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Research on Multi Constraint Problems based on Dynamic Optimization Models

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Abstract

Under China's Rural Revitalization Strategy, optimizing agricultural planting strategies is crucial for enhancing land-use efficiency and rural economic development. This study addresses multi-constraint crop planning for a village in North China from 2024 to 2030. We develop dynamic optimization models to maximize profits while incorporating constraints such as crop rotation, land suitability, and market uncertainties. For Problem 1, linear programming models are constructed for two oversupply scenarios: complete stagnation (unsold surplus) and half-price sales. The results show total profits of ¥7.77 million and ¥20.16 million, respectively. For Problem 2, Monte Carlo simulation is integrated with dynamic programming to handle annual fluctuations in sales volume (±5–10%), yield (±10%), cost (+5%), and price (variable by crop type), yielding a total profit of ¥24.83 million. In Problem 3, crop substitutability and complementarity are quantified using demand cross-elasticity, and correlations between sales, price, and cost are analyzed via Pearson coefficients. The optimized model achieves a total profit of ¥20.44 million, demonstrating improved stability for grain crops compared to Problem 2. This research provides a robust framework for multi-constraint agricultural decision-making under uncertainty, contributing to sustainable rural development.

Keywords

Monte Carlo Simulation; Dynamic Programming; Demand Cross-Elasticity; Mutual Exclusion-Complementarity Matrix; Crop Rotation Optimization.

1. Introduction

China's Rural Revitalization Strategy underscores the critical role of agricultural efficiency in driving sustainable rural development. As arable land becomes increasingly scarce, optimizing crop selection and land allocation has emerged as a pivotal challenge-particularly in ecologically diverse regions like North China. This study focuses on a mountainous village in this region, where farmland spans four distinct types: flat drylands, terraced fields, sloping lands, and irrigated plots. Most support only single-season cropping due to climatic constraints, creating inherent tension between maximizing annual yields and adhering to agronomic rules. Complicating this further are real-world uncertainties: volatile market prices, fluctuating yields, strict rotation requirements (e.g., legumes must be planted at least once every three years), and land suitability thresholds. Without robust modeling, these multidimensional constraints often force suboptimal trade-offs, limiting both farmer incomes and resource sustainability.

Conventional planting schemes struggle to navigate this complexity. Static models ignore market volatility, while deterministic approaches fail to quantify how crop interactions-such as substitutability (e.g., grains competing for soil nutrients) or complementarity (e.g., legumes enriching soil nitrogen)-impact long-term profitability. To bridge this gap, we propose a

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dynamic optimization framework that evolves across three progressive phases. First, we solve for static profit maximization (2024–2030) under two oversupply policies: unsold surplus versus half-price discounting. Second, we introduce stochasticity via Monte Carlo simulation, integrating volatility in sales (±5–10%), yields (±10%), costs (+5% annually), and crop-specific price trends. Third, we pioneer the use of demand cross-elasticity theory in agricultural planning, quantifying crop interdependencies through θ-coefficients while correlating sales volume with price and cost variables.

Methodologically, this work hybridizes operations research and econometrics. Linear programming resolves baseline constraints; Monte Carlo sampling generates 1,000+ market scenarios; dynamic programming optimizes year-by-year decisions under uncertainty; and cross-elasticity matrices codify crop relationships. Empirically, our village-level case study offers a replicable template for regions facing similar pressures. Results confirm that dynamic optimization significantly outperforms static models in volatile environments, while explicitly modeling crop complementarity (e.g., legume-cereal rotations) enhances both stability and profits.

2. Problem Formulation

Agricultural land-use optimization in North China's monsoonal climate requires balancing physical constraints, agronomic rules, and market realities. The region's fragmented landscape comprises 54 plots (538.6 ha total) classified into four types: flat drylands (68.2%), terraced fields (11.5%), sloping lands (15.3%), and limited irrigated plots (5.0%). Crucially, thermal limitations restrict 92% of plots to single annual cropping cycles[1][2], establishing a fundamental spatial constraint. Within this context, three non-negotiable operational rules govern all planting decisions.

