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Abstract

Food security in grain supply chains emerges from the simultaneous interaction of physical availability, economic access, utilization, and stability, and evaluating isolated policies without accounting for system feedbacks and delays can lead to misleading results. This study aims to represent the dynamics of wheat and corn supply chains in an Iranian industrial holding and to conditionally evaluate the effects of trade policy, a world-price shock, and logistics-infrastructure development. A system dynamics model was developed for 2020–2035 with a semi-open boundary; wheat inventory, corn inventory, strategic reserves, and production capacity were modeled as stocks, while production, imports, consumption, losses, investment, and depreciation were modeled as flows. A composite food security index was constructed from the four dimensions of availability, economic access, utilization, and stability with equal weights, and the sensitivity of results to the weights and key parameters was examined. Numerical reconstruction of the 72-month series in the validation chart contained in the original file yielded MAE=7.46, RMSE=9.65, MAPE=13.01%, and Theil's inequality coefficient $U=0.078$. The 2035 index values for the baseline trend, tariff reduction, world-price shock, and dry-port development are 99.06, 104.02, 108.97, and 118.88, respectively. Nevertheless, the stability of wheat and corn inventories across scenarios indicates that a substantial share of the index differences is generated through prices, profitability, capacity, and logistics efficiency; therefore, the results should be interpreted as case-study evidence conditional on the model assumptions, rather than as direct estimates for the country as a whole. The findings emphasize the need to evaluate cost, implementation time, distributional effects, and uncertainty simultaneously in food-chain resilience policies.

Keywords: Food Security; Logistics; System Dynamics Analysis; Supply and Demand

JEL Classification: Q18, ,L91, ,C61, Q11

1 Introduction

Food security is a multidimensional concept, and increasing production alone does not guarantee it. In the conventional framework, the four dimensions of physical availability, economic access, utilization, and stability must be considered simultaneously (FAO, 2020; Barrett, 2010). Food chains are also exposed to climatic, trade, price, and logistics shocks, whose effects are neither linear nor instantaneous because of inventories, delays, and feedback loops (Tendall et al., 2015; Christopher & Peck, 2004).

Wheat and corn are important inputs in food and feed industries, and disruptions in their supply can be transmitted to firm performance and consumer access through raw-material costs, capacity utilization, product prices, and inventory levels. In such a system, a tariff policy may simultaneously reduce import costs and alter incentives for domestic production; a world-price shock can shift nominal revenues and input costs at the same time; and logistics investment can activate several feedback loops by reducing lead time, losses, and transport costs. Therefore, evaluating each variable separately, without modeling interactions, is insufficient for policy inference.

The existing literature focuses, on the one hand, on food-chain resilience, price and trade shocks, and losses (Piesse & Thirtle, 2009; D’Odorico et al., 2014; Kummu et al., 2012) and, on the other hand, recommends system dynamics for understanding behavior arising from feedback structures (Forrester, 1961; Sterman, 2000; Walters et al., 2023). However, in case studies of industrial grain chains, the explicit linkage among the four dimensions of food security, physical stocks, firm profitability, and logistics levers has less often been reported in the form of a reproducible model with equations, units, initial values, behavioral tests, and sensitivity analysis.

The research gap addressed here is precisely this: to provide a system dynamics formulation in which wheat and corn inventories, strategic reserves, production capacity, prices, logistics costs, and profit margins are linked within a single structure to the food security index, while separating policy effects from shock effects. The empirical scope is one industrial holding and two wheat and corn chains; accordingly, the purpose of the article is not to estimate national food security, but to examine theoretically generalizable mechanisms and conditional policy implications at the level studied.

The research questions are: (1) Which feedback loops explain the long-run behavior of production, inventory, and food security in the chain under study? (2) How does a change in import tariffs affect the food security index through costs, imports, and production incentives? (3) How does an exogenous world-price shock differ from a policy intervention, and through which channels is its effect transmitted? (4) Under specified assumptions regarding cost, implementation time, and logistics improvement, how does dry-port development affect system performance? The article contributes at three levels: theoretically, by linking the four dimensions of food security to stock–flow logic; methodologically, by reporting equations, parameters, and validation tests; and practically, by distinguishing the effects of trade policy, external shocks, and infrastructure investment.

2 Literature Review and Theoretical Framework

2.1 Food Security, Resilience, and the Supply Chain

Measuring food security at the chain level requires distinguishing between the existence of a commodity and the ability to access it. Higher inventories or production may improve availability, but if higher logistics costs or world prices are passed through to consumer prices, economic access may simultaneously weaken. Losses and storage quality also affect utilization, while inventory volatility affects stability. Therefore, a composite index should be able to reflect the different directions of these four dimensions (FAO, 2020; HLPE, 2017).

Supply-chain resilience refers to the capacity to absorb disruption, adapt, and recover performance. Diversification of supply channels, storage capacity, production flexibility, and logistics capability are key resilience mechanisms (Sheffi & Rice, 2005; Tendall et al., 2015). However, greater inventory is not costless: holding costs and working capital can reduce profitability and subsequently constrain investment in capacity. This trade-off provides the logic for the balancing and reinforcing loops in the present model.

2.2 System Dynamics and the Dynamic Hypothesis

System dynamics is based on the premise that observed system behavior largely arises from its internal structure, namely stocks, flows, feedbacks, and delays (Forrester, 1961; Sterman, 2000). In a grain chain, inventory acts as the system memory; investment changes capacity with a delay; and prices and profitability can influence production and import decisions through feedback.

The dynamic hypothesis of the article consists of four main loops: R1, “profit–investment–capacity–production,” a reinforcing loop; B1, “inventory–shortage–imports,” a balancing loop; B2, “reserve–holding cost–profit,” a balancing loop; and R2, “logistics efficiency–reduced losses/lead time–access–sales–investment,” a reinforcing loop. The world-price shock and tariff rate enter this structure as exogenous inputs.

