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Digital Technology-Enabled Risk Reduction in Insurance for Mountainous Specialty Agriculture: Mechanism Design and a Chongqing Pathway

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Abstract: Mountainous agriculture combines fragmented plots, steep terrain, microclimates, and compound hazards, limiting insurance based on averages, manual adjustment, and ex post compensation. This paper develops a closed loop of data sensing, risk identification, explainable decisions, intervention, and feedback. Plot-level accounts convert remote-sensing, weather, terrain, management, and insurance data into actionable, auditable signals linking underwriting, pricing, warnings, services, and claims. It proposes differentiated pricing, risk-reduction contracts, performance-based public support, and multi-actor governance. For Chongqing, priorities are shared data infrastructure, terrain-specific models, and pilots for citrus, preserved mustard tuber, and medicinal crops. Evaluation should combine risk-adjusted losses, warning recall, uptake, claims speed, and farmer welfare. Digitalization should therefore support accountable whole-cycle risk governance.

Keywords: Agricultural insurance; Risk reduction; Mountainous specialty agriculture; Multi-source data; Explainable artificial intelligence; Chongqing

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1. Introduction

Agricultural production faces systemic, spatially correlated, and information-intensive risks. Indemnity insurance stabilizes income after shocks but does little to prevent losses. Chinese policy now calls for ex ante prevention, in-event control, risk zoning, data sharing, and technology-enabled precision in underwriting and claims [1–3]. The objective is therefore broader than compensation: reduce avoidable loss, accelerate recovery, and sustain farmers and insurers.

Chongqing is a demanding setting because mountains and hills account for 90.93% of its territory [4].

Elevation, slope, aspect, river-valley microclimates, and access create sharply differentiated exposure even within villages. Its primary sector generated CNY 212.414 billion in value added in 2025 [5]. Municipal subsidy rules already require policy records to be verifiable and traceable, providing an institutional basis for digital risk accounts, although data, model, incentive, and accountability standards remain fragmented [6].

Agricultural insurance supports welfare and resilience [7–10]. Index insurance can reduce information and transaction costs, but basis risk weakens protection and demand [11–16]. Remote sensing, crop models, and explainable AI improve measurement [17–22]. Research nevertheless underconnects technology with contracts, preventive incentives, and fragmented mountain farms. This paper develops an integrated mechanism and Chongqing pathway.

2. Theoretical foundations and analytical framework

2.1. Risk stratification and basis risk

Area-yield and weather-index contracts reduce manipulation and administration, but basis risk arises when payouts diverge from loss [11–12]. Evidence shows that sensors alone are insufficient; contract quality, complementary risk management, and public support also matter [13–16].

Chongqing plots differ by elevation, slope, variety, irrigation, and management. Terrain-aware zoning addresses spatial mismatch; phenology-aligned observation addresses temporal mismatch; management records and field checks address behavioral mismatch. Predictions should disclose uncertainty and permit human review.

2.2. Information asymmetry and incentive compatibility

Insurers cannot fully observe plot quality before underwriting or preventive effort after coverage begins. Subsidies may expand participation without aligning price, service, and action. Although insurance changes production and financial decisions, digital monitoring reduces information costs rather than automatically aligning incentives [23–25].

Audited risk classes can guide premiums, services, and inspections. Verified drainage, protective netting, resistant varieties, or pest management may earn benefits without reducing lawful indemnity. Warning records should evidence service performance, not automatically justify claim denial. Technology supports contract execution rather than surveillance.

2.3. Resilience governance and whole-cycle risk management

Resilience encompasses resistance, recovery, and adaptation. Indemnity supports recovery, while prevention and emergency response can reduce loss probability and severity. Insurance-based risk reduction is defined here as action by insurers and partners to identify, communicate, and mitigate risk before and during events without diminishing contractual rights.

For plot i at time t, $R(i,t) = P(D \mid X(i,t)) \times E[L \mid D, X(i,t)] \times V(i,t)$, combining damage probability, conditional severity, exposed value, and vulnerability. Technology must improve estimation and enable feasible action that alters vulnerability or exposure. The analytical unit is therefore the decision loop in **Figure 1**, not the model alone (**Table 1**).