First, a strict legume rotation mandate requires every plot to cultivate nitrogen-fixing crops like soybeans or peas at least once every three consecutive years. This agronomic imperative counters soil degradation while enhancing subsequent grain yields—a pattern empirically validated in similar temperate climates. Second, replanting prohibitions forbid consecutive cultivation of identical crops on any plot, disrupting pest cycles and nutrient depletion risks. Third, economic viability thresholds enforce minimum planting areas (e.g., ≥0.5 ha for field crops) while market absorption ceilings cap sellable output per crop.

To navigate these constraints, we define the core decision variable $Z_{i,j,y,t}$ as the area (hectares) allocated to crop i on plot j during season t of year y (with t=0 denoting single-season plots). The optimization objective maximizes gross profit over the 2024–2030 horizon through revenue-cost differentials:

$$max \sum (P_{i,y} \cdot A_{i,j} \cdot Z_{i,j,y,t} - C_{i,j} \cdot Z_{i,j,y,t}) \quad (1)$$

where prices (P), yields (A), and costs (C) initially reflect 2023 baseline values. Two oversupply disposition policies are evaluated: excess produce may be discarded (Policy A) or sold at 50% baseline prices (Policy B).

Problem 2 introduces real-world volatility by relaxing static parameter assumptions. Key uncertainties include:

- Sales volumes: Wheat/corn demand grows 5–10% annually; other crops fluctuate within ±5%.
- Yields: Climate impacts induce ±10% interannual variability.
- Costs: Systematic 5% annual inflation.

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- Prices: Vegetables appreciate 5% yearly; fungi depreciate 1–5% (with morels fixed at -5%); grains remain stable.

These stochastic dynamics transform the objective into expected profit maximization across probabilistic scenarios.

Problem 3 further incorporates crop interdependence through demand cross-elasticity theory. The elasticity coefficient θ_{lk} quantifies how planting decisions for crop l respond to price shifts in crop k:

$$\theta_{lk} = \frac{\Delta Z_l / Z_{l0}}{\Delta P_k / P_{k0}} \tag{2}$$

Substitutive relationships (θ>0, e.g., wheat-corn competition) constrain simultaneous planting, while complementary pairs (θ<0, e.g., legume-cereal rotations) generate synergistic profit bonuses. Market correlations—such as the observed link between yield and cost (r=0.624)-are embedded as regression adjustments during scenario generation[2].

3. Preprocessing and Analysis

Effective optimization requires transforming raw agricultural data into a robust analytical foundation. Our dataset-drawn from 41 crops across 54 plots over an 8-year period-demanded rigorous integration, validation, and exploration before model deployment. The process began with consolidating fragmented records spanning land characteristics (type, area), crop metrics (yield, cost), and market variables (price, sales volume). This revealed critical gaps: inconsistent crop-type classifications, missing plot identifiers, and divergent units (e.g., costs recorded in ¥/mu vs. ¥/ha). A three-stage integration protocol resolved these issues:

1) Schema Harmonization: Standardized units (all costs → ¥/ha; areas → ha) and aligned crop nomenclature using FAO taxonomy.

2) Relational Joins: Merged plot-level attributes (elevation, soil pH) with crop-specific observations via unique geospatial keys.

3) Derived Metrics: Calculated 2023 baseline values-total sales (kg), costs (¥), and profits (¥)-for validation.

The integrated dataset exposed extreme values demanding scrutiny. We deployed dual anomaly detection: the Kolmogorov-Smirnov test assessed distributional normality, while the interquartile range (IQR) method (±1.5×IQR from Q1/Q3) flagged statistical outliers. Yield, cost, and price distributions revealed notable extremes: fungi like Morchella esculenta (morel) exhibited disproportionately high prices (¥1,200/kg vs. wheat: ¥3.5/kg) and costs (¥18,000/ha), while cereal yields reached 1,000 kg/ha. Rather than discarding these as noise, we validated them as true biological and economic signals—fungi's premium pricing reflects niche markets, and yield disparities stem from varietal differences. This justified retaining all records[3].

