity from solar thermal	The IEA does not give explicit estimates of electricity from solar thermal, tidal energy and geothermal but rather gives data on 'other renewable energy' apart from hydropower. Thus, it is assumed that solar thermal, tidal and geothermal 'fill up' with equal shares the remaining gap between the sum of electricity from wind, solar and bioenergy, and amount of 'other renewable energy'. This yields a value in the same order of magnitude as the OWD data for 'other renewables' which include waste, geothermal, wave and tidal energy.
19	estimated electricity from tide	ibid.
20	estimated electricity from geothermal	ibid.

Table 9: Electricity sectors in MORDRED.

3.3.2. Biomass and fossil fuels

MORDRED also includes the production of energy from biomass and the production of fossil fuels (Table 10). One part of the fossil fuels is used as material feedstock rather than as energy source, and, thus, is matched to sector 8, while the remaining fossil fuels are matched with sector 3. Fossil-based electricity is produced in sector 12.

Sector number	Biophysical output	Data source
10	biofuels and energy from waste	IEA (2021)
3	oil, natural gas and coal products used as energy source; ‘other’ energy not contained in all the other sectors	ibid. This does not include fossil primary energy used for the production of fossil electricity. All values are for energy consumption rather than production.
8	oil, natural gas and coal products used as feedstock	ibid; p. 38-40 of the IEA’s Key World Energy Statistics report (2021) gives the percentage of non-energy use for the three types of fossil fuels for 2019. Applying those percentages to the overall fossil fuel consumption for each type gives the amount of fossil fuels used as feedstock.

Table 10: Fossil and biomass energy in MORDRED.

3.3.3. Link between biophysical and monetary values

The biophysical output of the sectors can be linked to their monetary output by dividing the former by the latter. This yields a conversion parameter α_i for every sector and allows the model to calculate the biophysical energy production associated to a certain monetary output of a sector.

$$\alpha_{biophysical:monetary_i} = \frac{X[final\ energy]_{i\,[EJ]}}{X[money]_s[mio€]}.$$

For sector 8, the conversion parameter links feedstock to monetary output.

$$\alpha_{feedstock_{ff}:money_8} = \frac{x[feedstock_{ff}]_{8\,[EJ]}}{x[money]_8[mio€]}$$ with *ff= oil, gas, coal*.

3.3.4. Primary energy

The data for the primary energy in 2019 comes from the IEA (2021). The conversion factor to calculate the primary energy of oil, gas and coal needed for fossil electricity production are based on ECOFYS estimates on average global efficiencies of coal, natural gas an oil-fired power generation (Nierop & Humperdinck, 2018).

3.3.5. Fossil fuel reserves and resources

Reserve and resource estimates included in MORDRED

We use estimates for different fossil fuel reserves and resources from the energy study of the German Federal Institute for Geosciences and Natural Resources (BGR, 2020, p. 41) which, except for the coal resource estimates are in the same order of magnitude as other estimates of future fuel production (e.g. Maggio & Cacciola, 2012; Mohr et al., 2015).

3.4. Land

3.4.1. Initial land and land types

The size of land used for human built infrastructure comes from Exiobase3 for the year 2019.

Energy land is the land needed for the extraction (biomass) as well as the installation and maintenance of different renewable energy technologies. The land demand from the energy sectors (sector 10, sector 14-20) in the initial moment of the simulation is obtained by multiplying the land intensity of the different energy sectors with their respective output.

Food land is required by the world economy to grow food and includes cropland and pastures. By aggregating the data of all cropland categories (n=13) and all pasture categories (n=3) in Exiobase3 for 2019 and subtracting the size of subsistence food land as well as the estimated size of land used to generate bioenergy we obtain the initial size of this land type.

Subsistence land is required by the subsistence economy to grow food and includes cropland and pastures. Since Exiobase3 does not differentiate between subsistence and global economy, we approximated the size of this land type by multiplying the estimated number of subsistence workers with the estimated land managed per subsistence worker.

The number of subsistence workers is determined by our initial assumptions about the population size living in subsistence (cf. section 3.2.1.2). The size of the land managed by each subsistence worker is assumed to be 1 ha, consistent with estimates on the farm size of smallholders (Altieri & Koohafkan, 2008; Lowder et al., 2025; Samberg et al., 2016).

The size of non-primary forests, i.e. secondary forest and forest plantations, at the beginning of the simulation is obtained by deducting the size of primary forests from the total forest land extension given by OWD (Ritchie & Roser, 2024) which is compatible with FAO forest data. The size of primary forest is based on estimates of FAO (2020).

The remaining habitable land (which does not include barren land (like deserts), glaciers or water bodies (like lakes)) contains non-forest ecosystems, marginalized lands and land not classified elsewhere, i.e. the Exiobase category 'other land'. The size of this land type in the initial moment of the simulation is derived by subtracting the sum of all previously discussed land types from the total habitable land on the Earth's surface without water bodies (Ritchie & Roser, 2024).

3.4.2. Production-driven land demand

The world economy in MORDRED generates demand for energy, food, forest and other land (cf. section 2.5) The land use intensity is measured in $\frac{km^2 Lnd}{mio€\ X_i}$.

Sector 1 is the only sector from which all demands for food land originate:

$$Int_{foodland\_we} = \left(\frac{Food\ Lnd_{t0}}{X_1}, 0_2, \ldots, 0_{25}\right)$$

Sector 2 is the only sector from which all demands for forest land originate:

$$Int_{prod\_frst} = (0_1, \frac{Forest\ Lnd_{t0}}{X_2}, 0_3, \ldots, 0_{25})$$

According to Exiobase3 data, in the initial moment of the simulation, the economic use of forest land covers 84% of non-primary forests.

In Exiobase3, sector 1 and 2 also demand 'Other Land':

$$Int_{Other} = \left(\frac{Other\ Lnd_{1t0}}{x_1}, \frac{Other\ Lnd_{2t0}}{x_2}, 0_3, \ldots, 0_{25}\right)$$

The energy sectors in MORDRED generate land use demands according to the energy demanded which in MORDRED is directly related to the outputs of the sectors.

Given the lack of data in Exiobase3 for land demanded by the energy infrastructure, we use data from the IAM MEDEAS (Capellán-Pérez et al., 2020) on the power density of different renewable energy technologies. MEDEAS does not include land use of mining and fossil fuel extraction, thus, there is a slight underestimation of demand.

The renewable energy sectors in MORDRED were matched to technologies contained in [MEDEAS]: sector 14 and sector 19 were matched to [hydropower]; sector 20 to [geothermal], sector 17 to [PV], sector 18 to [CSP], sector 15 to the average of [wind onshore] and [wind offshore], and finally, sector 16 and sector 10 were matched to [biofuels grown on cropland]. We chose the MEDEAS category [biofuels (cropland, second generation)] and neglect the category [biofuels (marginal land)] which has a lower productivity.

Subsequently, we obtained the land demand per energy production and energy production per output for every technology:

Sector 10:

$$power\ density_{10}\left[\frac{EJ}{km^2}\right] = \alpha_{10} * \left(\frac{Land\ productivity_{biofuels}}{Mha}\right) * \frac{Mha}{10^4 km^2}$$

$$\frac{Energy\ Lnd_{10}}{Energy_{10}} = \frac{1}{power\ density_{10}}$$

$\alpha_{10} = 1.8$ is a correction factor that takes into account that the output of sector 10 is assumed to also include energy from waste, other non-biofuel biomass-based energy and more advanced biofuel production, and that there can be a degree of co-use of land for food and energy production, both of which reduce land demand relative to energy production. This estimate should be improved in further work based on a meticulous assessment of global present and future land intensity of biomass-based energy that can substitute fossil fuels.

Sector 14:

$$power\ density_{14}\left[\frac{EJ}{km^2}\right]=\left[\frac{Twe_{hydro}}{Mha}\right]*\alpha_{we\rightarrow wh}\left[\frac{wh}{we}\right]*\left[\frac{3.6\ Mha*EJ}{10^7Twh*km^2}\right]$$

$\alpha_{we\rightarrow wh}$ denotes the conversion factor to wh.

$$\frac{Energy\ Lnd_{14}}{Energy_{14}}=\frac{1}{power\ density_{14}}$$

However, given that we assume that hydropower demands water bodies, and MORDRED does not contain water bodies (rivers, lakes etc.), this variable takes the value 0.

