

Multi-Objective Optimization of Socio-Ecological Systems for Global Warming Mitigation

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S1. Supplementary Material

1. Introduction

This supplementary material provides detailed results of the local sensitivity analysis conducted to identify the key parameters within the socio-ecological optimization model. The goal of this analysis was to quantify how small perturbations in each parameter affect environmental, economic, and social outcomes, thereby establishing a transparent criterion for selecting the most influential and policy-relevant decision variables. The following sections expand on the methodology, full sensitivity results, graphical comparisons, and rationale for the selection of the final six parameters used in the main manuscript.

2. Methodology

A local One-at-a-Time (OAT) sensitivity analysis was applied to all biophysical and economic parameters. Each parameter was perturbed by $\pm 5\%$ around its baseline value while keeping all others constant. The normalized sensitivity of each parameter i was calculated for the environmental, economic, and social dimensions as follows:

$$S_i = \frac{|f_i(+10\%) - f_i(-10\%)|}{2 * 0.1 * |f_{i\text{baseline}}|} \quad (1)$$

Additionally, a signed version of the sensitivity was computed to retain the direction of the parameter's influence:

$$S_i^{\text{signed}} = \frac{f_i(+10\%) - f_i(-10\%)}{2 * 0.1 * |f_{i\text{baseline}}|} \quad (2)$$

The total sensitivity (S_{total}) was defined as the arithmetic mean of the three dimension-specific sensitivities.

$$S_{\text{total}} = \frac{S_{\text{env}} + S_{\text{eco}} + S_{\text{soc}}}{3} \quad (3)$$

Parameters with $S_{\text{total}} > 0.15$ were considered high-influence.

3. Results

A total of 34 parameters were evaluated (Table 1). The threshold of $S_{\text{total}} = 0.15$, shown in Figure 1, was used to identify high-influence parameters. Those exceeding this threshold were considered significant contributors to model variability and thus potential candidates for inclusion as decision variables. However, only six were retained, balancing quantitative influence

with interpretability and feasibility for real-world policy interventions. Figure 2 depicts the comparative sensitivities of these six retained parameters, while Table 2 summarizes their values.

Table 1. Normalized sensitivities for all evaluated parameters ($\pm 10\%$).

Parameter	S_Environmental	S_Economic	S_Social	S_Total
mP2	1.152	5.415	0.023	2.197
aw	1.045	2.943	0.052	1.347
aISp	0.837	3.067	0.013	1.306
aP1p	0.854	2.398	0.019	1.090
lambda	0.288	1.300	0.027	0.538
aH1p	0.315	0.959	0.018	0.431
H1bar	0.147	0.493	0.010	0.216
gammaEEIS	0.138	0.439	0.010	0.195
dH1HH	0.068	0.218	0.186	0.157
aH1	0.072	0.270	0.072	0.138
dISHH	0.091	0.269	0.007	0.122
theta	0.057	0.238	0.003	0.099
aP1	0.060	0.118	0.101	0.093
dP1HH	0.020	0.105	0.117	0.081
etab	0.056	0.155	0.003	0.071
dEEHH	0.044	0.141	0.001	0.062
nISHH	0.038	0.126	0.002	0.055
aIS	0.020	0.071	0.004	0.032
nEEHH	0.022	0.070	0.002	0.031
gammaEEIRP	0.009	0.037	0.003	0.016
cEE	0.007	0.025	0.003	0.012

aEE	0.003	0.012	0.003	0.006
bEE	0.003	0.010	0.003	0.005
mH1	0.003	0.004	0.000	0.002
mP1	0.000	0.001	0.000	0.000
etaa	0.000	0.000	0.000	0.000
gP1H2	0.000	0.000	0.000	0.000
gP1H1	0.000	0.000	0.000	0.000
fP1H1	0.000	0.000	0.000	0.000
eP1H1	0.000	0.000	0.000	0.000
gH1C1	0.000	0.000	0.000	0.000
dP1H1	0.000	0.000	0.000	0.000
Wid	0.000	0.000	0.000	0.000
Wgid	0.000	0.000	0.000	0.000

Figure 1. Normalized total sensitivity (S_{total}) for all evaluated parameters. The dashed red line at $S = 0.15$ indicates the threshold applied to identify high-influence variables.