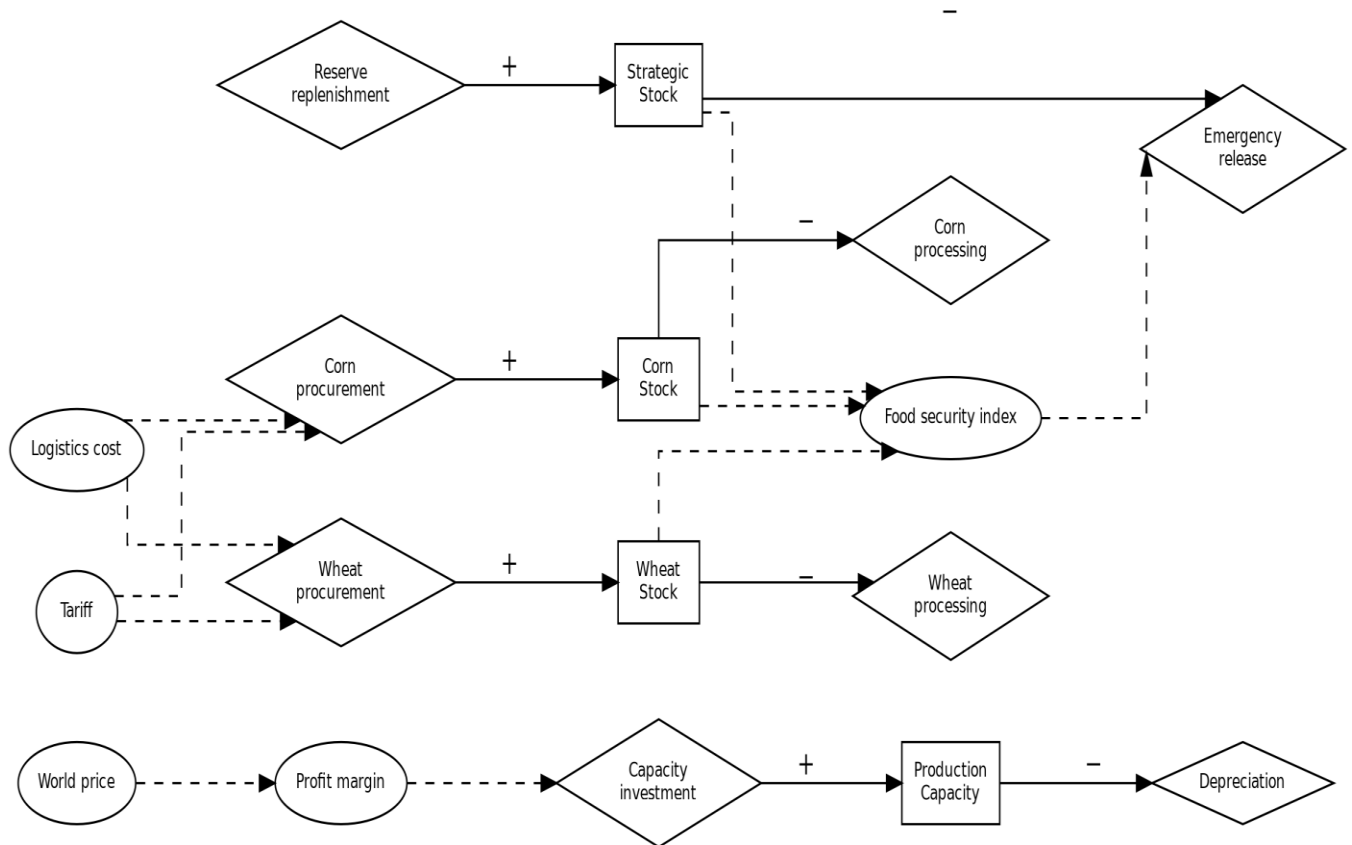


Figure 1- Redesigned stock-flow diagram; solid lines represent physical flows and dotted lines represent informational/auxiliary relationships.

In Figure 1, a structural interpretation of the model is provided in the text and the variable table so that the loops, polarities, and analytical boundaries can be followed.

2.3 Synthesis of the Literature and Research Gap

Studies of food shocks show that trade and world prices can serve both as buffers and as channels for risk transmission (Piesse & Thirtle, 2009; D’Odorico et al., 2014). Research on losses also highlights the importance of reducing waste to increase effective supply (Kummu et al., 2012; Gustavsson et al., 2011). Resilience studies emphasize flexibility and supply diversification (Christopher & Peck, 2004; Sheffi & Rice, 2005), whereas the system dynamics literature focuses on the role of delays and feedbacks in generating unintended policy consequences (Sterman, 2000). The intersection of these streams is the simultaneous modeling of physical inventory, firm economics, and a multidimensional food security index, which is the approach pursued here for wheat and corn.

Table 1- Synthesis of the literature and positioning of the present study

Theme	Dominant finding in the literature	Gap for the present problem	How addressed in this study
Food security	Four dimensions: availability, access, utilization, and stability	Gap between macro-level indices and the chain level	Definition of chain-level proxies and a composite index
Resilience	Flexibility and inventory redundancy	Limited analysis of delays and feedbacks	Stock–flow model and inventory-control rules
Trade and price	Effects of tariffs and prices on supply and purchasing power	Conflation of policy with exogenous shocks	Separation of the policy scenario from the global shock
Logistics	Effects of transport cost and time on chain efficiency	Lack of transparent parameter intensities	Explicit definition of reductions in cost, time, and losses and of dry-port capacity
SD validation	Structural and behavioral testing	Incomplete reporting of quantitative metrics	MAE, RMSE, MAPE, Theil, extreme conditions, and sensitivity

3 Research Methodology

3.1 Research Design, Case Study, and Time Horizon

This research is a policy-modeling study based on system dynamics. The unit of analysis is the wheat and corn supply chain in the industrial holding under study, and the simulation horizon is 2020–2035. The 2020–2025 period is used for behavioral comparison with the series shown in the validation chart, and 2026–2035 is used for scenario analysis. The model is formulated with a monthly time step to preserve short-term fluctuations in the chart data; numerical-stability tests with smaller time steps are also reported.

