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Supplementary Information for Article "Earth system modeling with complex dynamic human societies: the copan:CORE World-Earth modeling framework"

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Example model

Here we describe the model components of our example model in detail. `Typewriter font` is used for names of entity types, process taxa and variables as they occur in the code, uppercase italics denote endogenous variables, and lowercase italics denote exogenous variables (model parameters). As many processes add terms to variables time derivatives, we use the motation $\dot{X} \mathrel{+}= Y$ to indicate this.

Entity types

The example model contains one `World` representing an Earth-like planet, a small number (five) of `SocialSystems` interpreted as fictitious major economic world regions like the EU, a fair number (100) of `Cells` representing patches on the world's land surface that differ in their carbon stocks and potential for renewable energy production, and a somewhat large representative number (1000) of `Individuals` (humans) connected through a fixed acquaintance network.

Carbon cycle

Our simple carbon cycle is follows a simplified version of [1] presented in [4] with a spatially resolved vegetation dynamics.

On the `World` level, an immediate greenhouse effect translates the atmospheric carbon stock A linearly into a mean surface air temperature $T = T_{\text{ref}} + a(A - A_{\text{ref}})$ (a process of type `Explicit`) with a sensitivity parameter a, and there is ocean-atmosphere diffusion between A and the upper ocean carbon stock M, $\dot{A} \mathrel{+}= d(M - mA)$, $\dot{M} \mathrel{+}= d(mA - M)$ (processes of type `ODE`), with a diffusion rate d and a solubility parameter m.

On the level of a `Cell` c, A and the terrestrial carbon stock L_c are changed by a respiration flow RF_c and a photosynthesis flow PF_c, $\dot{A} \mathrel{+}= RF_c - PF_c$, $\dot{L}_c \mathrel{+}= PF_c - RF_c$. The respiration rate depends linearly on temperature, which is expressed as a dependency on atmospheric carbon density A/Σ, where Σ is the total land surface area, so that $RF_c = (a_0 + a_A A/\Sigma)L_c$ with a basic rate a_0 and carbon sensitivity a_A. The photosynthesis rate also depends linearly on temperature (and hence on A) with an additional carbon fertilization factor growing concavely with A/Σ and a space competition factor similar to a logistic equation, giving $PF = (l_0 + l_A A/\Sigma)\sqrt{A/\Sigma}(1 - L_c/k\Sigma_c)L_c$, where Σ_c is c's land area, l_0 and l_A are rate parameters, and k is a capacity-per-area parameter. Note that especially the linear temperature dependency and the missing water dependency make this model quite unrealistic, see also [3].

Economic production

As in [4], economic activity consists of producing a final good Y from labour (assumed to be proportional to population P), physical capital K, and energy input flow E which is the sum of fossil energy flow E_F, biomass energy flow E_B, and (other) renewable energy flow R. The process is described by a nested Leontieff/Cobb–Douglas production function for Y and Cobb–Douglas production functions for E_F, E_B, R, all of them here on the `Cell` level: $Y_c = y_E \min(E_c, b_Y K_{Y,c}^{\kappa_Y} P_{Y,c}^{\pi_Y})$, $E_{F,c} = b_F K_{F,c}^{\kappa_F} P_{F,c}^{\pi_F} G_c^{\gamma}$, $E_{B,c} = b_B K_{B,c}^{\kappa_B} P_{B,c}^{\pi_B} L_c^{\lambda}$, $R_c = b_R K_{R,c}^{\kappa_R} P_{R,c}^{\pi_R} S_s^{\sigma}$. In this, G_c is the cell's fossil reserves, S_s gives the renewable energy production knowledge stock of the corresponding social system s, $b_\bullet$ are productivity parameters and $\kappa_\bullet, \pi_\bullet, \gamma, \lambda, \sigma$ are elasticities. Furthermore, $K_{\bullet,c}, P_{\bullet,c}$ are the shares of a social system s's capital K_s and labour L_s that are allocated to the four production processes in cell s so that $K_s = \sum_{c\in s}(K_{Y,c} + K_{F,c} + K_{B,c} + K_{R,c})$ and similarly for its population P_s. The latter shares are determined on the `SocialSystem` level in a general equilibrium fashion by putting $E_c = b_Y K_{Y,c}^{\kappa_Y} P_{Y,c}^{\pi_Y}$) to avoid idle resources, equating wages (= marginal productivity of labour) in all cells and sectors, and equating rents (= marginal productivity of capital) in all cells and sectors, assuming costless and immediate labour and capital mobility between all cells and sectors within each social system. The production functions and elasticities are chosen so that the corresponding equations can be solved analytically (see [4] for details), allowing us to implement them as a process of type `Explicit` on the `SocialSystem` level that calculates the social system's economic output Y_s and carbon emissions, and all cells' fossil and biomass extraction flows. Given the latter, a second process of type `ODE` changes the carbon stocks A, G_c and L_c.