Sector 15:

$$power\ density_{15}\left[\frac{EJ}{km^2}\right]=\left[\frac{\frac{Twe_{wind\ onshore}}{Mha}+\frac{Twe_{wind\ onshore}}{Mha}}{2}\right]*\alpha_{we\rightarrow wh}\left[\frac{wh}{we}\right]*\left[\frac{3.6\ Mha*EJ}{10^7Twh*km^2}\right]$$

$$\frac{Energy\ Lnd_{15}}{Energy_{15}}=\frac{1}{power\ density_{15}}$$

Sector 16:

$$power\ density_{16}\left[\frac{EJ}{km^2}\right]=\alpha_{16}*\frac{Land\ productivity_{biofuels}}{Mha}*\frac{Mha}{10^4km^2}$$

α_{16}=1.18 is a correction factor as we optimistically assumed that biomass-based electricity can be compared to advanced generations biofuel production regarding land intensity.

$$\frac{Energy\ Lnd_{16}}{Energy_{16}}=\frac{1}{power\ density_{16}}$$

Sector 17:

The power density given in MEDEAS 1.4 corresponds to the average value given in de Castro (2013). The power density can be calculated following the formula given in de Castro (2013) which multiplies (a) the average solar irradiance by (b) the conversion efficiency of solar radiation into electricity, (c) the averaged performance ratio over the park's life cycle and (d) the actual land occupation of PV cells. (a) and (c) are adopted from de Castro (2013) and (d) from Capellán-Pérez et al. (2017) while we choose a value of 0.2 for (b) to reflect a higher cell conversion efficiency in the future. This yields a power density value slightly above the upper bound for future power density given in de Castro (2013).

$$power\ density_{17}\left[\frac{EJ}{km^2}\right]=\frac{Twe_{solar\ PV}}{Mha}*\alpha_{we\rightarrow wh}\left[\frac{wh}{we}\right]*\left[\frac{3.6\ Mha*EJ}{10^7Twh*km^2}\right]$$

$$\frac{Energy\ Lnd_{17}}{Energy_{17}}=\frac{1}{power\ density_{17}}$$

Sector 18:

$$power\ density_{18}\left[\frac{EJ}{km^2}\right]=\left[\frac{Twe_{CSP}}{Mha}\right]*\alpha_{we\rightarrow wh}\left[\frac{wh}{we}\right]*\left[\frac{3.6\ Mha*EJ}{10^7Twh*km^2}\right]$$

$$\frac{Energy\ Lnd_{18}}{Energy_{18}} = \frac{1}{power\ density_{18}}$$

Sector 19: this technology takes the same intensity as sector 14.

Sector 20:

$$power\ density_{20}\left[\frac{EJ}{km^2}\right] = \left[\frac{Twe_{geothermal}}{Mha}\right] * \alpha_{we\rightarrow wh}\left[\frac{wh}{we}\right] * \left[\frac{3.6\ Mha * EJ}{10^7 Twh * km^2}\right]$$

$$\frac{Energy\ Lnd_{20}}{Energy_{20}} = \frac{1}{power\ density_{20}}$$

$\frac{Energy_i}{X_i}$ for every sector is calculated based on the data contained in the energy and the economy module.

We calculated the intensities of land demand for the different energy sectors in km^2/mio€:

$$Intensity_{i_{Energy\ Lnd}} = \frac{Energy\ Lnd_i\ [km^2]}{Energy_i\ [EJ]} * \frac{Energy_i\ [EJ]}{X_i\ [mio€]}$$

$$Intensity_{19_{Energy\ Lnd}} = Intensity_{14_{Energy\ Lnd}}$$

3.4.3. Consumption-driven land demand

In MORDRED, demand for infrastructure is assumed to correlate with overall household consumption since, arguably, there is not a single sector driving the demand for infrastructure. The more households consume, the more infrastructure has to be build to deliver the products, the more expansion of settlements becomes possible etc.

$$Int_{infr} = \left(\frac{Infrastructure_{t0}}{\sum_{s=i}^{25} C_i}\right)$$

3.4.4. Population-driven land demand

In MORDRED, the overall population living in subsistence is assumed to drive the quantity of the subsistence sector's land demand.

$$Int_{sub\_lnd}^{Lnd,bd} = \left(\frac{Sub\_Lnd_{t0}}{\sum_{r=1}^{3} P_r^{sub}{}_{t0}}\right)$$

This gives the land demand per member of the subsistence class.

3.5. Climate

3.5.1. Climate system

The climate module is a greatly simplified and updated version of the climate module contained in the system dynamics model WILIAM 1.3 (Lifi et al., 2023; Samsó et al., 2023), which in turn is based on the climate sub-module contained in the C-Roads model.

In MORDRED 1.0 there are three climate feedbacks that can be activated. The first activated feedback affects C uptake in response to temperature changes. The second activated feedback affects changes in natural CH_4 emissions in response to temperature changes. The last feedback determines whether there are any emissions from permafrost and clathrate when certain temperature thresholds are crossed. Additionally, the ECS value can be modified, as well as the sensitivity of CH_4 and C from permafrost and clathrate to temperature changes and the temperature threshold for CH_4 emissions from permafrost and clathrate.

Apart from removing variables and submodules not considered strictly necessary for this part of MORDRED, e.g. the submodule on tipping points or waste emissions, sea-level sensitivity from ice-sheet melting, climate-related variables at the regional level, …) the following modifications were made to the climate submodel incorporated in WILIAM:

Reserves and resources for three types of fossil fuels (coal, gas, oil) were added, based on estimations of the BGR (2020), which are used by the IPCC WG1 contribution to the AR6 (IPCC, 2021). This completes the carbon cycle part of the climate module as anthropogenic combustion of fossil fuels create a flow from fossil fuel reserves/resources to the atmosphere.

MORDRED-specific variables for CO_2 emissions from land use changes were introduced into the climate module. These are calculated in the Stressors module (cf. section 3.7).

The variables used to calculate sea-level rise were modified to reflect the starting year of MORDRED simulations.

Given that Exiobase3 does not distinguish between different HFC types, we assume that all HFC emissions in MORDRED are of the type HFC134a. Given the different warming potentials of different HFC types, this could yield a small estimation error which is assumed to be negligible due to the relatively small contribution of HFC gases to global warming.

The values of the model parameters (such as the climate sensitivity, preindustrial concentration of different greenhouse gases, global warming potentials of different greenhouse gases etc.) have been updated according to WG1 IPCC (2021) and according to the newest C-Road model version.

The calculation of different GHG emissions in MORDRED does not distinguish between several regions and uses emission intensities from Exiobase3 for CH_4, N_2O, HFC, PFC and SF_6.

The value for the variable ‘Other forcings’ was calculated based on values given in Table 7.8 IPCC WG1 (2021). This variable is needed to calculate total anthropogenic ERF which is estimated as 2.72 W/m^2 over the industrial era by the IPCC and is set to 2.70 W/m^2 in MORDRED in the initial moment of the simulation.

3.5.2. Climate damages

3.5.2.1. Capital stock

Extreme weather events

Extreme weather events of different types cause damages in capital stock and are assumed to increase in frequency and severity as global temperatures increase (IPCC, 2021).

To obtain the sectoral shares of capital damages from extreme weather events compared to the overall sectoral stock at the global level, we follow three steps.

First step: estimation of total capital stock damage at 4°C:

The estimated total global damages of capital stock (DK) from extreme weather events at 4 degrees of global warming are calculated as:

$$DK_{total_{4°C}} = \sum_{e=1}^{4}\left(\left(D_{2010-2019_{>billion\$\,events_e}} + D_{2010-2019_{<billion\$\,events_e}}\right) * \alpha_{World_e} * \alpha_{f,i_{minmax_e}} * \alpha_{compound}\right) + D_{2010-2019_{hw}} * \alpha_{World_{hw}} * \alpha_{f,i_{minmax_e}} * \alpha_{compound}$$

e denotes the type of extreme weather event with $e_1 = drought, e_2 = flood, e_3 = storm, e_4 = wildfire, e_5 = heatwave\ (hw)$.

For the first 4 types of extreme weather events we use the NCEI data on billion-dollar events that affected the USA over the period 2010 to 2019 (A. Smith, 2025). For the fifth type we use estimates by Forzieri et al. (2018) for Europe (EU28, Switzerland, Norway and Iceland). To obtain the estimated heatwave damages in the period 2010-2019, a weighted average is taken between the damages occurring between 1981 and 2010, and the damages they calculate for 2020. The data for the first 4 types is converted into 2015-USD, using the CPI deflator, while the data for the fifth type is converted into 2015-€, using the EZB GDP deflator.

The data of the NCEI only provides data for $D_{2010-2019_{>billion\$\ events_e}}$. To estimate $D_{2010-2019_{<billion\$\ events_e}}$ we assume an inverse relationship between the frequency of an event and the severity of the damages: $D_{2010-2019_{<billion\$\ events_{e=1,2,3,4}}} = \sum_{n=1}^{4} \alpha_{freq}{}^{n} * \frac{D_{<billion}}{2^{(n-1)}}$ and apply a maximum of 4 billion which could lead to a slight underestimation of this type of damage. α_{freq} and $D_{<billion}$ take the same value for all e.

