# A New Way of Understanding Agricultural Rebound Phenomenon Using a Global Sensitivity Analysis Approach


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## Problem

- Improving irrigation systems has been recognized as a means to reduce the water loss caused by traditional irrigation systems, requiring considerable investments. Evidence indicated such investments may not lead to a reduction in water use in the long-run, which may even increase paradoxically - the rebound phenomenon.
- Explicit evaluation of coevolutionary dynamics and the interactions among socio-economic factors in the agricultural rebound phenomenon is needed, calling for the application of systems-based methodologies such as a global sensitivity analysis (GSA).

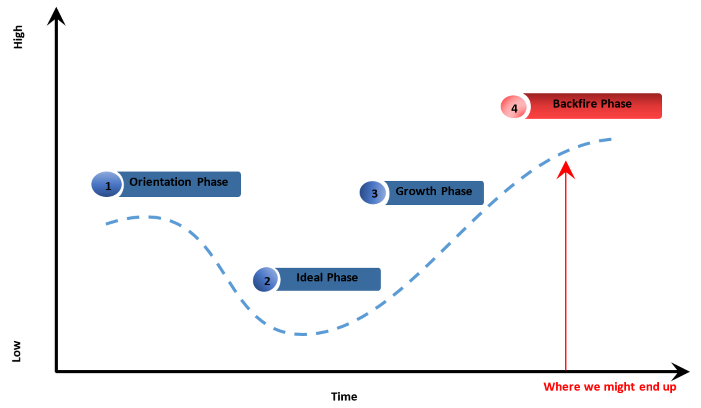


Figure 1. Different phases in the agricultural rebound phenomenon

## Case Study

- The government of Alberta released the Water for Life program to decrease the water demand by 30% through conservation, productivity and efficiency by 2015 compared to the year 2005.
- This improvement in conservation was achieved through several measures including upgrading on-farm irrigation system and changing crop patterns.
- Alberta subsidized the farmers to switch from flood irrigation system to more efficient one like sprinklers.
- This study focused on the Bow River Basin in Alberta, Canada, as a case study.

## Purpose and Methodology

- We use a previously developed Agent-Based Agricultural Water Demand (ABAD) model (Ghoreishi et al., under review in Hydrological Science Journal). We perform a time-dependent variance-based GSA on the ABAD model to examine the individual effect of factors and their joint influence due to their interactions (total-order effect) on the rebound phenomenon.
- The ABAD model is consists of two submodels: the monthly water submodel and the yearly human submodel. The water submodel is a lumped hydrological model, based on the FAO Penman-Monteith method.
- The human submodel simulates the individual farmers as agents (2000 agents based on the BRB population). These agents make three decisions: adopting sprinkler systems, changing crops, and expanding irrigated areas. Agents switch irrigation system to conserve water. The second conservation decision is to change forages to other crops that require less water. When the agents save water through conservation measures, they may expand their irrigated area.
- To make the yearly decisions, agents assign different weights to the socio-economic factors, reflecting their relative importance. In the ABAD model, these weights are sampled from normal distributions, which represent the heterogeneity in a farming society.
- We conduct the GSA on the ABAD model's rebound index to the potential ranges of the model factors for identifying the most influential model factors over time. We investigate to what extent the interactions among these factors are important in giving rise to the model response. The variance of the model output (V), the first-order (Si), and total-effect (STi) indices (Sobol indices) can be written by the following formulas:

$$V=\sum_{i} V_i+\sum_{i<j} V_{ij}+\sum_{i<j<m} V_{ijm}+\cdots+V_{12\ldots k} \quad (1)$$

$$S_i=\frac{\mathrm{V_i}}{\mathrm{V}}=\frac{V[E(Y|X_i)]}{V(Y)} \quad (2)$$

$$S_{Ti}=1-\frac{V[E(Y|X_{-i})]}{V(Y)} \quad (3)$$

- $V_i$ represents the sensitivity of the model output to model factor $X_i$, $V_{ij}$ represents the sensitivity of the model output to the interaction between model factors $X_i$ and $X_j$. Similarly, $V_{ijm}$ represents the sensitivity of the model output to the interaction between model factors $X_i$, $X_j$, and $X_m$. $S_i$ represents a fractional contribution of a variability in factor $i$ to $V$ independent of other model factors ($k$-1). $S_{Ti}$ represents the overall contribution of a given model factor $i$, including its interaction with other model factors. $X_{-i}$ menas all factors but $X_i$.


Fig2. Decision making's factors in the ABAD model

## Design of Experiment

- We use a pre-specified factor grouping strategy for the time-dependent variance-based GSA. This strategy helps reduce the dimensionality of the factor space to analyze the ABAD model (Saltelli et al., 2008). Furthermore, as the interpretations of the GSA results are used to explore the implications for sustainable water management, presenting model factors through a few groups can improve the understanding of policymakers to control the agricultural rebound phenomenon.
- We determine the first group as the economy group that includes all monetary factors, including the means of normal distributions corresponding to the past profit, future profit, risk-aversion, and water conservation goal factor. Besides, we specify the heterogeneity group that implies the variability in the farmers' decision-making on different socio-economic values. Therefore, all standard deviations are determined as the heterogeneity group. We determine the rest of the factors as the single factors for our analysis.
- We use the progressive Latin hypercube sampling (PLHS) strategy proposed by Sheikholeslami and Razavi (2017):10 sub-samples with 20,000 points (total sample size of 10*20,000 = 200,000).