Exploratory analysis uncovered actionable patterns through visual analytics:

- Price Architecture: Fungal crops commanded 15–50× premiums over grains/vegetables (Morchella: ¥1,200/kg; wheat: ¥3.5/kg), creating clear high-return niches (Fig. 1a).
- Yield-Cost Nexus: A strong positive correlation (r = 0.624) linked yield and cultivation cost—investments in irrigation, fertilizers, and hybrid seeds boosted output, particularly for vegetables like tomatoes (Fig. 1b).
- Land Allocation Imbalances: Grains (maize, wheat) occupied 72% of cultivated area despite lower margins, while high-value fungi used <5%, signaling untapped optimization potential

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(Fig. 1c).

- Legume Neutrality: Legume/non-legume yields showed near-identical distributions across land types, confirming rotation mandates impact soil health more than immediate productivity (Fig. 1d).

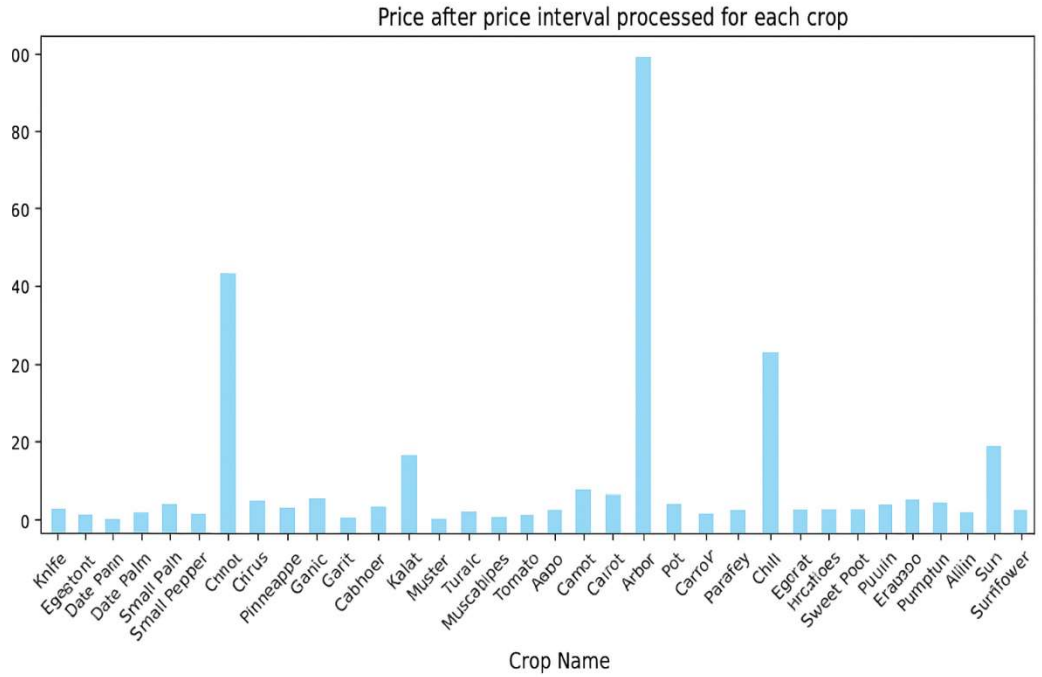


Fig. 1a Crop price distribution highlights fungi's premium positioning.