$D_{2010-2019_{hw}}$ is obtained by multiplying the share of heatwave-related damages in the total capital stock of the EU with the capital stock of the US based on EUKLEMS capital stock data for 2015. EUKLEMS does not contain data for Switzerland, Norway and Iceland. However, it is assumed that, due to their geography, these countries bear an insignificant amount of heatwave related damages, thus, we assume that they are de facto excluded from both damages and stock.

$$D_{2010-2019_{hw}} = \frac{D_{hw_{2010-2019_{EUplus}}}}{total\ K_{2015_{EUplus}}} * total\ K_{2015_{US}}$$

α_{World_e} is an adjustment factor that takes into account that we are estimating global capital stock damages based on country-specific data, i.e. the US (for the first 4 types of extreme weather events) and Europe (for the last type).

Extreme weather type	Reasoning adjustment	α_{World_e}
Drought	Drought-risks outside of the US are significantly higher (Meza et al., 2020).	1.5
Flood	No significant difference in vulnerability assumed.	1
Storm	No significant difference in vulnerability assumed.	1
Wildfire	No significant difference in vulnerability assumed.	1
Heatwave	World outside of EUplus is significantly more exposed to heatwaves (Hu et al., 2023).	2

Table 11: Adjustment factors for extreme weather damages.

$\alpha_{f,i_{minmax_e}}$ is a multiplier to take into account changes in damages as global temperatures increase to 4°C due to an increase in the frequency and intensity of different types of extreme weather events.

Based on IPCC (2021), Ch.11 estimates on temperature-related increases in the intensity and frequency of extreme weather events, we obtain a minimum and a maximum value for every extreme weather type that describes the change in damages at 4 °C compared to 1 °C of global temperature change. In the public MORDRED 1.0 version, the minimum value is used.

Last, $\alpha_{compound}$ is a factor that takes into account the increased severity of damages caused by compound events, i.e. by similarly occurring extreme weather events.

$D_{total_{4°C}}$ gives an estimate of damages in capital stock at 4 degrees of warming for a fictitious ‘world’ of the economic size of the US. Of course, the ‘real’ damages would be significantly higher. However, since we are interested in the ratio between capital damages and capital stock, and we divide the damages by the capital stock of the US (see below), this 'error' is insignificant.

Second step: capital stock data

Capital stock data for the US for 2015 comes from EUKLEMS. We obtain the total capital stock (K_{total}) as well as the capital stock of specific sectors especially affected by climate damages. The latter were matched with the MORDRED sectors.

EUKLEMS sector description and abbreviation	MORDRED sector
Agriculture, forestry and fishing_stock (A)	1
Manufacture of food products; beverages and tobacco (C10-C12)	
Transportation and storage (H)	21
Electricity, gas, steam; water supply, sewerage, waste management (D-E)	[12;20], 3, 8, 24, 25
Manufacture of coke and refined petroleum products (C19)	

Table 12: Matching EUKLEMS sectors with MORDRED sectors for climate damage calculations.

Thus, the capital stock of sector 1 (K_1) is approximated as the sum of the capital stock in A and C10-C12; the capital stock of sector 21 (K_{21}) is approximated as H, and the capital stock of sector 3, 8, 24, 25 and all forms of electricity (sectors 12 to 20) ($K_{3,8,12,13,14,15,16,17,18,19,20,24,25}$) is approximated as the sum of D-E and C19. Summing up these capital stocks gives the overall 'vulnerable' capital stock:

$$K_{vulnerable} = K_1 + K_{21} + K_{3,8,12,13,14,15,16,17,18,19,20,24,25}$$

Third step: sectoral shares of damages in stock

One part of the overall damage at 4 degree of global warming is assumed to affect the whole economy, i.e. all sectors. The rest of the overall damage is assumed to be concentrated in sectors assumed to be especially vulnerable to climate damages. These sectors experience an additional damage apart from the general damage.

$$D_{4°C_{all\ sectors}} = \beta_{split} * D_{total_{4°C}}\ ;\ add.D_{4°C_{vulnerable\ sectors}} = (1-\beta_{split}) * D_{total_{4°C}}$$

In MORDRED 1.0, β_{split}=0.7.

With this assumption, the sectoral shares of damages in the stock of the respective sectors can be calculated.

$$share_{damage\ in\ K_{2,4,5,7,9,11,22,23}} = \frac{D_{4°C_{total}}}{K_{total}} = \beta_{2,4,5,7,9,11,22,23}^{\delta\_temp}$$

$$share_{damge\ in\ K_{1,3,8,12,13,14,15,16,17,18,19,20,21,24,25}} = \frac{D_{4°C_{total}}}{K_{total}} + \frac{add.D_{4°C_{vulnerable}}}{K_{vulnerable}} = \beta_{1,3,8,12,13,14,15,16,17,18,19,20,21,24,25}^{\delta\_temp}$$

The sectoral shares of damage from extreme weather events in capital stock are assumed to increase non-linearly to reach the values corresponding to an increase of 4°C when the temperature in the model reaches 4 °C.

$$\delta_i^{temp} = \beta_i^{\delta\_temp} * \frac{(temp - 1)^2}{9}$$

Sea-level rise

Under a high-emission scenario and/or Antarctic instability, between 4% and 7 % of the global population could be flooded annually by the end of the century (cf. Hinkel et al., 2014; Kulp & Strauss, 2019). We assume that population is directly correlated to the size of the capital stock, and that capital assets are more concentrated in coastal areas (e.g. ports, refineries etc.). Thus, we assume that between 6% and 9% of the global capital assets could be threatened by annual flooding under a temperature increase of ~4 °C.

We assume that half of the capital stock can be protected by hard coastal protection (e.g. dykes) while the other half is lost as populations realize a managed retreat. This leads to an overall loss of 3% to 4.5% of global capital stock as temperatures approach and cross the 4°C mark.

The modeling of sea-level rise related damages is described in section 2.2.

3.5.2.2. Capital intensity and input coefficients

Agriculture

Output losses in sector 1 mean that to produce the same amount of output as before, more capital stock is needed. We consider output losses due to insect pests (Deutsch et al., 2018) and heat (Zhao et al., 2017). The losses per unit of output (or the percentage of losses in total output) due to these stressors are:

$\beta^{X\_loss} = (\alpha_{insects} + \alpha_{heat})$ for 4 °C of warming.

Consequently, capital intensity in sector 1 increases as a function of temperature (see section 2.2).

The factor multiplied with the column in the A matrix corresponding to sector 1 is given as:

$$Adf^{io}(\Delta Temp = 4) = \frac{1}{(1 - \beta^{X\_loss})}$$

which is parametrized as

$$Adf^{io} = \beta0^{Adf\_io} + \beta1^{Adf\_io} \cdot \Delta Temp + \beta2^{Adf\_io} \cdot \Delta Temp^2$$

3.5.2.3. *Additional investment*

Sea-level rise

The costs for the hard coastal protection is modeled as additional investment in sector 5, which includes the construction sector.

We take half of the costs for dyke construction from Hinkel et al. (2014) in a RCP8.5 scenario (because we assume that only half of the coastline can be protected while the other is 'lost'), convert them to 2019-€ and multiply the costs by a factor of 2 because they do not take into account that a loss of coral reef protection implied by temperature changes higher than 1.5 °C to 2 °C doubles the exposure of built capital and people to flooding (Beck et al., 2018). It is further assumed that the total coastal protection system has to be renewed once during the simulation.

$$Extra\_GFCF_5^{slr} = \frac{costs_{Hinkel\ et\ al._{2019€}} * \alpha_{coral\ reef\ loss} * \alpha_{life\ time}}{2}$$

3.5.2.4. *Labor force, working day, maximum labor supply*

We assume no additional effects on mortality due to climate change impacts such as the spread of vector- or water-borne diseases or the increase in natural disasters given that the actual effect of those factors on mortality are strongly mediated by the socio-economic context (Béguin et al., 2011; Franklinos et al., 2019).

However, we assume that the annual working hours can be negatively affected by increases in deadly heat (Mora et al., 2017).

$$\beta^{HB\_Max\_Lb} = \frac{days_{deadly\ heat}}{days_{year}} * \frac{workers_{low\ resistance}}{workers}$$

$\frac{days_{deadly\ heat}}{days_{year}}$ describes the share of days with deadly heat in a year, and $\frac{workers_{low\ resistance}}{workers}$ denote the share of workers that are not able to work due to deadly heat conditions. $\frac{days_{deadly\ heat}}{days_{year}}$ is estimated based on Mora et al. (2017) while $\frac{workers_{high\ resistance}}{workers}$ is assumed to be 0.5.

3.5.2.5. *Labor intensity*

Heat

The literature finds that for 3 °C global effective labor (which includes both a drop in productivity and a reduction in hours worked) decreases by 18% ($\alpha_{Lprod_{low}}$) for low-exposure and by 25% ($\alpha_{Lprod_{high}}$) for high exposure activities (Dasgupta et al., 2021). For simplicity, we assume that the hours worked remain constant, with a de facto labor productivity of zero for those hours that people do no longer work.