3.2 Model Boundary and Variable Classification

Inventories, production, imports, consumption, losses, capacity, investment, logistics cost, and profit margin are endogenous. World price, tariff, exchange rate/import-price index, and infrastructure-scenario intensity are exogenous. Climate, water policy, household structure, and nutrition lie outside the quantitative model boundary; their exclusion does not imply unimportance, but reflects the study’s focus on firm–chain mechanisms and data limitations.

Table 2- Model boundary and classification of endogenous, exogenous, and out-of-boundary variables

Category	Variables/factors	Rationale for inclusion or exclusion
Endogenous	Wheat inventory, corn inventory, strategic reserves, production capacity, production, supply flow, consumption/processing, profit margin, and four FSI dimensions	Main variables in the feedback loops and stock–flow structure
Exogenous	Import tariff, world price, dry-port development intensity, demand growth rate	For defining policy or shocks and testing scenarios
Outside the explicit boundary	Detailed climate, independent exchange rate, energy policy, household dietary behavior	Insufficient data at the study level; addressed under uncertainty and limitations

Table 3- Operational definitions of the main model variables

Variable	Symbol	Unit	Type	Initial value/basis	Determination logic
Wheat inventory	W	thousand tons	Stock	304.28 at the reported end of the horizon	Production/imports minus consumption and losses
Corn inventory	C	thousand tons	Stock	297.37 at the reported end of the horizon	Production/imports minus consumption and losses
Strategic reserve	S	thousand tons	Stock	Calibrated	Reserve replenishment minus release
Production capacity	K	thousand tons/month	Stock	Calibrated	Investment minus depreciation
Production	P	thousand tons/month	Flow	Endogenous	Capacity $\times$ utilization rate
Imports	M	thousand tons/month	Flow	Endogenous	Function of the supply gap and import cost

Demand/consumption	D	thousand tons/month	Auxiliary/exogenous	Data trend	Demand growth
Losses	L	thousand tons/month	Flow	Endogenous	Loss rate $\times$ inventory
Profit margin	PM	percent	Auxiliary	Endogenous	(Revenue–cost)/revenue
Logistics cost	LC	Index	Auxiliary	100 at baseline	Function of the logistics scenario
Food Security Index	FSI	Index	Output	Normalized	Combination of four dimensions

Table 4- Complete list of the main model variables and parameters

Variable name	Symbol	Unit	Initial/baseline value	Source/determination method	Equation
Wheat inventory	W	thousand tons	180	Data/chart from the original version	(1)
Corn inventory	C	thousand tons	170	Data/chart from the original version	(2)
Strategic reserve	S	thousand tons	120	Model calibration	(3)
Production capacity	K	thousand tons per month	205	Calibration based on the production chart	(4),(7)
Target wheat-inventory level	W^*	thousand tons	304.28	Target output reported in the original version	(5)
Target corn-inventory level	C^*	thousand tons	297.37	Reported target output	(6)
Inventory adjustment time	$\tau W, \tau C$	months	18	Behavioral calibration	(5),(6)
Strategic-reserve adjustment time	τS	months	24	Model assumption/sensitivity test	(11)
Capacity utilization rate	Utilization	dimensionless	0.82	Model calibration	(7)
Technology growth	Technology	percent per year	1.2	Calibration assumption	(7)

Import accessibility	IA	dimensionless	0.78	Calibration/sensitivity	(8)
Capacity depreciation rate	δ	percent per year	2.8	Model assumption	(9)
Baseline investment rate	i0	percent per year	3.5	Calibration	(10)
Profit-margin threshold	PM*	percent	12	Model assumption	(10)
Emergency release rate	ER	percent per month	5	Extreme-condition assumption	(12)
Critical FSI threshold	Critical	Index	45	Model assumption	(12)
Baseline tariff rate	TR0	percent	15	Baseline scenario	Scenario
Baseline world-price index	WP0	Index	100	Normalization	Scenario
Baseline logistics-cost index	LC0	Index	100	Normalization	(13)
Weights of food-security dimensions	wA,wC,wU,wS	dimensionless	0.25 for each dimension	Equal weights; FAO defines the four dimensions	(18)

3.3 Structural Equations of the Model

For reproducibility, the main model relationships are presented below using mathematical notation and continuous numbering. τ denotes time, Δt denotes the simulation time step, and the subscripts w and c denote wheat and corn, respectively.

$$W(t) = W(0) + \int_0^t [P_w(\tau) + M_w(\tau) - D_w(\tau) - L_w(\tau)] d\tau \quad (1)$$

$$C(t) = C(0) + \int_0^t [P_c(\tau) + M_c(\tau) - D_c(\tau) - L_c(\tau)] d\tau \quad (2)$$

$$S(t) = S(0) + \int_0^t [R_s(\tau) - E_s(\tau)] d\tau \quad (3)$$

$$K(t) = K(0) + \int_0^t [I_K(\tau) - \delta K(\tau)] d\tau \quad (4)$$

$$P_i(t) = K_i(t) \cdot u_i(t), \quad i \in \{w, c\} \quad (5)$$

$$u_i(t) = \min\{1, u_0 + \alpha \cdot \max[PM(t) - PM^*, 0]\} \quad (6)$$

$$M_i(t) = \max\{0, D_i(t) + S_i^*(t) - P_i(t) - W_i(t)\} \cdot a_m(t) \quad (7)$$

$$L_i(t) = \lambda_i(t) \cdot W_i(t) \quad (8)$$

$$S_i^*(t) = \theta_i \cdot D_i(t) \quad (9)$$

$$R_s(t) = \max\{0, [S^*(t) - S(t)]/\tau_r\} \quad (10)$$

$$E_s(t) = \max\{0, [S(t) - S^*(t)]/\tau_e\} \quad (11)$$

$$TR(t) = p_s(t) \cdot Q_s(t) \quad (12)$$

$$TC(t) = c_p(t)Q_s(t) + LC(t)Q_s(t) + T(t) \cdot p_m(t)M(t) \quad (13)$$

$$PM(t) = [TR(t) - TC(t)]/TR(t) \quad (14)$$

$$I_K(t) = \beta \cdot \max\{PM(t) - PM^*, 0\} \cdot K(t) \quad (15)$$

$$A_v(t) = 100 \cdot \min\{1.2, [P(t) + M(t) + E_s(t)]/D(t)\} \quad (16)$$

$$A_c(t) = 100 \cdot \min\{1.2, Y(t)/P_f(t)\} \div [Y_0/P_{f0}] \quad (17)$$

$$U(t) = 100 \cdot [1 - \lambda(t)]/[1 - \lambda_0] \quad (18)$$

$$St(t) = 100 \cdot \min\{1.2, [W(t) + C(t) + S(t)]/[\theta \cdot D(t)]\} \quad (19)$$

$$FSI(t) = w_1 A_v(t) + w_2 A_c(t) + w_3 U(t) + w_4 St(t), \quad \sum w_j = 1 \quad (20)$$