Economic growth

Again as in [4], but here on the `SocialSystem` level, a fixed share of economic production Y_s is invested into physical capital K_s, $\dot{K}_s \mathrel{+}= iY_s$. Capital also depreciates at rate that depends linearly on surface air temperature to represent damages from climate change, $\dot{K}_s \mathrel{+}= -(k_0 + k_T(T - T_K))K_s$.

In addition, renewable energy production knowledge S_s grows proportional to its utilization in the same social system, $\dot{S}_s \mathrel{+}= R_s$, and to some degree also proportional to its utilization in other social systems s' due to spillover effects, $\dot{S}_s \mathrel{+}= \alpha R_{s'}$, $\alpha \leqslant 1$. Finally, we interpret S_s as a form of human capital that also depreciates at a constant rate (due to forgetting or becoming useless because of changing technology, etc.), $\dot{S}_s \mathrel{+}= -\beta S_s$.

Population growth

Like in [4], but here again on the `SocialSystem` level, population has a wellbeing-dependent fertility rate that was roughly fitted against country-level data of fertility vs GDP per capita. We chose the functional form $\mathrm{fert}_s = p_0 + 2(p - p_0)W_s W_P^{\omega_p}/(W_s^{1+\omega_p} + W_P^{1+\omega_p})$, where wellbeing $W_s = w_Y(1-i)Y_s/P_s + w_L L_s/\Sigma_s$ depends on per-capita consumption $(1-i)Y_s/P_s$ and the mean terrestrial carbon density in that social system, L_s/Σ_s. For small W_s, f grows linearly, reaching its maximum at $W_s = W_P$, then decaying towards p_0 with an asymptotically power-law shape with exponent ω_p for large W_s. Similarly, for mortality we roughly fitted the function $q/(W_s/W_P)^{\omega_q}$ against data and added a term representing increased mortality from climate change impacts, $q_T(T - T_q)$, and one representing competition for space, $q_C P_s/\Sigma_s\sqrt{K_s}$, where the factor $1/\sqrt{K_s}$ represents the assumption that housing is a form of physical capital with decreasing marginal value.

Note that while population P_s changes over time, the number of representative individuals in s remains constant in our example model, implying that the share of the population in s that a certain `Individual` i represents will change over time. A more elaborate model could try to keep the ratio of population and number of representative individuals roughly constant by generating or deactivating instances of `Individual` in s at the current birth and death rate of s.

Wellbeing-driven migration

In addition to births and deaths, `SocialSystems`’ populations change due to migration depending on differences in wellbeing. We assume each person in s has a probability of emigrating to s' that is proportional to the available information about differences in wellbeing for which we use the population in s'’ as a proxy. We also assume that the probability of migration depends on a sigmoidal function of the wellbeing ratio, $f(\log W_{s'} - \log W_s)$ with $f(-\infty) = 0$ and $f(\infty) = 1$. More specifically, the absolute emigration flow from s to s' is $\mu P_s P_{s'}(1/2 + \arctan(\pi\phi(\log W_{s'} - \log W_s - \log\rho))/\pi)$, where μ is a basic rate and ϕ and ρ are slope and offset parameters.