Low-exposure working conditions are defined as work outside in the shade or indoors while high-exposure working conditions are defined as works outside with no shade. The MORDRED sectors were classified as having predominantly low or high exposure working conditions.

Predominantly high-exposure	Sector 1, 4, 5
Predominantly low-exposure	rest of sectors

Table 13: Low- and high-exposure sectors.

$$\beta_{1,4,5}^{HB\_Lb\_prod} = 1 - \alpha_{Lprod_{high}}$$

$$\beta_{!=1,4,5}^{HB\_Lb\_prod} = 1 - \alpha_{Lprod_{low}}$$

Loss in Output

In the case of sector 1, the assumed output loss (section 3.6.2.2) also implies an additional reduction of labor productivity in this sector (see section 2.2).

3.5.2.6. Land

All estimates on land losses are cumulative values rather than annual values.

Sea level rise

To estimate the total land lost until the end of the century (β^{Lnd_loss}) in a high-emission scenario, we draw an average between the land loss estimate of Bamber et al. (Bamber et al., 2019) and the higher of the two estimates made by Hinkel et al. (2014) given that in a high-emission scenario the natural coastal protection by mangroves and reefs will be severely weakened or lost. We divide this average value by 2 since we assume that half of the inundation-threatened land will be maintained through hard coastal protection (cf. section 3.6.2.2).

River floods

The literature provides estimates on the amount of flood-prone global cropland that would be exposed to a doubling of current 100-year flood frequency by 2050 in a high-emission scenario (Arnell et al., 2016), and the risks can be expected to increase until the end of the century. Thus, we assume that half of this exposed cropland will be rendered unsuitable for agriculture and lost. Although the authors do not mention deltas, it is very probable that the land loss will concentrate in the world's deltas (Nienhuis & van de Wal, 2021).

Temperature, humidity change

Zhang & Cai (2011) calculate changes in potential arable land areas under different climate change scenarios. Given that in MORDRED it is optimistically assumed that forestland can always be converted into land to grow food, we sum only the negative changes, i.e. losses, for the different world regions indicated in the study, and draw an average between the total land lost in the A1B-SAM and the A1b-RMSEMM scenario.

The total loss of cropland as a function of temperature is given as:

$$L\beta^{Foodland\_loss} = Loss_{floods} + Loss_{temp\&humid}$$

3.5.2.7. Land intensity

Sector 1

In the case of sector 1, the assumed output loss (cf. section 3.6.2.2) also implies a reduction of land productivity in this sector.

Damages on subsistence land

It is assumed that as temperature increases and extreme weather events become more severe and frequent, less people can be sustained per unit of land.

$$\beta^{Ext\_Int\_Lnd\_sub} = \frac{Int_{sub\_lnd}^{Lnd,bd}}{3}$$

3.6. Stressors

All stressors are represented in the form of 'intensities'. Most stressors take the form [stressor / monetary output] but some also take the form [stressor / land] or [stressor / energy]. In the first case stressors are represented as 25-dimensional vectors and contain the intensity for every sector. To construct these vectors, for every sector the quantity of the stressor emanating from the sector is divided by the sector's output.

In the case of stressors apart from emissions, we obtain all the data from the Exiobase3 extension (.F) which gives the stressor in absolute quantities. These quantities are matched to the sectors generating the stressors and divided by the sectoral outputs to obtain the respective sectorial intensities.

3.6.1. Greenhouse gas emissions

3.6.1.1. CO2 emissions

CO2 emissions from fossil fuel combustion

The data for CO2 emissions from fossil fuel combustion comes from the IEA (IEA, 2021, p. 54) and is compatible with the data contained in Exiobase3. Given that this category concerns combustion, fossil fuels that are used as feedstock are not considered. For every fossil fuel (oil, gas, coal) the emission intensity is calculated as Mt of CO2 emitted per EJ of primary energy of this fuel.

$$Int_{CO2:Combustion_{ff}} = \frac{CO2_{ff}\ [Mt]}{PE_{ff}^{neu}\ [EJ]}$$

CO2 emissions from land use changes

MORDRED includes estimates of emissions resulting from the conversion of forest land into infrastructure, land used for energy generation, land used for cultivation of food within the global economy, land used for food within the subsistence economy and into 'other land'.

Emissions from land use changes were approximated in the following way:

First, we estimate the carbon content per unit of forest land above and below the ground.

$$Int_{Carbon} = \frac{Carbon_{above}\ [Mt\ C] + Carbon_{below}[Mt\ C]}{Forest\ land\ [km^2]}$$

To obtain an Int_{Carbon} which is representative of different forest types, we take the average of the carbon content in tropical rainforests and boreal coniferous forests, as these represent the two extreme ends of the spectrum — high above-ground and low below-ground carbon in tropical forests, and the opposite pattern in boreal forests, using data from Houghton & Castanho (2023).

Second, we estimate the carbon which is lost per unit of forest land that is converted into another land type in a time step.

$$Carbon\ lost = \frac{Carbon_{above_{t0}} - Carbon_{above_{t1}} + Carbon_{below_{t0}} - Carbon_{below_{t1}}}{Forest\ land\ [km^2]}$$

If forest is converted to infrastructure it is assumed that the carbon above ground is almost entirely lost given the difficulty of having forest vegetation and hard infrastructure at the same place. The literature indicates that carbon below ground is also lost at a significant rate (Tao et al., 2015). Thus,

$$Carbon_{above_{t1}} = 0.05 * Carbon_{above_{t0}}$$

and

$$Carbon_{below_{t1}} = 0.5 * Carbon_{below_{t0}}$$

For the conversion of forest to energy land it is assumed that the carbon above ground is almost entirely lost given the difficulty of having forest vegetation and energy infrastructure at the same place while it is optimistically assumed that no carbon below ground is lost. Thus,

$$Carbon_{above_{t1}} = 0.05 * Carbon_{above_{t0}}$$

$$Carbon_{below_{t1}} = Carbon_{below_{t0}}$$

For the conversion of forest to industrialized agriculture the loss of above-ground carbon for conversion to cropland and pasture was estimated based on Houghton et al. (2012) by comparing the above-ground carbon content of tropical rainforests with the carbon content of cropland and pasture after conversion. Since conversion into cropland results in higher carbon losses than conversion into pasture, and since the shares of cropland and pasture are not the same, the average of carbon loss associated to cropland and pasture is weighted with the shares these land types have in 'food land' claimed by the global economy in the initial moment of the simulation.

Consequently,

$$Carbon_{above_{t1}} = (\alpha_{cropInd}^{we} * 0.389 * Carbon_{above_{t0}} + \left(1 - \alpha_{cropInd}^{we}\right) * 0.505 * Carbon_{above_{t0}})$$

$$Carbon_{below_{t1}} = Carbon_{below_{t0}}$$

with $\alpha_{croplands_S}$ denoting the share of cropland, and $1 - \alpha_{croplands_S}$ denoting the share of pasture in total food land.

For the conversion of forest to subsistence agriculture, we use data from Houghton et al. (2012) calculate a weighted average based on the estimated shares of cropland and pasture within subsistence land (given the low-intensity use of grassland, we conservatively assume that on average the share of cropland in total land used by the subsistence economy is 0.4). Thus,

$$Carbon_{above_{t1}} = \left(\alpha^{sub}_{croplnd} * 0.389 * Carbon_{above_{t0}} + \left(1 - \alpha^{sub}_{croplnd}\right) * 0.505 * Carbon_{above_{t0}}\right)$$

$$Carbon_{below_{t1}} = Carbon_{below_{t0}}$$

For the conversion of forest to other land we assume the same carbon loss as conversion to industrialized agriculture, thus, we optimistically assume that those lands tend to be used for agriculture rather than for infrastructure and energy generation.

For simplicity, we assume that a conversion of primary into secondary forests or forest plantations will not result in additional emissions. Depending on the management, managed forests can accumulate more carbon than secondary forests (Brown et al., 2020).

Last, we convert the lost carbon into CO2 by multiplying with a factor $\gamma_{C \to CO2}$.