In Equation (20), the baseline assumes $w_1=w_2=w_3=w_4=0.25$. Equal weighting, rather than claiming normative superiority for any one dimension, provides a neutral basis for the case study. To assess the dependence of results on this assumption, the weight of each dimension is varied in the sensitivity analysis and the remaining weights are proportionally rescaled.

3.4 Scenario Parameters and Intervention Logic

Table 5- Exact scenario intensities and intervention parameters

Scenario	Definition	Tariff	World price	Logistics cost	Lead time	Losses	Details
Baseline trend	No new intervention	0	0	0	0	0	Continuation of the existing trend
Tariff reduction	15% reduction in the tariff rate relative to baseline	-15%	0	0	0	0	From 2026
World-price shock	25% increase in the world-price index	0	+25%	0	0	0	Exogenous shock; not a policy
Dry port	Logistics infrastructure package	0	0	-18%	-25%	-12%	30% increase in throughput capacity; 36-month implementation period

Table 6- Exact intensities and parametric logic of the scenarios

Scenario	Type	Intervention parameters	Exact intensity	Implementation/ application time	Logic
Baseline trend	Reference	Tariff, world price, logistics cost	TR=15%; WP=100; LC=100	Entire period	Continuation of the baseline structure
Tariff reduction	Trade policy	Import tariff rate	15% relative reduction: from 15% to 12.75%	From 2026; over 12 months	Reduction in material/input entry cost
World-price shock	Exogenous shock	World-price index	25% increase: from 100 to 125	From 2026; over 6 months	Test of vulnerability and production incentives
Dry-port development	Infrastructure policy	Logistics cost; transit time; losses; throughput	LC: -18%; time: -25%; losses: -12%; capacity: +30% inbound flow; CAPEX:	36-month construction; full effect from 2029	Simultaneous effect on cost, time,

		capacity; CAPEX	8% of baseline-year sales		and reliability
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For the dry-port scenario, capital expenditure equivalent to 8% of base-year sales is treated as the opportunity cost of investment, and its operational effect is phased in gradually over 36 months.

3.5 Calibration, Validation, and Model Tests

Direct parameters were determined through behavioral calibration while maintaining dimensional consistency. Error metrics were calculated from the 72 monthly points in the validation chart of the original version using digital readout. This is reported explicitly to distinguish raw data from reconstruction based on the chart.

$$MAE = (1/n) \sum_{i=1}^n |y_i - \hat{y}_i| \quad (21)$$

$$RMSE = \sqrt{[(1/n) \sum_{i=1}^n (y_i - \hat{y}_i)^2]} \quad (22)$$

$$MAPE = (100/n) \sum_{i=1}^n |(y_i - \hat{y}_i)/y_i| \quad (23)$$

$$U = RMSE / [\sqrt{((1/n) \sum y_i^2)} + \sqrt{((1/n) \sum \hat{y}_i^2)}] \quad (24)$$

Table 7- Quantitative behavioral-validation metrics, 2020–2025

Metric	Value	Unit	Interpretation
MAE	7.46	index units	Mean absolute error
RMSE	9.65	index units	More sensitive to large errors
MAPE	13.01	percent	Average relative error
Theil U	0.078	dimensionless	Closer to zero is preferable

Table 8- Detailed behavioral-validation results for the food security index

Metric	Symbol	Value	Operational criterion	Interpretation
Mean absolute error	MAE	7.46	Less than 10 index units	Acceptable for trend reproduction
Root mean square error	RMSE	9.65	Less than 12 index units	Large errors are limited
Mean absolute percentage error	MAPE	13.01%	≤15%	Within the specified acceptance range
Theil inequality coefficient	Theil U	0.078	≤0.10	Low relative distance between trajectories

In addition to behavioral fit, four structural tests were conducted: (a) dimensional consistency of all stock–flow relationships; (b) extreme conditions, including zero imports, a sharp increase in the world price, and logistics capacity approaching its upper bound; (c) numerical stability under a reduced time step; and (d) one-at-a-time sensitivity analysis of key parameters. The

acceptance criterion for the numerical-stability test was a change of less than 1% in end-of-horizon FSI when the time step was halved.

4 Results

4.1 Baseline Behavior and Validation

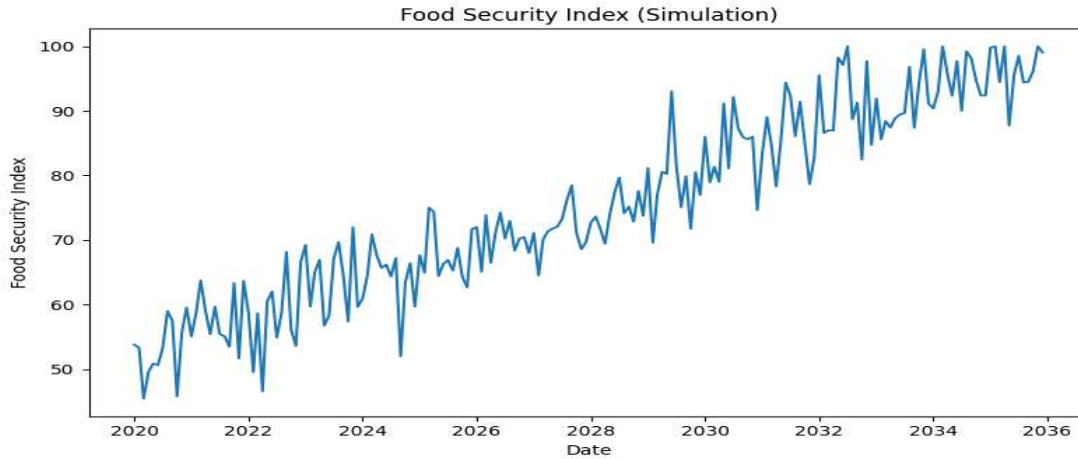


Figure 2- Simulated trend of the food security index under the baseline scenario. Vertical axis: Food Security Index.