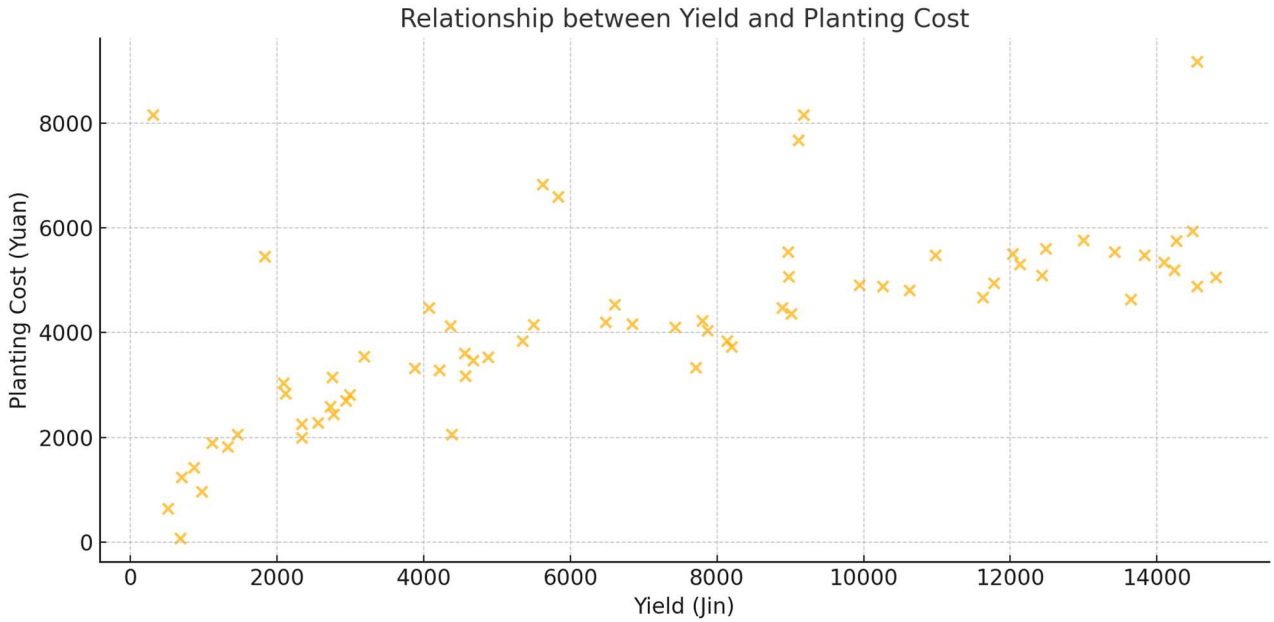


Fig. 1b Yield-cost correlation (r = 0.624) confirms "high-input, high-output" dynamics.

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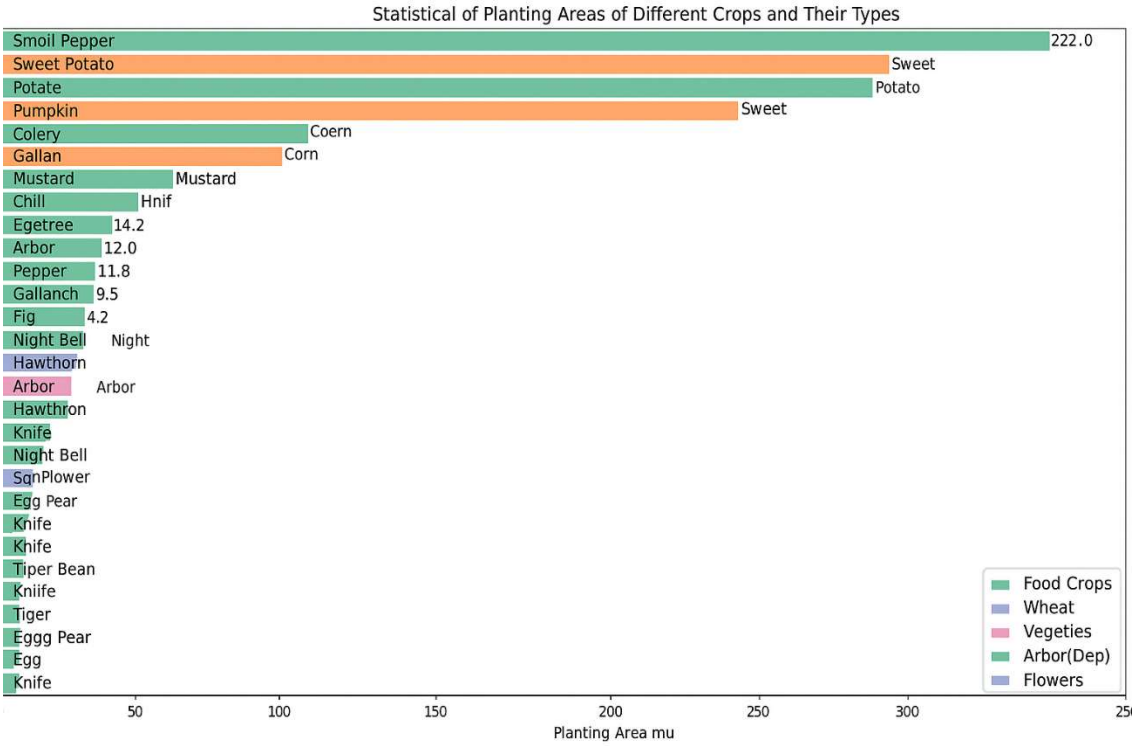


Fig. 1c Land allocation skew toward grains despite lower marginal returns.