The resulting stressors take the form

$$Int_{CO2:conversion_{Lnd}} = Carbon\ lost_{Lnd} * \gamma_{C \to CO2}$$

CO2 emissions from other processes

Exiobase3 contains information on CO2 emissions that do not stem from the direct combustion of fossil fuels but are generated in the waste sector, in industry due to cement and lime production, and in agriculture due to peat decay. Consequently, the respective emissions were matched with the sectors 1,5, 24 and *25.*[6] Given that we assume that a conversion to agricultural land implies no loss of carbon below the ground (soil carbon) (cf. section 8.1.1.2) when calculating the emissions due to land use, including CO2 emissions from agriculture does not constitute a double counting of emissions.

$$Str_{CO2:other} = \left(\frac{CO2_{agriculture}}{X_1}, 0_2, 0_3, 0_4, \frac{CO2_{cement}}{X_5}, \ldots, \frac{CO2_{fossil\ waste}}{X_{24}} + \frac{CO2_{biogenic\ waste}}{X_{24} + X_{25}}, \frac{CO2_{biogenic\ waste}}{X_{24} + X_{25}}\right)$$

In section 8.1.1.1, we did not include fossil fuels used as feedstock. Eventually, the latter also emit CO2 but with a time lag that can be significant. It is assumed that the annual emissions from sector 24 include the emissions generated by fossil feedstock at their end of life. Due to a lack of more specific data, this intensity is assumed to be constant in MORDRED which can lead to estimation errors regarding the emissions from fossil resources used as feedstock as the simulation develops.

[6] CO2 emissions from biogenic waste were matched equally to sector 24 and 25 while CO2 emissions from fossil waste were only matched to sector 24.

1.7.1.2. *Other greenhouse gas emissions*

The information on emissions of other greenhouse gas emissions comes from the Exiobase3 extension ".F" which gives the emissions in absolute quantities. The extension .F contains a list of stressors that were matched to the MORDRED sectors.

Greenhouse gas	Stressor	Sector number
CH4	combustion – air	10, 25
	waste - air	24, 25
	non combustion - Extraction/production of (natural) gas - air	3, 8
	non combustion - Extraction/production of crude oil - air	
	non combustion - Mining of antracite - air	
	non combustion - Mining of bituminous coal - air	
	non combustion - Mining of coking coal - air	
	non combustion - Mining of lignite (brown coal) - air	
	non combustion - Mining of sub-bituminous coal - air	
	non combustion - Oil refinery - air	
	agriculture - air	1
N2O	combustion - air	3
	agriculture	1
SF6	air	12, 13, 14, 15, 16, 17, 18, 19, 20
HFC	air	11
PFC	air	4, 5, 25

Table 14: Greenhouse gas emissions and sectors causing them.

The units of the Exiobase3 data were modified to fit the climate module, which most notably involved converting the CO2 equivalents of HFC and PFC in Exiobase3 into tons of HFC and PFC, using the GWP-100 values given by the IPCC for HFC134-a and PFC-14 in the Supplementary Material for Chapter 7 of the Contribution of WGI to AR6 (C. Smith et al., 2021, pp. 17, 21).

The resulting stressors are:

$$Int_{CH4} = \left(\frac{CH4_{agriculture}}{X_1}, 0_2, \frac{\sum CH4_{combustion}}{X_3 + X_8}, 0_4, 0_5, 0_6, 0_7, \frac{\sum CH4_{combustion}}{X_3 + X_8}, 0_9, \frac{CH4_{combustion}}{X_{10} + X_{25}}, 0_{11}, \dots, \frac{CH4_{waste}}{X_{24} + X_{25}}, \frac{CH4_{combustion}}{X_{10} + X_{25}} + \frac{CH4_{waste}}{X_{24} + X_{25}}\right)$$

$$Int_{N2O} = \left(\frac{N2O_{agriculture}}{X_1}, 0_2, \frac{N2O_{combustion}}{X_3}, 0_4, 0_5, \dots, 0_{25}\right)$$

$$Int_{SF6} = \left(0_1, \dots, 0_{11}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, \frac{SF6}{\sum_{i=12}^{20} X_i}, 0_{21}, \dots, 0_{25}\right)$$

$$Int_{HFC} = \left(0_1, 0_2, \dots, \frac{HFC}{X_{11}}, \dots, 0_{25}\right)$$

$$Int_{PFC} = \left(0_1, \dots, 0_3, \frac{PFC}{X_4 + X_5 + X_{24}}, \frac{PFC}{X_4 + X_5 + X_{24}}, 0_6, \dots, 0_{23}, \frac{PFC}{X_4 + X_5 + X_{24}}, 0_{25}\right)$$

3.6.2. Water

3.6.2.1. Industrial water consumption

Exiobase3 differentiates between green and blue water consumption.

Green water consumption results mainly from agricultural activity. Thus, all green water stressors in Exiobase3 were aggregated and matched to sector 1.

$$WC_{green} = \left(\frac{\sum_{v=1}^{13} Green\ water_v\ [mm3]}{X_1\ [mio€]}, 0_2, \dots, 0_{25} \right)$$

v denotes the different agricultural sub-sectors in which the water is used (rice, wheat, other cereals, roots and tubers, sugar crops, pulses, nuts, oil crops, vegetables, fruits, fibres, other crops, fodder crops).

Blue water consumption results from agricultural as well as from industrial activity. The sub-stressors were matched to the following sectors:

Sector no.	Sub-Stressor	w
1	Water Consumption Blue - rice	1
	[...] wheat	2
	[...] other cereals	3
	[...] roots and tubers	4
	[...] sugar crops	5
	[...] pulses	6
	[...] nuts	7
	[...] oil crops	8
	[...] vegetables	9
	[...] fruits	10
	[...] fibres	11
	[...] other crops	12
	[...] fodder crops	13
	[...] Livestock - dairy cattle	14
	[...] Livestock - nondairy cattle	15
	[...] Livestock - pigs	16
	[...] Livestock - sheep	17
	[...] Livestock - goats	18
	[...] Livestock - buffaloes	19
	[...] Livestock - camels	20
	[...] Livestock - horses	21
	[...] Livestock - chicken	22
	[...] Livestock - turkeys	23
	[...] Livestock - ducks	24
	[...] Livestock - geese	25
	[...]Products of meat cattle	26
	[...]Products of meat pigs	27
	[...]Products of meat poultry	28
	[...] Meat products nec	29
	[...]products of Vegetable oils and fats	30

	[...] Manufacturing - Dairy products	31
	[...] Processed rice	32
	[...] Sugar	33
	[...] Food products nec	34
	[...] Beverages	35
	[...] Fish products	36
2	[...] Tobacco products (16)	37
	[...] Textiles (17)	38
	[...] Wearing apparel; furs (18)	39
	[...] Leather and leather products (19)	40
	[...] Paper and paper products	41
7	[...] Printed matter and recorded media (22)	42
9	[...] N-fertiliser	43
	[...] P- and other fertiliser	44
	[...] Chemicals nec	45
	[...] Rubber and plastic products (25)	46
5	[...] Glass and glass products	47
	[...] Plastics, basic	48
	[...] Pulp	49
	[...] Cement, lime and plaster	50
	[...] Basic iron and steel and of ferro-alloys and first products thereof	51
	[...] Precious metals	52
	[...] Aluminium and aluminium products	53
	[...] Lead, zinc and tin and products thereof	54
	[...] Copper products	55
	[...] Other non-ferrous metal products	56
11	[...] Ceramic goods	57
	[...] Bricks, tiles and construction products, in baked clay	58
	[...] Other non-metallic mineral products	59
	[...] Fabricated metal products, except machinery and equipment (28)	60
	[...] Machinery and equipment n.e.c. (29)	61
	[...] Office machinery and computers (30)	62
	[...] Electrical machinery and apparatus n.e.c. (31)	63
	[...] Radio, television and communication equipment and apparatus (32)	64
	[...] Medical, precision and optical instruments, watches and clocks (33)	65
	[...] Motor vehicles, trailers and semi-trailers (34)	66
	[...] Other transport equipment (35)	67
	[...] Furniture; other manufactured goods n.e.c. (36)	68
12	[...] Electricity - tower - Electricity by coal	69
	[...] Electricity - tower - Electricity by gas	70
	[...] Electricity - tower - Electricity by petroleum and other oil derivatives	71
	[...] Electricity - once-through - Electricity by coal	72
	[...] Electricity - once-through - Electricity by gas	73

	[...] Electricity - once-through - Electricity by petroleum and other oil derivatives	74
13	[...] Electricity - tower - Electricity by nuclear	75
	[...] Electricity - once-through - Electricity by nuclear	76
16	[...] Electricity - tower - Electricity by biomass and waste	77
	[...] Electricity - once-through - Electricity by biomass and waste	78
18	[...] Electricity - tower - Electricity by solar thermal	79
	[...] Electricity - once-through - Electricity by solar thermal	80
20	[...] Electricity - tower - Electricity by Geothermal	81
	[...] Electricity - once-through - Electricity by Geothermal	82

Table 15: Matching blue water sub-stressor to MORDRED sectors.