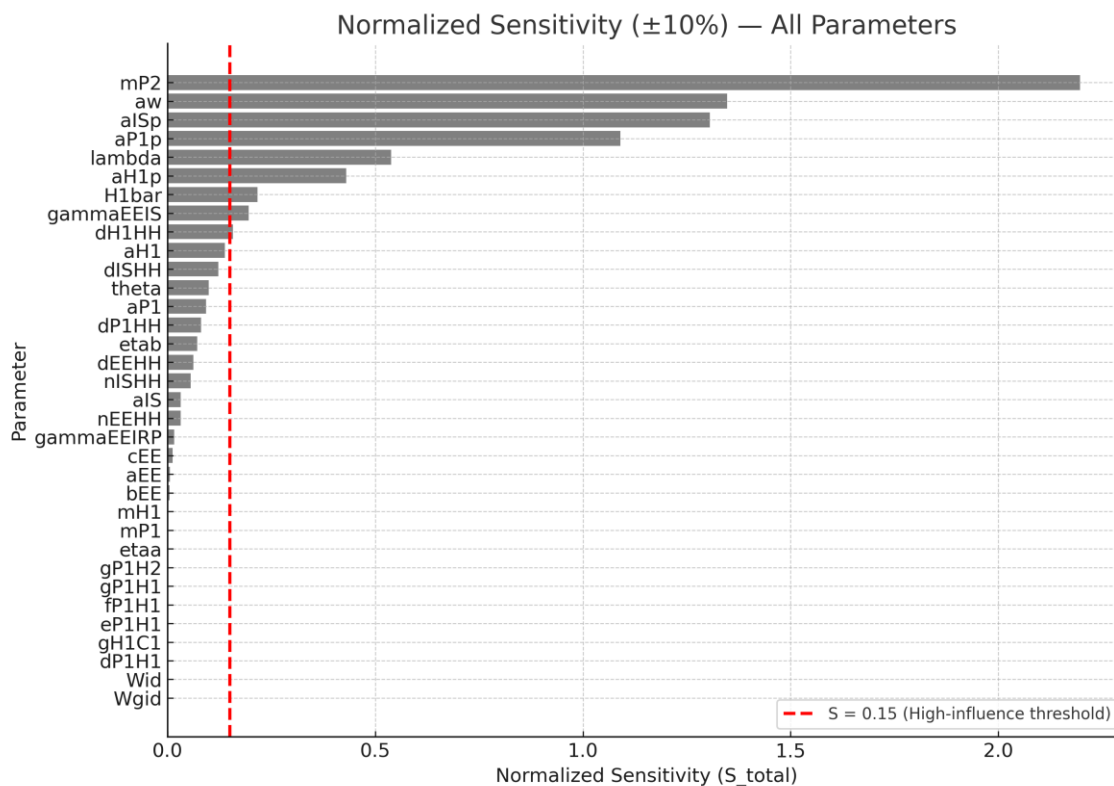


Figure 2. Normalized sensitivity ($\pm 10\%$) for the six retained parameters (mP2, aP1p, aISp, aw, aH1p, and λ). Blue: Environmental; Red: Economic; Green: Social.

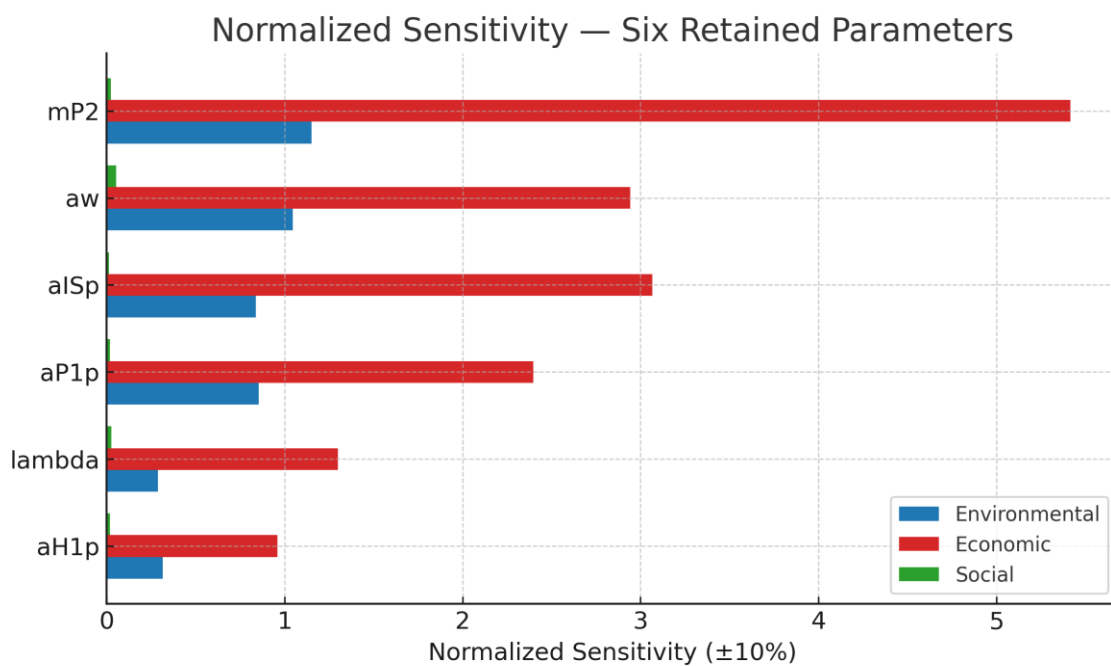


Table 2. Sensitivities for the six parameters retained for policy-oriented modeling.

Parameter	S_Environmental	S_Economic	S_Social	S_Total
mP2	1.152	5.415	0.023	2.197
aw	1.045	2.943	0.052	1.347
aISp	0.837	3.067	0.013	1.306
aP1p	0.854	2.398	0.019	1.090
lambda	0.288	1.300	0.027	0.538
aH1p	0.315	0.959	0.018	0.431

Overall, the environmental dimension exhibited the largest sensitivity magnitudes, followed by economic and social dimensions. Parameters mP2, aP1p, and aISp strongly influenced both environmental and economic outcomes, highlighting their relevance to resource use and industrial performance. Parameter aw showed a negative signed sensitivity, indicating that excessive water allocation can reduce overall system efficiency. Lambda (λ) and aH1p acted as stabilizing variables with moderate influence across all sustainability dimensions. These findings support the use of the six retained variables as the most effective and interpretable levers for sustainable policy design.

4. Conclusion

The OAT sensitivity analysis demonstrated that only a small subset of parameters substantially influences system outcomes. While nine parameters exceeded the $S_{total} = 0.15$ threshold, the final selection of six variables offers a balance between analytical importance, conceptual clarity, and implementation feasibility. These six parameters—mP2, aP1p, aISp, aw, aH1p, and λ —represent actionable decision levers for sustainable optimization within the socio-ecological model.

This supplementary analysis corresponds to Section 2.2. Decision variables (policy levers) in the main manuscript.