Environmental awareness

On the `Culture` level, “awareness updating” events occur at random time points with a constant rate (i.e., as a Poisson process), representing times at which many people become aware of the state of the environment, e.g., because of notable environmental events. At each such time point, each `Individual` i independently updates her environmental friendliness, which is a Boolean variable (i.e., either “true” or “false”) with a certain probability. When i updates her environmental friendliness, she switches from “false” to “true” with a probability ψ^+ depending on the terrestrial carbon density in her cell c, $TCD_c = L_c/\Sigma_c$, given by $\psi^+ = \exp(-TCD_c/TCD^{\perp})$, and switches from “true” to “false” with a probability $\psi^- = 1 - \exp(-TCD_c/TCD^{\top})$, where $TCD^{\perp}$ and $TCD^{\top}$ are sensitivity parameters with $TCD^{\perp} < TCD^{\top}$ to generate hysteresis behaviour.

On the `SocialSystem` level, a fraction of the terrestrial carbon L_s is protected from harvesting for economic production. This fraction is proportional to the social system’s population share represented by those individuals i which are environmentally friendly.

Social learning of environmental friendliness

Similarly, on the `Culture` level, “social learning” events occur at random time points with a constant rate (i.e., as a Poisson process), representing times at which the state of the environment becomes a main topic in the public debate. At each such time point, each `Individual` i independently compares her environmental friendliness with that of a randomly chosen acquaintance j with a certain fixed probability. j then convinces i to copy j’s environmental friendliness (“true” or “false”) with a probability ψ that depends via a sigmoidal function on the difference-in-logs between both home cells’ terrestrial carbon densities TCD_i and TCD_j, $\psi = 1/2 + \arctan(\pi\phi'(\log TCD_j - \log TCD_i - \log\rho'))/\pi$ where ϕ' and ρ' are slope and offset parameters.

Voting on climate policy

Every `SocialSystem` performs general elections at regular time intervals (hence implemented as a process of type `Step`) which may lead to the introduction or termination of three possible climate policies. If at the time t of the election, more than a certain threshold of the population is environmentally friendly, a subsidy for renewables is introduced. Similarly, if more than a certain higher threshold of the population is environmentally friendly, a GHG emissions tax is introduced. Both lead to a shift in the energy price equilibrium that determines the energy sector’s allocation of labour and capital, which

Variable	Value	Remarks
total land area Σ	1.5e8 km^2	
global atmospheric carbon A	830 GtC	
global upper ocean carbon M	1065 GtC	
global terrestrial carbon L	2480 GtC	
global fossil carbon G	1125 GtC	
global population P	6e9 humans	
global physical per-capita capital K/P	10,000 $ / human	
renewable energy production knowledge S_s	1e12 GJ	see [2]

Table 1: Initial values for model runs. Mathematical symbols refer to this SI and to [4].

reads

$$\begin{aligned}&\text{marginal production cost of fossil energy} + \text{emissions tax}\\&= \text{marginal production cost of biomass energy} + \text{emissions tax}\\&= \text{marginal production cost of renewable energy} - \text{renewable subsidy}.\end{aligned}$$

Finally, if more than a certain still higher threshold of the population is environmentally friendly, use of fossils is banned altogether in this social system. Conversely, if any of these policies is already in place but the environmentally friendly population share is now below some other, smaller, thresholds, these policies are terminated.

Parameters and initial conditions

For variables and parameters taken from [4] we chose values equivalent to those given in Table 1 of that paper, mainly except for l_0, which was chosen higher to accommodate for our additional space competition factor and make the initial photosynthesis flow fit current amounts; p, which was chosen higher because of the different decay exponent of fertility vs wellbeing. See Table 2 for additional parameter values and deviations from [4]. All social systems and cells had the same parameters except for cells' renewable sector productivity, which was randomly distributed around the listed average to represent different local conditions.

As initial conditions for the year 2000, we used rough global aggregates where data was available, see Table 1, and distributed them randomly onto the five social systems or 100 cells without aiming for realistic distributions or correlations.

Each social system had a 1/4 or 1/5 probability of starting with a renewable subsidy or emissions tax in place, respectively, and none started with a fossil ban in place.

Likewise, each individual had a 30 % chance of being environmentally friendly at the beginning. The acquaintance network was generated using a block model; each individual was acquainted to 150 others on average, half of them from the same cell and another 35 % from the same social system.