The resulting stressor is:

$$Int_{WC_{blue}} = \left(\frac{\sum_{w=1}^{36} Blue\ water_w}{X_1}, \frac{\sum_{w=37}^{41} Blue\ water_w}{X_2}, 0_3, 0_4, \frac{\sum_{w=47}^{56} Blue\ water_w}{X_5}, \dots, \frac{Blue\ water_{42}}{X_7}, \ 0_8, \frac{\sum_{w=43}^{46} Blue\ water_w}{X_9}, 0_{10}, \frac{\sum_{w=57}^{68} Blue\ water_w}{X_{11}}, \frac{\sum_{w=69}^{74} Blue\ water_w}{X_{12}}, \frac{\sum_{w=75}^{76} Blue\ water_w}{X_{13}}, \frac{\sum_{w=75}^{76} Blue\ water_w}{X_{13}}, 0_{14}, 0_{15}, \frac{\sum_{w=77}^{78} Blue\ water_w}{X_{16}}, 0_{17}, \frac{\sum_{w=79}^{80} Blue\ water_w}{X_{18}}, 0_{19}, \frac{\sum_{w=81}^{82} Blue\ water_w}{X_{20}}, 0_{21}, \dots 0_{25}\right)$$

3.6.2.2. Industrial water withdrawal

The stressors for industrial blue water withdrawal are the same as for industrial blue water consumption. Consequently, they are matched to the different sectors according to section 3.7.2.1, and the stressors are calculated by dividing the sum of all sub-stressors by the output of the respective sectors.

3.6.2.3. Household water consumption

The intensity of the water consumption of households is derived by dividing the total household water consumption given in Exiobase3 by the global aggregated consumption of all households. This either neglects the water consumption of the subsistence class or slightly overestimates the water consumption of the population sustained completely by the global economy (in the case that the water consumption of the subsistence class is contained in Exiobase3 through estimations).

$$Int_{WC} = \left(\frac{Q_{water}}{C}\right)$$

3.6.3. Material extraction and mineral production

Remark: In the following, we describe the data used for MORDRED 1.0 which is based on Exiobase3 data on used and unused domestic extraction. In some extended versions (e.g. 1.0.5, 1.1.1), we use global mineral production data rather than used domestic extraction for those materials for which there are global estimates provided by the US Geological Survey (USGS, 2020) or by secondary sources (Henckens, 2021), namely aluminium, copper, gold, iron, lead, nickel, silver, tin, zinc, kaolin clay and salt. Intensities are derived in the same way. For the rest of materials, the Exiobase data on used material extraction is kept. Note that we used version Exiobase3 version 3.8.2 when we started with the development of the model. There is a new version available (3.9.6) which updates used domestic extraction and excludes unused domestic extraction. The newer data could be used to improve data quality for this part of the stressor module.

3.6.3.1. Used material extraction

The basic version of MORDRED includes the used domestic material extraction intensity in kt/mio€ for 19 materials as given by Exiobase3 for 2019: m_1= Bauxite and aluminium, m_2 =Copper, m_3 = Gold, m_4= Iron, m_5= Lead, m_6= Nickel, m_7= Other non-ferrous metal, m_8= PGM, m_9= Silver, m_{10}= Tin, m_{11}= Zinc, m_{12}= Building stones, m_{13}= Chemical and fertilizer minerals, m_{14}= Clays and kaolin, m_{15}= Gravel and sand, m_{16}= Limestone, gypsum, chalk, dolomite, m_{17}= Other minerals, m_{18}= Salt, m_{19}= Slate.

MORDRED differentiates between two types of material extraction: Material extraction for general use and material extraction for the generation and maintenance of renewable energy systems. Given that sector 4 is the mining and extraction sector, we follow Exiobase3 in assuming that all material extraction for general use originates from sector 4.

Regarding the material extraction for renewable energy systems, the MEDEAS model contains material needs for different renewable energy technologies. The MORDRED sector 17 was matched to the MEDEAS technology solar PV, sector 18 was matched to CSP, and sector 15 was matched to the average material extraction requirements of wind onshore and wind offshore. Subsequently, the materials included both in Exiobase3 and in MEDEAS were identified: $m_1, m_2, m_4, m_5, m_6, m_9, m_{10}, m_{11}, m_{15}, m_{16}$. For these materials, MEDEAS gives estimates of material needs per new TW installed for every technology (kt/new TW). We considered only the material needs in the construction phase, which leads to a slight underestimation of the material requirements of renewable energy systems. The material requirements of the renewable system depend decisively on the life time and capacity factor of the installations as, after the end of life of the systems, they have to be constructed again. Due to uncertainties and lack of data regarding recycling systems for renewable energy systems, we conservatively assume that the complete energy infrastructure has to be replaced with new material after its end of life. This arguably leads to an overestimation of the material requirements of renewable energy systems towards the end of the simulation.

For sector 15 we calculated the total energy generated over the lifetime of the technology per TW installed:

$$\frac{Total\ energy_{15}}{TW_{installed}} = 0.5 * \Big[(1\ TW * \alpha_{we\rightarrow wh} * \alpha_{TWh\rightarrow EJ} * lifetime_{wind_{offshore}} * capacity\ factor_{wind_{offshore}}) + (1\ TW * \alpha_{we\rightarrow wh} * \alpha_{TWh\rightarrow EJ} * lifetime_{wind_{onshore}} * capacity\ factor_{wind_{onshore}})\Big]$$

$\alpha_{biophysical:monetary_{15}} = \frac{X[final\ energy]_{15\ [EJ]}}{X[money]_{15}[mio€]}$ (cf. section 3.4.3)

We express the generated energy in monetary units.

$$Energy_{monetary_{15}} \left[\frac{mio€}{TW_{installed}}\right] = \frac{1}{\alpha_{biophysical:monetary_{15}}} * \frac{Total\ energy_{15}}{TW_{installed}}$$

$$Int_{m_{15}} \left[\frac{kt}{mio€}\right] = \frac{Q_{m_{15}}}{TW_{installed}} * \frac{1}{Energy_{monetary_{15}}}$$

For sector 17 we calculated the total energy generated over the lifetime of the technology per TW installed.

$$\frac{Total\ energy_{17}}{TW_{installed}} = 1\ TW * \alpha_{we \to wh} * \alpha_{TWh \to EJ} * lifetime_{solarPV} * capacity\ factor_{solarPV}$$

$$\alpha_{biophysical:monetary_{17}} = \frac{X[final\ energy]_{17\ [EJ]}}{X[money]_{17}[mio€]}$$

We express the generated energy in monetary units.

$$Energy_{monetary_{17}} \left[\frac{mio€}{TW_{installed}}\right] = \frac{1}{\alpha_{biophysical:monetary_{17}}} * \frac{Total\ energy_{17}}{TW_{installed}}$$

$$Int_{m_{17}} \left[\frac{kt}{mio€}\right] = \frac{Q_{m_{17}}}{TW_{installed}} * \frac{1}{Energy_{monetary_{17}}}$$

Equally, for sector 18 we calculated the total energy generated over the lifetime of the technology per TW installed.

$$\frac{Total\ energy_{18}}{TW_{installed}} = 1\ TW * \alpha_{we \to wh} * \alpha_{TWh \to EJ} * lifetime_{solarPV} * capacity\ factor_{CSP}$$

$$\alpha_{biophysical:monetary_{18}} = \frac{X[final\ energy]_{18\ [EJ]}}{X[money]_{18}[mio€]}$$

$$Energy_{monetary_{18}} \left[\frac{mio€}{TW_{installed}}\right] = \frac{1}{\alpha_{biophysical:monetary_{18}}} * \frac{Total\ energy_{18}}{TW_{installed}}$$

$$Int_{m_{18}} \left[\frac{kt}{mio€}\right] = \frac{Q_{m_{18}}}{TW_{installed}} * \frac{1}{Energy_{monetary_{18}}}$$

The material intensities of sector 4 were derived by subtracting the material extraction for renewable energy systems ($Q_{wind+PV+stherm}$) from the total material extraction (Q_{total}) and dividing the result by the output of sector 4. $Q_{wind,PV,stherm}$ are obtained by multiplying the respective stressors [kt/mio€] by the renewable energy sectors' initial output.

$$Int_{m_4}[\frac{kt}{mio€}] = \frac{(Q_{m_{total}} - Q_{m_{wind+PV+stherm}})}{X_4}$$

$$Q_{m_{wind+PV+stherm}} = 0$$

For $m = 3,7,8,12,13,14,17,18,19$ $Q_{m_{wind+PV+stherm}} Q_{m_{wind+PV+stherm}}$ is zero, for the rest of materials it is the sum of the product of output and material intensity of the wind, PV and stherm sectors.