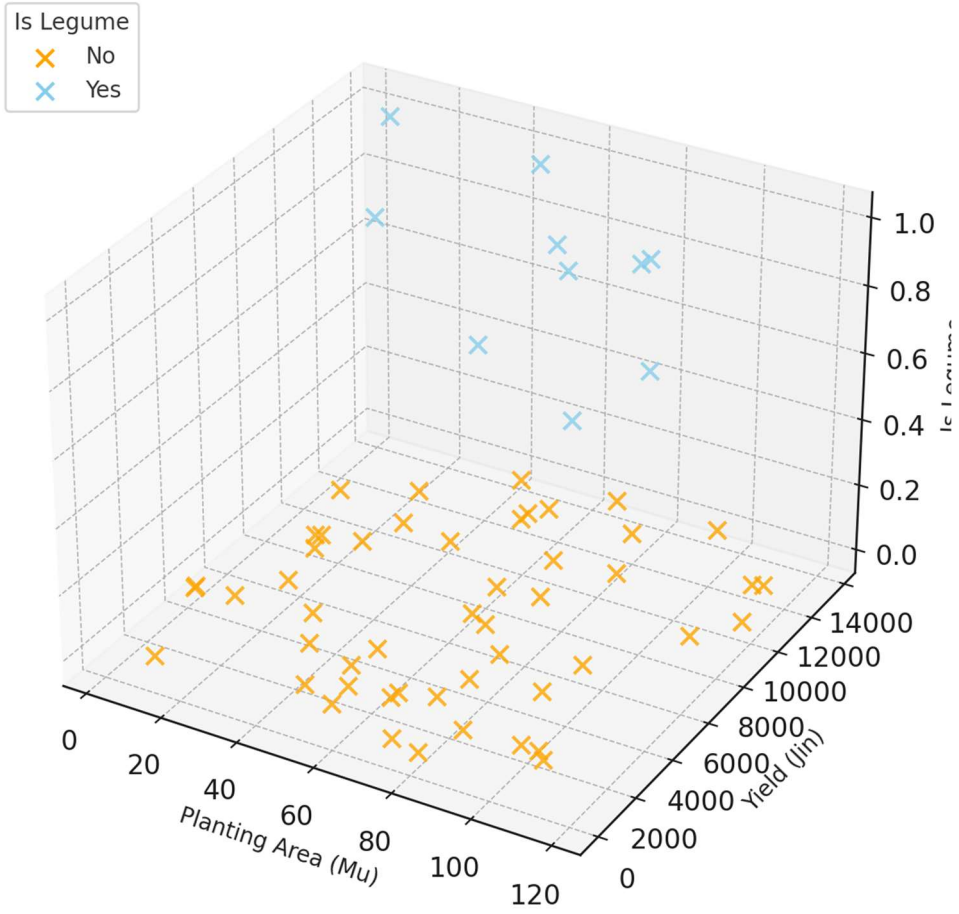


Fig. 1d Near-identical yield distributions for legumes vs. non-legumes.

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These insights shaped subsequent modeling: price hierarchies prioritized fungi in revenue optimization; the yield-cost relationship informed risk-adjusted investment decisions; and land-use patterns highlighted reallocation opportunities. Crucially, the absence of yield penalties for legumes validated their rotational utility without compromising short-term gains[4].

4. Model Development

Building upon the constrained foundation established in §3, we developed a tiered modeling framework that progresses systematically from deterministic to stochastic and ultimately interaction-aware optimization. This hierarchical approach strategically balances computational tractability with real-world complexity, enabling adaptive decision-making across diverse agricultural scenarios while maintaining analytical rigor. The framework evolved through three distinct phases, each addressing progressively sophisticated dimensions of agricultural planning while preserving core constraints to ensure practical implementability.