Necessary improvements

We'd like to repeat that the example model was designed to showcase the concepts and capabilities of copan:CORE in a rather simple WEM, and its components were chosen so that all entity types and process taxa and most features of copan:CORE are covered. The example model is not intended to be a serious representation of the real world that could be used directly for studying research questions, and the shown time evolutions may not be interpreted as any kind of meaningful quantitative prediction or projection.

To develop the example model into a serious World-Earth model, very many things remain to be done, including a careful selection of processes to include or exclude, improvements in model equations and agent's behavioural rules, both by fitting data where available and adopting model components

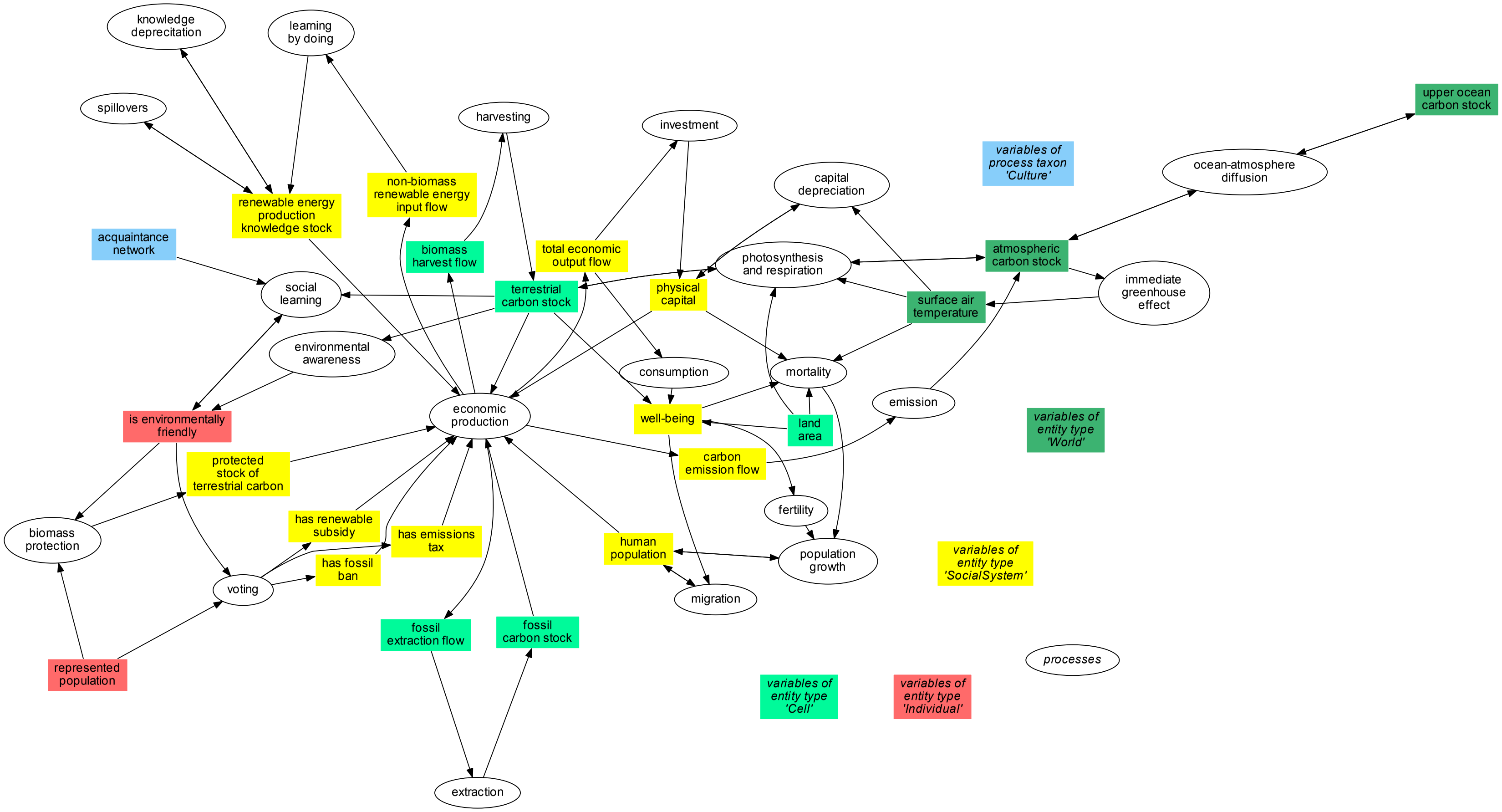

Figure 1: Main variables and processes of the example model.