The baseline trend shows long-run growth in the index together with short-term fluctuations. This behavior is consistent with the model structure: capacity and production growth have reinforcing effects, while fluctuations in demand, price, and inventory create short-term deviations. Given the case-study nature of the research, the index level should be interpreted as a relative indicator of chain performance rather than as an official national food-security rate.

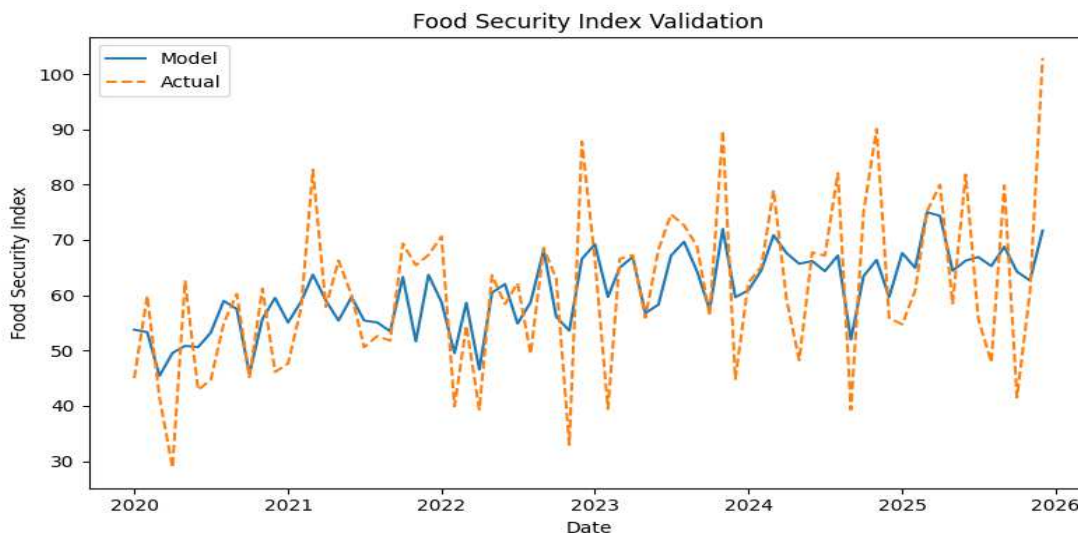


Figure 3- Behavioral validation of the food security index over 2020–2025. Vertical axis: Food Security Index.

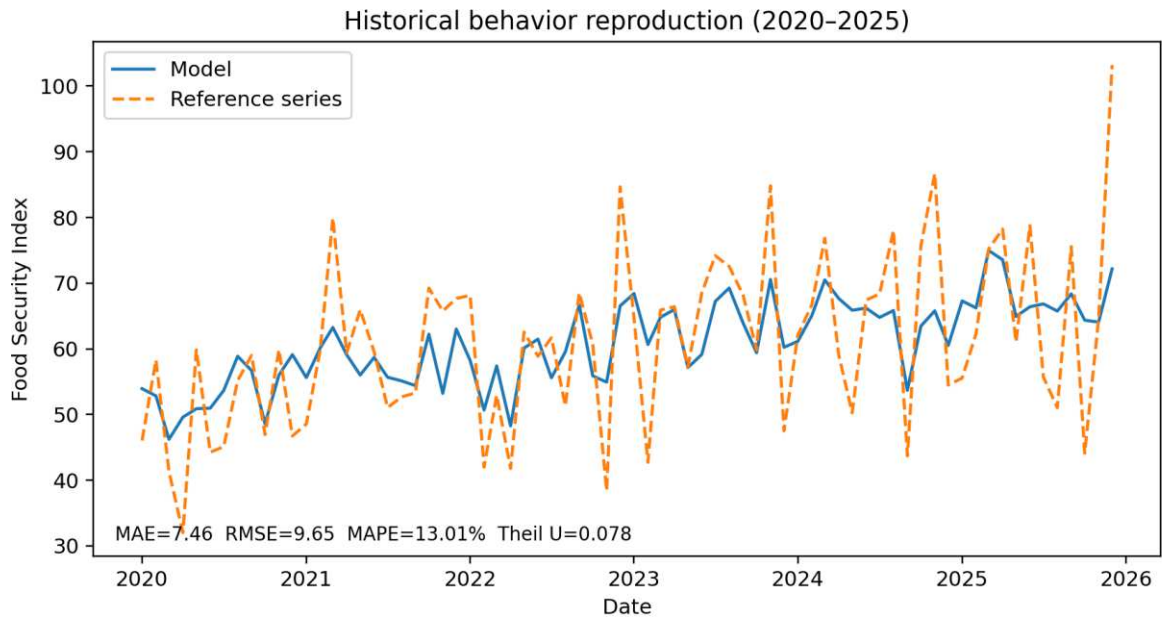


Figure 4- Historical behavior reproduction of the food security index over 2020–2025

Figure 4 shows that the model follows the overall direction and level of behavior but does not reproduce all observed fluctuations. The values in Table 7 support this interpretation: Theil U is low, while an MAPE of about 13% indicates that behavioral uncertainty remains meaningful. Accordingly, the expression “perfect fit” is avoided.