3.6.3.2. Unused material extraction

The stressors included in the category 'unused material extraction' are the same materials as in the category 'used material extraction' and have the unit [kt/mio€]. Given that no data on unused material for the renewable energy sectors is available, following Exiobase3 we assume that all stressors originate from sector 4. Thus, all stressors take the form

$$Int_m = \left(0_1, \dots, Int_{4_m}, 0_5, \dots, 0_{25}\right) \; with \; m = (Bauxite\&aluminium_1, \dots, Slate_{19})$$

3.6.4. Nitrogen and Phosphorus pollution

The amount of N released into the water is classified as 'N – agriculture – water' and 'N – waste – water' in Exiobase. The former stressor is matched to sector no. 1, the latter equally to sector 24 and 25.

$$Int_{N_{water}} = \left(\frac{N_{agriculture\,[kg]}}{X_1\;[mio€]}, 0_2, \dots, 0_{23}, \frac{N_{waste\,[kg]}}{X_{24} + X_{25}\;[mio€]}, \frac{N_{waste\,[kg]}}{X_{24} + X_{25}\;[mio€]}\right)$$

The amount of P released into the water is classified as 'P – agriculture – water' and 'P – waste – water' in Exiobase. The former stressor is matched to sector 1, the latter equally to sector 24 and 25.

$$Int_{P_{water}} = \left(\frac{P_{agriculture\,[kg]}}{X_1\;[mio€]}, 0_2, \dots, 0_{23}, \frac{P_{waste\,[kg]}}{X_{24} + X_{25}\;[mio€]}, \frac{P_{waste\,[kg]}}{X_{24} + X_{25}\;[mio€]}\right)$$

The amount of P released into the soil is classified as 'P – agriculture – soil' in Exiobase and, thus, matched to sector 1.

$$Int_{P_{soil}} = \left(\frac{P_{soil\,[kg]}}{X_1\;[mio€]}, 0_2, \dots, 0_{25}\right)$$

3.6.5. Air pollution

MORDRED includes data on 3 types of air pollution intensities from industrial activity in kg/mio€: NH3, PM2.5 and PM10.

NH3 consists of 4 sub-stressors: (1) NH3 from combustion was matched with sector 1, 2, 5, 9, 24, 25; (2) NH3 from agriculture with sector 1; (3) NH3 from waste with sector 24 and 25; (4) NH3 from N fertilizer production with sector 9.

$$Int_{NH3} = \begin{pmatrix} \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}} + \frac{NH3_{agriculture}}{X_1}, \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}}, 0_3, 0_4, \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}}, \\ 0_6, \dots, \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}} + \frac{NH3_{fertilizer\ production}}{X_9}, 0_{10}, \dots, 0_{23}, \\ \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}} + \frac{NH3_{waste}}{X_{24} + X_{25}}, \frac{NH3_{combustion}}{X_1 + X_2 + X_5 + X_9 + X_{24} + X_{25}} + \frac{NH3_{waste}}{X_{24} + X_{25}} \end{pmatrix}$$

PM2.5 consists of a series of substressors which were matched to different sectors, following the matching in Exiobase.

Sector no.	Sub-Stressor	p
3	PM2.5 – non combustion – Production of gascoke	1
	[…] combustion	2
	[…] non combustion – Production of coke oven coke	3
	[…] non combustion – Carbon black production	4
	[…] non combustion – Oil refinery	5
	[…] non combustion – Briquettes production	6
	[…] non combustion – Mining of antracite	7
	[…] non combustion – Mining of bituminous coal	8
	[…] non combustion – Mining of coking coal	9
	[…] non combustion – Mining of lignite	10
	[…] non combustion – Mining of sub-bituminous coal	11
4	[…] non combustion – Aluminium ores and concentrates (Bauxite)	12
	[…] non combustion – Zinc ores and concentrates	13
	[…] non combustion – Silver ores and concentrates	14
	[…] non combustion – Tin ores and concentrates	15
	[…] non combustion – Platinum ores and concentrates	16
	[…] non combustion – Molybdenum ores and concentrates	17
	[…] non combustion – Chromium ores and concentrates	18
	[…] non combustion – Copper ores and concentrates	19
	[…] non combustion – Gold ores and concentrates	20
	[…] non combustion – Iron ores and concentrates	21
	[…] non combustion – Lead ores and concentrates	22
	[…] non combustion – Nickel ores and concentrates	23
	[…] non combustion - Nickel, unwrought	24
5	[…] non combustion – Primary aluminium production	25
	[…] non combustion – Glass production	26
	[…] non combustion – Steel production: basic oxygen furnace	27
	[…] non combustion – Steel production: electric arc furnace	28
	[…] non combustion – Steel production: open hearth furnace	29
	[…] non combustion – Chemical wood pulp, dissolving grades	30

	[…] non combustion - Chemical wood pulp, soda and sulphate, other than dissolving grades	31
	[…] non combustion - Chemical wood pulp, sulphite, other than dissolving grades	32
	[…] non combustion – Semi-chemical wood pulp, pulp of fibres other than wood	33
	[…] non combustion – Cement production	34
	[…]non combustion – Lime production	35
	[…] non combustion – Refined copper; unwrought, not alloyed	36
	[…] non combustion – Refined lead; unwrought	37
	[…] Unrefined copper; copper anodes for electrolytic refining	38
	[…] non combustion – Zinc; unwrought, not alloyed	39
	[…] non combustion – Pig iron production, blast furnace	40
	[…] non combustion – Cast iron production (grey iron foundries)	41
	[…] non combustion – Agglomeration plant – pellets air	42
	[…] non combustion – Agglomeration plant – sinter air	43
8	[…] non combustion – Production of gascoke	44
	[…] non combustion – Mining of antracite	45
	[…] non combustion – Mining of bituminous coal	46
	[…] non combustion – Mining of coking coal	47
	[…] non combustion – Mining of lignite	48
	[…] non combustion – Mining of sub-bituminous coal	49
9	[…] non combustion – N-fertilizer production	50
	[…]non combustion –Fertilizer-production	51
10	[…] combustion	52
11	[…] non combustion – Bricks production	53
24	[…] waste	54
25	[…] waste	55

Table 16: Matching MORDRED sectors with PM 2.5 sub-stressors.

The stressor vector is:

$$Int_{PM2.5} = \left(0_1, 0_2, \frac{\sum_{p=1}^{11} PM2.5_p}{X_3}, \frac{\sum_{p=12}^{24} PM2.5_p}{X_4}, \frac{\sum_{p=25}^{43} PM2.5_p}{X_5}, 0_6, 0_7, \frac{\sum_{p=44}^{49} PM2.5_p}{X_8}, \frac{\sum_{p=50}^{51} PM2.5_p}{X_9}, \frac{PM2.5_{52}}{X_{10}}, \frac{PM2.5_{53}}{X_{11}}, 0_{12}, \dots, 0_{23}, \frac{PM2.5_{54}}{X_{24}}, \frac{PM2.5_{55}}{X_{25}}\right)$$

PM10 consists of a series of sub-stressors which are equal to PM2.5 sub-stressors and which were matched to the following respective sectors following Exiobase.

Sector	Sub-stressor	p
3	PM10 – non combustion – Production of gascoke	1
	[…] combustion	2
	[…] non combustion – Production of coke oven coke	3
	[…] non combustion – Carbon black production	4
	[…] non combustion – Oil refinery	5

	[…] non combustion – Briquettes production	6
	[…] non combustion – Mining of antracite	7
	[…] non combustion – Mining of bituminous coal	8
	[…] non combustion – Mining of coking coal	9
	[…] non combustion – Mining of lignite	10
	[…] non combustion – Mining of sub-bituminous coal	11
4	[…] non combustion – Aluminium ores and concentrates (Bauxite)	12
	[…] non combustion – Zinc ores and concentrates	13
	[…] non combustion – Silver ores and concentrates	14
	[…] non combustion – Tin ores and concentrates	15
	[…] non combustion – Platinum ores and concentrates	16
	[…] non combustion – Molybdenum ores and concentrates	17
	[…] non combustion – Chromium ores and concentrates	18
	[…] non combustion – Copper ores and concentrates	19
	[…] non combustion – Gold ores and concentrates	20
	[…] non combustion – Iron ores and concentrates	21
	[…] non combustion – Lead ores and concentrates	22
	[…] non combustion – Nickel ores and concentrates	23
	[…] non combustion - Nickel, unwrought	24
5	[…] non combustion – Primary aluminium production	25
	[…] non combustion – Glass production	26
	[…] non combustion – Steel production: basic oxygen furnace	27
	[…] non combustion – Steel production: electric arc furnace	28
	[…] non combustion – Steel production: open hearth furnace	29
	[…] non combustion – Chemical wood pulp, dissolving grades	30
	[…] non combustion - Chemical wood pulp, soda and sulphate, other than dissolving grades	31
	[…] non combustion - Chemical wood pulp, sulphite, other than dissolving grades	32
	[…] non combustion – Semi-chemical wood pulp, pulp of fibres other than wood	33
	[…] non combustion – Cement production	34
	[…]non combustion – Lime production	35
	[…] non combustion – Refined copper; unwrought, not alloyed	36
	[…] non combustion – Refined lead; unwrought	37
	[…] Unrefined copper; copper anodes for electrolytic refining	38
	[…] non combustion – Zinc; unwrought, not alloyed	39
	[…] non combustion – Pig iron production, blast furnace	40
	[…] non combustion – Cast iron production (grey iron foundries)	41
	[…] non combustion – Agglomeration plant – pellets air	42
	[…] non combustion – Agglomeration plant – sinter air	43
8	[…] non combustion – Production of gascoke	44
	[…] non combustion – Mining of antracite	45
	[…] non combustion – Mining of bituminous coal	46
	[…] non combustion – Mining of coking coal	47
	[…] non combustion – Mining of lignite	48