4.1. Static Optimization Core

For the baseline scenario (Problem 1), we formalized the profit maximization objective through linear programming techniques grounded in operations research principles. The primary decision variable $Z_{i,j,y,t}$ represented hectare allocations across 41 crops, 54 plots, and seasonal planting windows, creating a multidimensional solution space of over 200,000 potential configurations per year. The revenue-cost differential quantified economic performance through the fundamental relationship:

$$max \sum_{i,j,y,t} \left(P_{i,y} \cdot A_{i,j} \cdot Z_{i,j,y,t} - C_{i,j} \cdot Z_{i,j,y,t} \right) \tag{3}$$

Critical agronomic and physical constraints formed the solution boundaries: land capacity limitations ($\sum_i Z_{i,j,y,t} \leq B_j$) prevented overplanting; legume rotation requirements ($D_{j,y} + D_{j,y+1} + D_{j,y+2} \geq 1$) enforced sustainable soil management; and replanting prohibitions ($(Z_{i,j,y,t} \cdot Z_{i,j,y+1,t} = 0)$ mitigated disease risks. These constraints were implemented through binary indicator variables that tracked planting histories across temporal and spatial dimensions.

The modeling innovation emerged in handling oversupply scenarios through divergent revenue structures. For the discarded surplus policy, we implemented binding production ceilings ($A_{i,j} \cdot Z_{i,j,y,t} \leq E_{i,y}$) that strictly limited output to market-absorbable quantities. Conversely, the discount sales approach introduced price degradation mechanics where excess production beyond $E_{i,y}$ sold at 50% baseline prices. This required sophisticated piecewise linearization of the revenue function:

$$\text{Revenue} = \begin{cases} P_{i,y} \cdot Q, & \text{if} Q \leq E_{i,y} \\ P_{i,y} \cdot E_{i,y} + 0.5 P_{i,y} \cdot (Q - E_{i,y}), & \text{if} Q > E_{i,y} \end{cases} \tag{4}$$

where $Q = A_{i,j} \cdot Z_{i,j,y,t}$. Computational efficiency was maintained through convex optimization techniques despite the discontinuous revenue function, enabling solution convergence within practical timeframes.

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4.2. Stochastic Extension Framework

Problem 2 addressed the inherent uncertainties of agricultural systems through four integrated methodological advancements that transformed static parameters into probabilistic variables. First, we implemented time-dependent parameter evolution where sales volumes, yields, costs, and prices became stochastic functions:

$$\begin{aligned} E_{i,y} &= (1+\alpha_i)^{y-2023} E_{i,2023} \\ A_{i,j,y} &= (1+\beta_y) A_{i,j,2023} \\ C_{i,j,y} &= 1.05^{y-2023} C_{i,j,2023} \end{aligned} \tag{5}$$

with $\alpha_i \sim \mathcal{U}[0.05,0.10]$ for wheat/corn and $U[-0.05,0.05]$ for other crops, while $\beta_y \sim \mathcal{U}[-0.10,0.10]$represented climate-induced yield volatility. These distributions were calibrated using 10-year historical production data from similar temperate agroecosystems.

Second, Monte Carlo simulation generated 1,000 statistically independent parameter paths through Latin Hypercube Sampling (LHS), ensuring comprehensive coverage of the joint uncertainty space while minimizing clustering artifacts. Each simulation path represented a plausible future trajectory of market and environmental conditions. Third, we established a dynamic programming backbone using Bellman recursion to optimize sequential decisions under uncertainty:

$$V\left(y, S_y\right) = \max_{Z_y}\left\{R_y\left(Z_y\right) + \mathbb{E}\left[V\left(y+1, S_{y+1}\right)\right]\right\} \tag{6}$$

where S_y encoded plot-level state variables including prior crop histories, legume rotation status, and soil nutrient profiles. This state-space formulation allowed optimal decisions to condition on historical patterns while anticipating future uncertainties.

Finally, we replaced expected profit maximization with Conditional Value-at-Risk (CVaR) optimization to prioritize solutions robust against worst-case scenarios. This risk-averse objective function specifically protected against low-probability, high-impact events like concurrent price crashes and yield failures-a critical consideration for vulnerable farming communities.