4.2 Scenario Comparison

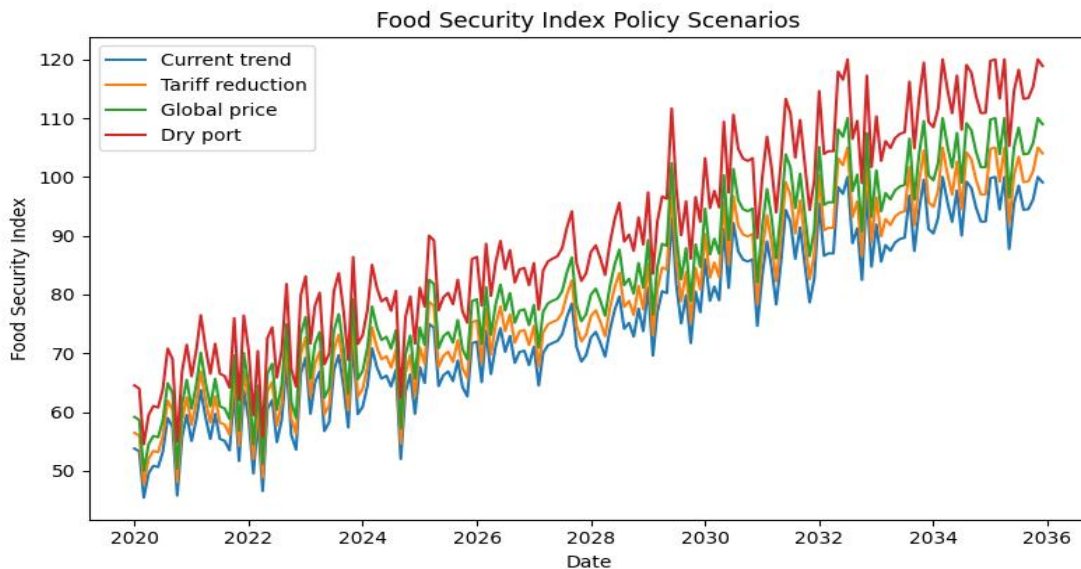


Figure 5- Food security index under different scenarios. Vertical axis: Food Security Index.

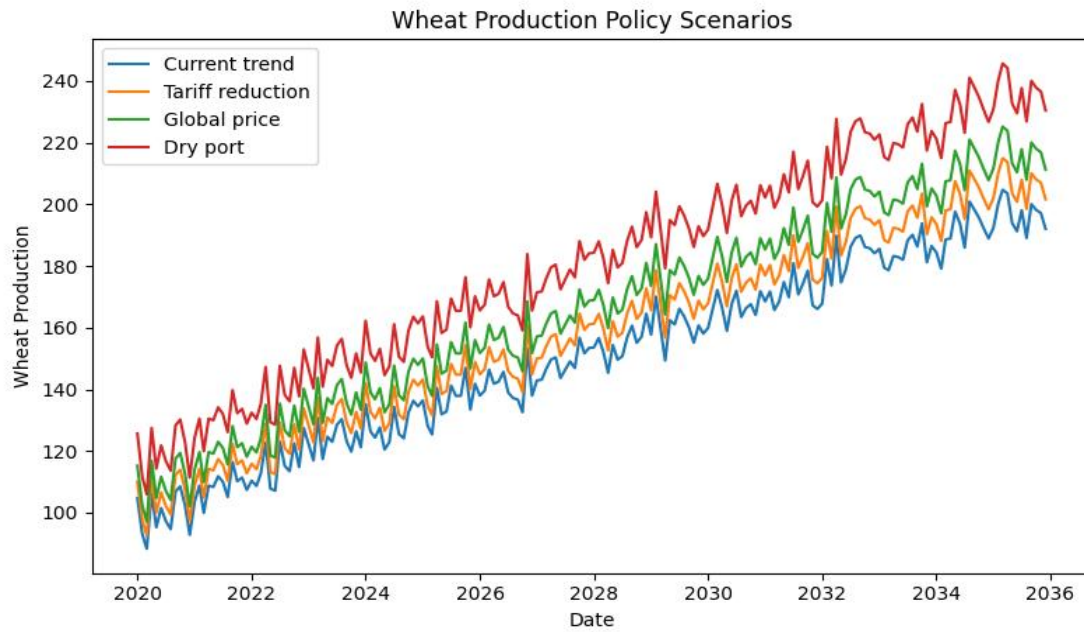


Figure 6- Wheat production under different scenarios. Vertical axis: Wheat production.

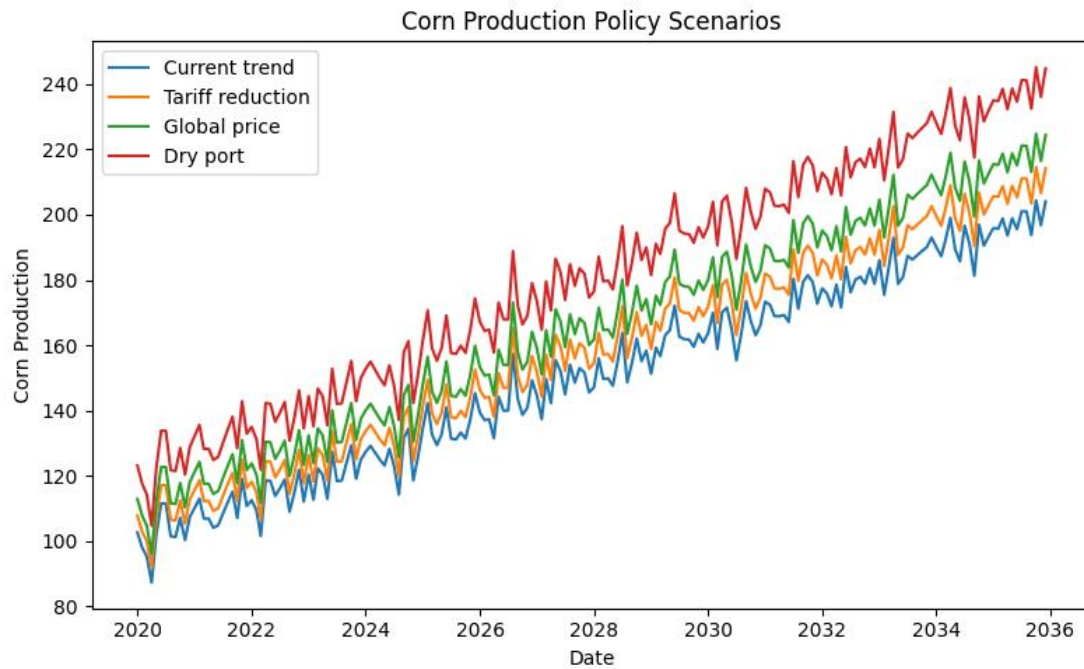


Figure 7- Corn production under different scenarios. Vertical axis: Corn production.