## Result

### Time-varying GSA Results

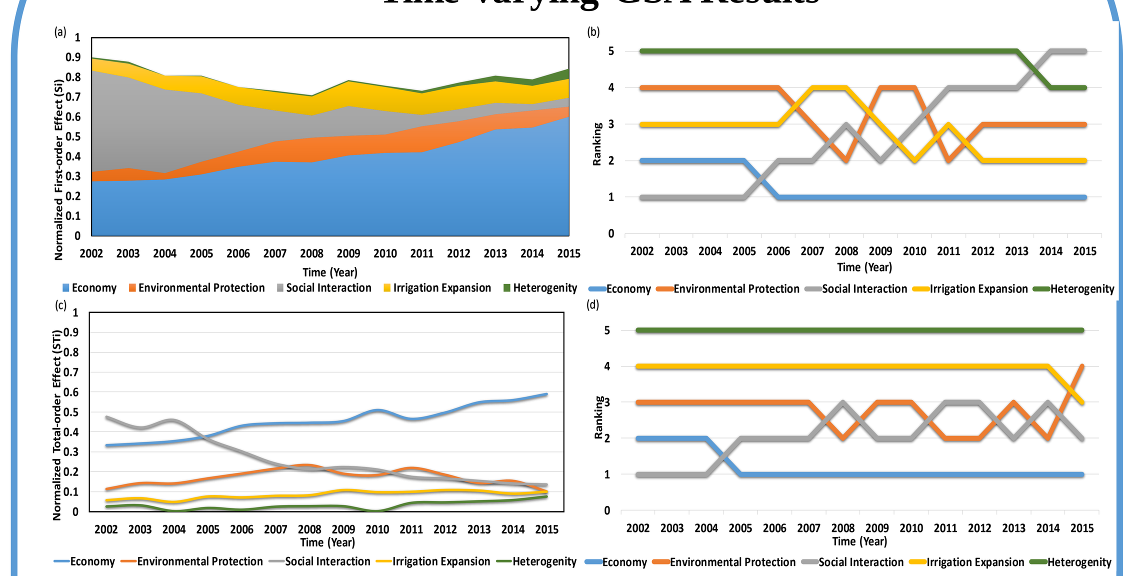


Fig3. a) The normalized first-order effect (Si), b) the factor rankings of the normalized first-order effect (1 is the most important factor, and 5 is the least important factor), c) The normalized total-order effect (STi), and d) the factor rankings of the normalized total-order effect (1 is the most important factor, and 5 is the least important factor), using the time-dependent GSA on the rebound index to the socio-economic factors and the prespecified groups of the factors in the BRB for a representative period (2002-2015) by sampling across the potential ranges of the ABAD model's factors

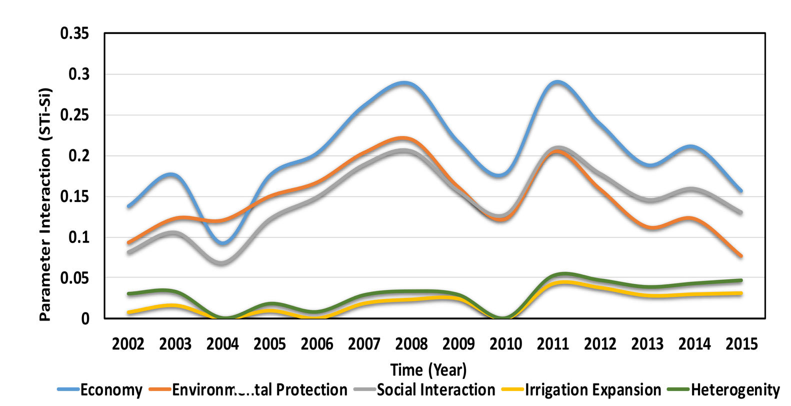


Fig4. The time-dependent GSA with the factor interaction (STi–Si) on the rebound index to the socio-economic factors and the prespecified groups of the factors in the BRB for a representative period (2002-2015) by sampling across the potential ranges of the ABAD model's factors

### Stability and Convergence of GSA Results

Table1. The maximum errors in the estimation of the Sobol indices (as a value below zero) among all model factors over time for the different number of model executions

| *Experiment* | *Model Runs* | *Si* | *STi* |
|---|---|---|---|
| *1* | 140,000 | 0.01409 | 0.07027 |
| *2* | 280,000 | 0.03001 | 0.01121 |
| *3* | 420,000 | 0.04523 | 0.13668 |
| *4* | 560,000 | 0.01101 | 0.14985 |
| *5* | 700,000 | 0.00739 | 0.10922 |
| *6* | 840,000 | 0.00569 | 0.10034 |
| *7* | 980,000 | 0.00488 | 0.07122 |
| *8* | 1,120,000 | 0.00606 | 0.06162 |
| *9* | 1,260,000 | 0.00611 | 0.03641 |
| *10* | 1,400,000 | 0.00276 | 0.02025 |

## Conclusion

- Using a time-dependent GSA, this study provides a better understanding of the coevolutionary dynamics of the coupled human-natural systems with an ABM approach.
- Using a variance-based GSA, this study showed to what extent the ABAD model behaves additive over time. Besides, the variance-based method indicated the degree to which the socio-economic factors interact in the ABAD model.
- The economy group is the most influential element in the agricultural rebound phenomenon in the BRB, followed by an upward trend over time. This study suggests the water pricing strategy, the green tax strategy, changing crop patterns as a means to undermine the economic incentives for individual farmers to avoid the rebound phenomenon.
- The GSA result showed the high individual effect of the social interaction factor in the rebound phenomenon in the BRB. Compared to its individual effect, the total effect of the social interaction indicated a more important role in the rebound phenomenon as a result of the interaction with other socio-economic factors. We highlight the significant role of community participation as a strategy to improve community awareness and avoid the rebound phenomenon.
- The irrigation expansion factor plays a vital role in the rebound phenomenon in the BRB. We propose restrictions on irrigated areas and farmers' water rights. These strategies could prevent individual farmers from using their saved water to prevent the rebound phenomenon.

## References


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