Parameter	Value	Remarks / comparison to [4]
terrestr. carbon density capacity	25,000 GtC / 1.5e8 km^2	10 times current mean density
temperature sensitivity on atmospheric carbon	1.5 K / 1000 GtC	
fossil sector productivity a_F	5e6 $(\text{GJ/yr})^5$ / $(\text{GtC \$ humans})^2$	results in approx. 8 GtC fossil input in 2000
biomass sector productivity a_B	3e5 $(\text{GJ/yr})^5$ / $(\text{GtC \$ humans})^2$	results in approx. 1 GtC biomass input in 2000
average renewable sector productivity a_R	7e-18 $(\text{GtC/yr})^5$ / $(\text{GtC \$ humans})^2$	results in approx. 100 GW in 2000
fossil energy density e_F	47e9 GJ / GtC	slightly larger
biomass energy density e_B	40e9 GJ / GtC	
total energy intensity $1/y_E$	1 GJ / 147 $	results in a GWP of approx. 6e13 $ in 2000
savings rate i	24.4%	slightly smaller
physical capital depreciation rate sensitivity on temperature k_T	(5%/yr) / K	
physical capital depreciation reference temperature T_K	287 K	
renewable energy production knowledge depreciation rate β	2% / yr	
renewable energy production knowledge spillover fraction α	10%	
wellbeing sensitivity to terrestrial carbon density w_L	0.55 $ km^2 / humans yr GtC	very low arbitrary value
minimum fertility p_0	0.008 / yr	
maximum fertility p	0.05 / yr	
fertility decay exponent ω_p	1/2	
mortality decay exponent ω_q	1/12	
mortality at fertility maximum	0.02 / yr	results in 56 yr avg. life expectancy in 2000 (too low)
mortality sensitivity on temperature	(5e-5/yr) / K	
coefficient of mortality due to space competition	0 $\$^{1/2}$ / humans km^2 yr	currently zero since hard to estimate
basic migration rate μ	16e-13 / yr humans^2	chosen to match currently migrants of approx. 5 mio./yr
characteristic wellbeing quotient for emigration ρ	3	at this quotient, emigration reaches half its maximum
maximal slope of emigration probability vs. wellbeing quotient ϕ	1	
environmental awareness update rate	1 / yr	
environmental awareness update fraction	10%	
lower characteristic carbon density for awareness, $TCD^{\perp}$	1e-4 GtC / km^2	
upper characteristic carbon density for awareness, $TCD^{\top}$	2e-4 GtC / km^2	high compared to currently ~0.16e-4 GtC / km^2
maximal protected terrestrial carbon	90% of initial L_s	
social learning update rate	1 / yr	
social learning update fraction	10%	
characteristic quotient of TCDs for imitation ρ'	1	at this quotient, imitation probability is 1/2
maximal slope of imitation probability vs. quotient of TCDs ϕ'	1	
time between votes	4 yr	
vote shares for introducing renewable subsidy / emissions tax / fossil ban	1/2, 2/3, 3/4	
vote shares for keeping renewable subsidy / emissions tax / fossil ban	1/3, 1/2, 2/3	
level of renewable subsidy	50 $ / GJ	same order of magnitude as current price
level of emissions tax	100 $ / ton CO_2	

Table 2: Additional parameter values. Mathematical symbols refer to this SI and to [4]. Cells' renewable sector productivity a_R was randomly distributed around the listed average.

from the literature, suitable choice of real-world social systems to include as entities, appropriate gridding of the surface into cells, and a solid estimation of parameters and initial conditions and their local and societal differences.

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