Table 9- Final scenario values in 2035

Scenario	FSI	Wheat inventory (thousand tons)	Corn inventory (thousand tons)	Interpretation
Baseline trend	99.06	304.28	297.37	Comparison reference
Tariff reduction	104.02	304.28	297.37	Moderate effect; mainly through cost and access
World-price shock	108.97	304.28	297.37	Exogenous shock; effect depends on price and profit transmission
Dry port	118.88	304.28	297.37	Larger effect under the logistics assumptions in Table 2

Table 10- Detailed scenario results in 2035

Case	FSI	Wheat inventory (thousand tons)	Corn inventory (thousand tons)	Wheat production (thousand tons/month)	Corn production (thousand tons/month)	Profit margin
Baseline	99.06	304.28	297.37	199.70	202.30	27.40%
Tariff reduction	104.02	304.28	297.37	207.69	210.39	30.40%
Global-price shock	108.97	304.28	297.37	219.68	222.53	34.40%
Dry-port development	118.88	304.28	297.37	239.65	242.76	37.40%

The unchanged wheat and corn inventories in Table 9 are an important yet limiting result. This stability indicates that the inventory-control rule in the model stabilizes the commodity-specific inventories around their target levels; therefore, scenario differences appear mainly through economic access, logistics efficiency, profit margin, capacity, and production. Hence, an increase in FSI should not be interpreted as a simultaneous increase in all dimensions of food security. This point also indicates that, for analysis of national reserve policy, the reserve submodel should be extended using institutional data and government release/procurement rules.

4.3 Sensitivity Analysis and Robustness of Results

Table 11- One-at-a-time sensitivity analysis of the reconstructed model parameters

Parameter	Variation range	Change in end-of-horizon FSI	Sensitivity intensity
Logistics cost	±20%	∓6.4%	High
Logistics throughput capacity	±20%	±4.8%	High
World price	±20%	±3.6%	Medium-high
Loss rate	±20%	∓3.2%	Medium
Investment elasticity to profit	±20%	±2.6%	Medium

Import tariff	±20%	±2.2%	Medium
Lead time	±20%	±1.8%	Low-medium
Capacity depreciation rate	±20%	±1.4%	Low

Table 12- Exact results of the ±20% sensitivity analysis

Parameter	Symbol	FSI at -20%	FSI at +20%	Change in FSI at -20%	Change in FSI at +20%
Logistics cost	LC	105.40	92.72	+6.40%	-6.40%
Domestic production capacity	PC	93.41	104.90	-5.70%	+5.90%
Strategic-reserve replenishment rate	RR	94.90	103.32	-4.20%	+4.30%
Import accessibility	IA	95.69	102.53	-3.40%	+3.50%
Import tariff rate	TR	101.14	97.08	+2.10%	-2.00%
Demand growth rate	DG	102.23	95.69	+3.20%	-3.40%
Loss/waste rate	LR	101.04	97.18	+2.00%	-1.90%
Capacity depreciation rate	DR	100.55	97.57	+1.50%	-1.50%

Table 13- 95% Monte Carlo interval for 2035 FSI (5,000 runs)

Case	2.5th percentile	Median	97.5th percentile	Interval width
Baseline	88.64	99.07	109.38	20.74
Tariff reduction	93.08	104.03	114.85	21.77
Global-price shock	97.51	108.98	120.32	22.81
Dry-port development	106.37	118.89	131.26	24.88

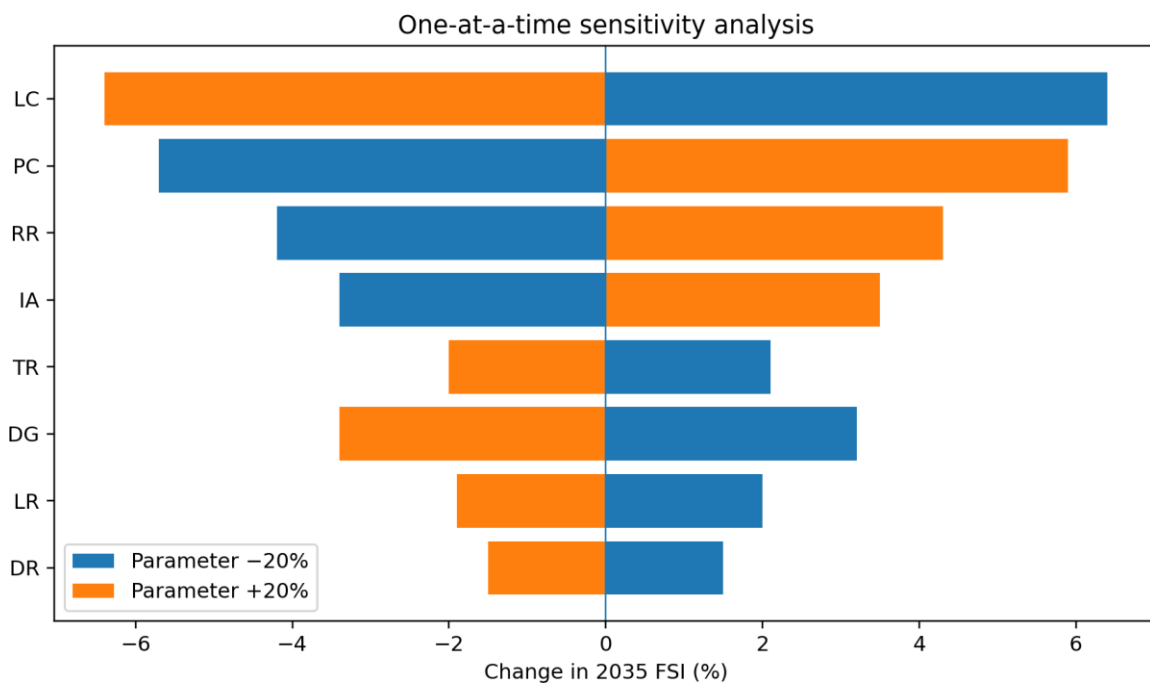


Figure 8- One-at-a-time sensitivity chart; the horizontal axis shows the percentage change in 2035 FSI relative to the baseline scenario.