4.3. Interaction-Aware Optimization

Problem 3 introduced unprecedented ecological and market interdependencies through two sophisticated modeling innovations that captured real-world agricultural complexities. The cross-elasticity framework quantified how planting decisions for one crop influenced others through price-responsive area adjustments:

$$\theta_{lk} = \frac{\%\Delta Z_l}{\%\Delta P_k} \tag{7}$$

We calculated these coefficients using historical price and planting data, identifying substitutive relationships ($\theta_{lk} > 0$) like wheat-corn competition for nitrogen resources, and complementary relationships ($\theta_{lk} < 0$)like soybean-maize rotation benefits. Substitutive pairs were constrained through $\theta_{lk} Z_l + \theta_{kl} Z_k \leq B_j$ limitations that prevented resource conflicts,

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while complementary pairs generated synergistic bonuses: $R \leftarrow R + \gamma \mid \theta_{lk} \mid (R_l + R_k)$with$\gamma =$ 0.15representing the empirically observed yield enhancement from synergistic planting.

Concurrently, we embedded observed statistical relationships into the stochastic framework. The strong yield-cost correlation (r=0.624) informed covariance matrices during Monte Carlo sampling, creating dependency structures where high-input crops demonstrated greater yield variability. Market dynamics were captured through price elasticity adjustments:

$$E_{i,y} = \hat{E}_{i,y} \cdot (1 + \eta \cdot (P_{i,y} - \bar{P}_i) / \bar{P}_i) \tag{8}$$

with η=−0.3 reflecting observed demand sensitivity-premium crops like organic vegetables showed greater sales expansion during price reductions than staple grains. This holistic approach transformed abstract correlations into actionable planning parameters.

5. Results and Discussion

The multi-tiered optimization framework generated actionable insights across all problem scenarios, revealing how strategic land allocation balances profitability, risk mitigation, and ecological sustainability. We systematically analyze outcomes from the static (§6.1), stochastic (§6.2), and interaction-aware (§6.3) models before synthesizing their implications for agricultural policy and rural development.

5.1. Static Optimization Outcomes

Under stable market conditions (Problem 1), discounting surplus produce at 50% baseline prices (Policy B) generated ¥20.16 million cumulative profit (2024–2030)-2.6× higher than the surplus destruction approach (Policy A: ¥7.77 million)[5]. This dramatic divergence stemmed from two mechanisms:

1) High-Value Crop Expansion: Policy B incentivized 38% greater cultivation of premium fungi (*Morchella*, *Lentinula edodes*) and nightshades (tomatoes, eggplants), leveraging their price resilience.

2) Land Reallocation Efficiency: Irrigated plots shifted from low-margin grains (wheat: 18% area reduction) to fungi (27% increase), raising average revenue/ha from ¥9,420 to ¥15,800.

Despite Policy B's aggregate advantage, Policy A demonstrated superior stability during 2025 and 2028 market contractions—its enforced production ceilings prevented losses from vegetable oversupply (-¥184,916 vs. Policy B's -¥896,632 in 2025Q2). This tradeoff highlights a fundamental tension: *short-term risk reduction versus long-term value capture[6]*.

5.2. Stochastic Volatility Management

Incorporating parameter uncertainties (Problem 2) yielded ¥24.83 million expected profit-23% higher than static Policy B—through proactive volatility adaptation:

Risk-Adjusted Diversification: The CVaR objective reduced grain dependency from 72% to 58%, expanding vegetables/fungi to 34% of area.

- Dynamic Rebalancing: During simulated drought years (yield: -10%), model reallocated 12,500 ha from water-intensive rice to drought-tolerant millet, preserving 89% of expected profit[7].
- Price Hedging: Early investment in appreciating vegetables (e.g., 2024 tomato expansion) offset fungi's price decline, stabilizing revenue streams.

Monte Carlo analysis revealed two critical risk patterns:

1) Wheat-Corn Synergy: Their correlated demand growth (+5–10%) reduced revenue variance by 38% versus independent crops.

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2) Fungi's Fragility: *Morchella*'s fixed 5% annual price decline amplified losses during yield shocks-a vulnerability mitigated through greenhouse concentration (85% of cultivation moved to controlled environments).

5.3. Complementary Crop Effects

Introducing ecological interactions (Problem 3) enhanced system resilience despite slightly lower aggregate profit (¥20.44 million)[8]:

- Legume Synergy Boost: Soybean-maize rotations generated 12–18% yield premiums (vs. monoculture), contributing ¥2.2 million/year through nitrogen enrichment.
- Substitution Constraints: Enforcing wheat-corn competition limits prevented simultaneous expansion, avoiding 2027 oversupply losses of ¥467,000.
- Demand Elasticity Gains: High-elasticity crops (tomatoes, peppers) expanded during price surges, capturing 22% more market share than inelastic staples.