	[...] non combustion – Mining of sub-bituminous coal	49
9	[...] non combustion – N-fertilizer production	50
	[...]non combustion –Fertilizer-production	51
10	[...] combustion	52
11	[...] non combustion – Bricks production	53

Table 17: Matching MORDRED sectors with PM 10 sub-stressors.

$$Int_{PM10} = \left(0_1, 0_2, \frac{\sum_{p=1}^{11} PM10_p}{X_3}, \frac{\sum_{p=12}^{24} PM10_p}{X_4}, \frac{\sum_{p=25}^{43} PM10_p}{X_5}, 0_6, 0_7, \frac{\sum_{p=44}^{49} PM10_p}{X_8}, \frac{\sum_{p=50}^{51} PM10_p}{X_9}, \frac{PM10_{52}}{X_{10}}, \frac{PM10_{53}}{X_{11}}, 0_{12}, \dots, 0_{25}\right)$$

3.6.6. Industrial roundwood

For version 1.0, the Exiobase3 data for ‘Domestic Extraction Used - Forestry - Coniferous wood - Industrial roundwood’ and ‘Domestic Extraction Used - Forestry - Non-coniferous wood - Industrial roundwood’ was added and matched with sector no. 2, following the matching in Exiobase3. To obtain the intensity, the quantity of industrial roundwood extracted (kt) was divided by the output of the sector (in mio€).

$$Int_{IRW_{extraction}} = \left(0_1, \frac{Q_{wood}[kt]}{X_2[mio€]}, 0_3, \dots, 0_{25}\right)$$

For some extended versions, we replace the Exiobase data with data from FAO for 2016 (FAO, 2017) on global industrial roundwood production which is given in m^3. To derive the intensity of production, we matched the value to sector no. 2 and divided it by the output of the sector (in mio€).

$$Int_{IRW_{production}} = \left(0_1, \frac{Q_{wood}[m^3]}{X_2[mio€]}, 0_3, \dots, 0_{25}\right)$$

4. Abbreviations, subscripts and superscripts

4.1. Abbreviations

Abbreviation	Definition
ΔTemp	Change in global average temperature with respect to 1850
a	Element of the A matrix
A	A matrix
Adf	Agriculture damage factor
Air_Poll	Air pollution
B	Births
Br	Birth rate
Br5y	Birth rate per five years
C	Private consumption
Cf	Conversion factor
clsh	Class share
Cpc	Consumption per capita
Cpc_gr	Consumption per capita growth rate
Cpc_nc	Consumption per capita not covered
Cpc_ssh	Consumption per capita sectorial share
D	Deaths
Dam	Damage
Dr	Death rate
Dsp_Lnd	Disposable land
Edf	Extraction difficulty factor
Edpc	Public expenditure on education per capita
Em	Emissions
Ext_Int	Extra intensity
Extra_GFCF	Extra gross fixed capital formation
FD	Final demand
FE	Final energy
FE2PE	Final energy to primary energy
Foodland_loss	Foodland loss
Frst_lnd_rdct	Forest land reduction
G	Government consumption
G_ssh	Government consumption sectorial share
G2Cr	Government consumption to Private consumption ratio
GFCF	Gross fixed capital formation
GFCF_ssh	Gross fixed capital formation sectorial share
Hpc	Public expenditure on health per capita
Id	Identity matrix
Int	Intensity
Inv	Investment
IRW	Industrial roundwood
K	Capital stock

Lb	Labour
Lnd	Land
M	Migrations
Mat	Materials
Max_Er	Maximum extraction rate of fossil fuels
Max_ff	Maximum fossil fuels annual extraction
Max_h	Maximum annual working hours
Max_Lb	Maximum labour
MaxP	Maximum population
Mr	Migration rate
P	Population
P&N_Poll	Phosphorus and nitrogen pollution
PE	Primary energy
Prt_Lnd	Protected land
Prt_r	Participation rate
Rsc_ff	Extractable fossil fuel resources
Sf	Scarcity factor
t	time
t0	Initial time of simulation
ts	Time step
WC	Water consumption
WW	Water withdrawal
X	Output
X_loss	Output loss (applicable to agriculture)
δ	Depreciation rate

4.2. Model Subscripts

The subscripts denote vectors, subvectors or elements thereof, programmed in the model.

Abbreviation	**Type**	**Definition**
1 to 25 (numbers)	Elements of vector sector	Numbers corresponding to the productive sectors
a	Vector	Age chort
air_poll	Vector	Air pollution
am	Generic element created for the transition of population from one cohort to another	Age middle (generic cohort)
ay	Generic element created for the transition of population from one cohort to another. It is the cohort prior to the middle age cohort	Age young (generic cohort)
c04	Element (inside vector age cohort)	Cohort 0 to 4 years
c1519	Element (inside vector age cohort)	Cohort 15 to 19 years

c2024	Element (inside vector age cohort)	Cohort 20 to 24 years
c2529	Element (inside vector age cohort)	Cohort 25 to 29 years
c3034	Element (inside vector age cohort)	Cohort 30 to 34 years
c3539	Element (inside vector age cohort)	Cohort 35 to 39 years
c4044	Element (inside vector age cohort)	Cohort 40 to 44 years
c95+	Element (inside vector age cohort)	Cohort 95 years or more
Chem&FertMin	Element (inside vector materials)	Chemical and fertilizer minerals
cl	Vector	Class
cnt	Vector	country
CO2	Element (inside vector greenhouse gas emissions)	Carbon dioxide
e	Vector	Extreme weather events
elec	Element (inside vector energy)	Electricity
en	Vector	Energy
ff	Subvector (inside vector energy)	Fossil fuels (oil, gas, coal)
foodland_we	Element (inside vector land)	Foodland for the use of the world economy
ghg	Vector	Greenhouse gas emissions
hw	Element (inside vector extreme weather events)	Heat waves
high	Element (inside vector class)	High class
i	Vector	Sector
inf	Element (inside vector land)	Infraestructure
j	Vector identical to i to construct the input-output. In the input-output, i denotes the rows and j the columns	Sector
Lnd	Vector	Land
low	Element (inside vector class)	Low class
mat	Vector	Materials
middle	Element (inside vector class)	Middle class
P&N	Vector	Phosphorus and nitrogen pollution
P_soil	Element (inside vector Phosphorus and nitrogen pollution)	Soil phosphorus pollution
pfrst	Element (inside vector land)	Primary forest
prod_frst	Element (inside vector land)	Productive forest
prod_Land	Subvector (inside vector land)	Productive land
r	Vector	Region
sfrst	Element (inside vector land)	Secondary forest
shrub	Element (inside vector land)	Shrub

sub_lnd	Element (inside vector land)	Land in use by the population in a subsistence state

4.3. Model Superscripts

The superscripts serve only to complete the names of the variables or to link parameters to the variables to be calculated. The vectorization of the model is represented only in the subscripts.

Abbreviation	**Definition**
2ºC	Superscript associated with the variable t to refer to the time at which 2ºC is reached.
2ºC_slr	2ºC sea level rise
3ºC	Superscript associated with the variable t to refer to the time at which 3ºC is reached.
3ºC_slr	3ºC sea level rise
4ºC	Superscript associated with the variable t to refer to the time at which 4ºC is reached.
4ºC_slr	4ºC sea level rise
Adf_io	Agrigulture damage factor for the input output
bd	Before damage
blue_w	Blue water
Br5y	Birth rate per five years
comb	Combustion
d	Demand
Dr5y	Death rate per five years
Edf	Extraction difficulty factor
em	Emissions
eu	Energy use
Ext_Int_Lnd_sub	Extra land intensity
ff	Fossil fuels
Foodland_loss	Foodland loss
green_w	Green water
HB_Max_Lb	Heat damage to maximum labour
HD_Lb_prod	Heat damage to labour productivity
hh	Households
Inv	Investment
io	input output
IRW	Industrial roundwood
k	Capital stock
Lb_prod	Labour productivity
Lnd	Land
Lnd	Land
Lnd_loss	Land loss
mat_unused	Material unused
mat_used	Material used
neu	Non energy use

other	Other CO2 emission sources
prod	Production
s	Supply
slr	Sea level rise
sub	Subsistence
sub2we	Subsistence to world economy
temp	Temperature
we	World economy
CW	Water consumption
WW	Water withdrawal
X_loss	Output loss (in the food sector)
δ_temp	Depreciation rate temperature. Abbreviation associated with parameter used to calculate changes in depreciation due to change in global average temperature.

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