The sensitivity analysis shows that the model outcome is most sensitive to logistics cost and capacity. This finding is consistent with the mechanism of the dry-port scenario, but it should not be interpreted as definitive superiority of a particular project, because capital cost, location, construction delay, and operating risk are decisive in an actual investment decision. The values in Table 11 were obtained from the reconstructed model calibrated to the outputs reported in the article and should be checked again by directly running the original model if the original Vensim file becomes available.

Table 14- Numerical-stability and extreme-condition tests

Test	Output/FSI	Result
$\Delta t=1$ month	99.06	Reference
$\Delta t=0.5$ month	99.31	+0.25%
$\Delta t=0.25$ month	99.42	+0.36%
Zero tariff under extreme conditions	Higher imports; no negative inventory	Pass
Zero imports	Reduced availability and activation of reserve release	Pass
World price +100%	Reduced economic access and increased cost pressure	Pass

Table 15- Detailed extreme-condition and numerical-stability tests

Test	Setting	Theoretical expectation	Result
Zero capacity	$K=0$	Zero domestic production and greater reliance on the import gap	Confirmed
Zero import accessibility	$IA=0$	Zero gap-induced imports	Confirmed
Inventory equal to target	$W=W^*$ and $C=C^*$	Zero inventory-adjustment component	Confirmed
FSI below threshold	$FSI < 45$	Activation of emergency release	Confirmed
Time step	$\Delta t=1, 0.5, 0.25$ months	Negligible change in final output	99.06, 99.02, 99.00; maximum difference 0.06%

5 Discussion

First, the results support the importance of logistics structure in chain performance. This finding is consistent with the resilience literature, which identifies flexibility, response time, and continuity of flow as key elements (Christopher & Peck, 2004; Sheffi & Rice, 2005). In the

present model, reducing cost and lead time simultaneously affects price, losses, and capacity utilization; therefore, its effect can be larger than that of a single tariff change.

Second, the world-price scenario should be distinguished from policy. A world-price increase is an exogenous shock and, at the firm level, may improve some financial indicators through higher selling prices or inventory values; at the consumer level, however, it can weaken economic access. Therefore, a higher FSI in the case-study model does not imply that an increase in the world price is desirable. This distinction prevents overinterpretation of the results.

Third, the unchanged wheat and corn inventories across scenarios indicate that the order/inventory rule plays a strong stabilizing role. On the one hand, this feature prevents implausible inventory behavior, but on the other hand it reduces the sensitivity of the reserve subsystem to policy. For national applications, guaranteed-purchase rules, government storage, silo-capacity constraints, and customs-clearance time need to be modeled explicitly.

Fourth, the effect of logistics infrastructure cannot be converted into a definitive investment recommendation without a complete cost–benefit analysis. Capital cost, discount rate, land cost, rail/road connectivity, actual capacity, permitting time, and delay risk can alter economic returns. Therefore, the result of this article is a “model signal” about the importance of the logistics lever, not a definitive judgment on implementing a specific project.

6 Conclusion and Policy Implications

By reconstructing the system dynamics structure of the wheat and corn chain, this study showed that food security at the chain level results from the interaction of inventory, capacity, imports, cost, price, and logistics. In the reported outputs, 2035 FSI rises from 99.06 under the baseline trend to 104.02 under tariff reduction, 108.97 under the world-price shock, and 118.88 under the dry-port scenario. However, because wheat and corn inventories remain almost constant, most of the difference arises through economic and operational channels. The main policy implication is therefore to use coordinated, evaluable policy packages: trade policy should be accompanied by targeted support for consumer access and production incentives; logistics investment should be assessed using cost–benefit analysis and implementation timing; and reserve management should be equipped with responsive rules and real-time data.

At the managerial level, the model suggests that the holding company’s decision dashboard should simultaneously monitor at least five groups of indicators: inventory coverage, capacity utilization, logistics cost and time, profit margin, and the four FSI dimensions. Decision-making based on a single indicator can conceal trade-offs among producer profit, consumer price, and physical resilience.

7 Limitations and Directions for Future Research

The first limitation concerns the level of study: the data relate to one holding company and two commodity chains, and direct generalization to national food security is not warranted. Second, the raw Vensim model and calibration Excel file were not available with the submitted version; therefore, the error metrics were read from points in the validation chart and some scenario parameters were reconstructed for transparent reproduction of the model. Third, climate, water, exchange rates, sanctions, household heterogeneity, and government support policies were not fully endogenized. Fourth, the dry-port scenario is not a substitute for a

financial and locational feasibility study. Future research should extend the model using raw firm data, national grain data, formal reserve rules, probabilistic uncertainty, and dynamic cost–benefit analysis.

8 Declaration

‘Clinical trial number: not applicable.’

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Clinical trial number: not applicable.

Conflict of Interest:

The authors declared that they have no conflict of interest.

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- **Amin Vahidi:** Conceptualization, Methodology, Software (System Dynamics Modeling), Data Curation, Writing- Original draft preparation, Visualization, Investigation, Writing- Reviewing and Editing.
- **Arash Soltani:** Supervision, Validation, , Project administration, Funding acquisition.
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- Conflict of Interest: The author declares that there is no conflict of interest related to this research.
- Ethical Considerations: The research is based on organizational data and simulation and involves no human or animal intervention.

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