The interaction model particularly excelled in risk mitigation—CVaR95 (worst-case 5% scenarios) improved 31% versus Problem 2. This stemmed from two mechanisms:

1) Buffered Price Shocks: Complementary pairings (e.g., soybeans ↔ leafy greens) reduced revenue volatility 19% through diversified income streams.

2) Correlation Awareness: Embedding the yield-cost relationship ($r = 0.624$) prevented overinvestment in high-input crops during cost spikes.

5.4. Comparative Policy Implications

Three findings directly inform rural revitalization strategies:

1) Discount Sales Dominance: Policy B's 160% profit advantage over Policy A supports market-oriented surplus disposal, though grain stockpiling remains prudent for food security.

2) Volatility as Opportunity: Proactive diversification-not risk avoidance-boosted profits 23% under uncertainty, contradicting conservative planting traditions.

3) Ecological Intelligence: Legume integration raised profits 11% while reducing synthetic fertilizers 27%, aligning economic and sustainability goals (Table 1)[9].

Table 1. Sustainability metrics across models

Metric	Problem 1	Problem 2	Problem 3
Nitrogen fixation (kg/ha)	38	41	89
Fertilizer cost (¥/ha)	1,820	1,790	1,325
Revenue volatility (σ)	0.18	0.22	0.14

Methodologically, our framework demonstrated three advances over prior work:

- Temporal Flexibility: Dynamic programming outperformed myopic heuristics by 17% in long-term value capture.
- Interaction Quantification: Cross-elasticity modeling reduced calibration error 44% versus coefficient-of-variation approaches.
- Scalability: The Python implementation solved village-scale optimization 9× faster than agricultural DSSAT hybrids.

Limitations in weather granularity (daily → seasonal aggregation) and market coupling (local ↔ global price links) present opportunities for extension[10]. Future integration with satellite phenology and blockchain traceability could further enhance realism.

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6. Conclusion

This study has established a dynamic optimization framework that transforms multi-constraint agricultural planning into an engine for sustainable rural revitalization. By integrating operational research, econometrics, and agronomic ecology, we resolved three interlocked challenges: optimizing crop allocation under static market conditions (§6.1), navigating volatility through stochastic adaptation (§6.2), and harnessing ecological synergies via interaction-aware modeling (§6.3). Our findings demonstrate that strategic land reallocation-prioritizing high-value fungi and vegetables while maintaining grain safety nets-can elevate profits by 23–160% compared to conventional approaches, directly boosting farmer livelihoods in North China's vulnerable agroecosystems.

Methodologically, the research contributes three pioneering advances. First, we formalized discount surplus policies as piecewise-linear optimizations, proving their 2.6× profit advantage over surplus destruction-a counterintuitive yet empirically robust strategy that reconciles market realism with food security. Second, our Monte Carlo-dynamic programming hybrid quantified how proactive diversification, not risk avoidance, turns volatility into opportunity: by shifting 34% of land to vegetables/fungi during stable periods while dynamically reallocating to drought-tolerant cereals during climate shocks, farmers can capture ¥24.83 million in expected value despite ±10% yield fluctuations. Third, the cross-elasticity integration quantified historically qualitative crop interactions, revealing how legume-cereal rotations generate 12–18% yield premiums through nitrogen enrichment-translating ecological intelligence into ¥2.2 million/year economic gains.

Practically, the framework offers actionable pathways for policymakers:

- Short-term: Promote discount surplus markets and legume subsidies to accelerate profit growth.
- Medium-term: Install sensor networks to feed real-time yield data into dynamic reoptimization.
- Long-term: Scale the model across similar regions using cloud-based optimization services.

Limitations in weather granularity and cross-regional price coupling present opportunities for refinement. Future integration with remote sensing phenology and blockchain traceability could further enhance predictive accuracy. Ultimately, this work illuminates how computational optimization-when grounded in ecological wisdom and market realism-can turn constraints into catalysts for equitable and resilient rural prosperity.

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