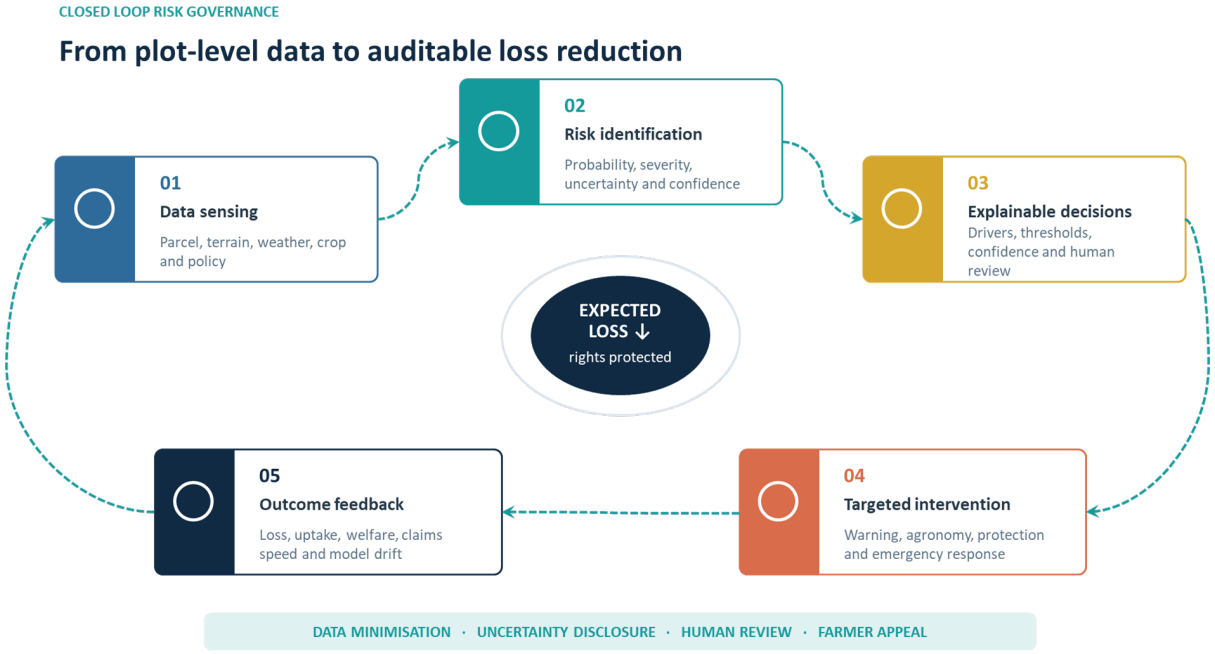

Figure 1. Closed-loop mechanism for technology-enabled risk reduction. Source: Authors' conceptualization based on risk measurement, remote sensing, and explainable AI literature [13–21]

Table 1. Analytical framework for intelligent risk reduction in mountainous agricultural insurance

Stage	Core question	Principal data	Technology and rules	Expected outcome
Data sensing	Is the insured object authentic and complete?	Plots, crops, weather, terrain, IoT, policies	Common IDs, time-space alignment, quality audit	Plot-level risk account
Risk identification	Where and when may damage occur, and how severe?	Remote-sensing series, forecasts, farm conditions, past losses	Zonal models, probabilistic prediction, uncertainty intervals	Lower spatial and temporal basis risk
Explainable decisions	Can staff and farmers understand the model?	Model output, feature contributions, comparable cases	SHAP or local explanations, expert review, threshold governance	Transparent and contestable decisions
Risk-reduction intervention	Does warning translate into action?	Risk class, service capacity, farmer feedback	Tiered warning, agronomic prescriptions, emergency dispatch, incentives	Lower probability and severity of loss
Outcome feedback	Does the service create net benefit?	Loss ratio, uptake, speed, satisfaction, cost	Counterfactual evaluation, drift monitoring, performance payments	Continuous model and process improvement

3. Mechanisms of intelligent risk reduction in mountainous areas

3.1. Multi-source data and plot-level risk accounts

A plot-level account links boundaries, crop cycle, tenure, and insurance obligations. Static data cover terrain, soil, and hydrology; dynamic data cover weather, moisture, crop condition, and biological threats; business data cover insurance, claims, inspections, and services. Common identifiers make underwriting-to-claims records traceable. Chongqing's policy records are a starting point for parcel alignment [6].

Clouds, terrain shadows, mixed pixels, irregular fields, and sparse stations create uncertainty. Inputs

should disclose source, resolution, timeliness, missingness, and confidence. Official observations and verified boundaries may be high-trust; derived and device data need uncertainty labels. Remote sensing reduces assessment cost, but mountain smallholdings still require ground samples, audits, and suitable delineation [17–19].

3.2. Zonal modelling of compound hazards and heterogeneous risk

Models should combine common indicators, zonal parameters, and cross-zone validation. Hazards include rain, drought, cold, hail, wind, and biological threats; exposure covers area, phenology, and value; vulnerability covers slope, infrastructure, resistance, and management. Outputs should report probabilities, loss distributions, drivers, and confidence.

Compound-hazard analysis should represent event chains such as heat, moisture deficits, and pests or rain, runoff, landslides, and transport disruption. Model choice follows the task: identification for underwriting, recall and lead time for warnings, calibration for pricing, and evidence quality for claims. No single accuracy measure suffices.

3.3. Explainable artificial intelligence as a bridge to insurance decisions

LIME and SHAP provide local explanations and feature attribution [20–21]. Insurance needs portfolio explanations for managers, case reasons for plot classifications, and rule-level links to action. Actuaries need diagnostics, field staff need priorities, and farmers need plain-language reasons, feasible measures, and appeals.

Model explanations cannot replace contract terms or required loss-adjustment procedures [22]. Low confidence caused by missing data, device failure, weak samples, or distribution shift should trigger manual review. High-impact decisions should log the model version, observation date, main drivers, confidence, and human overrides so technical error is not transferred to small farmers.

3.4. Risk-reduction intervention and service-chain redesign

Risk maps can guide inspections, training, drainage, protection, and disease control. Event warnings can trigger harvesting, relocation, pest control, and emergency mobilization; afterwards, change detection can prioritize payment and inspection. These services follow China's risk-reduction framework [2].

Interventions should record recipient, timing, content, acknowledgement, and result. Tiered warnings need predefined actions and multiple delivery channels. Plot improvements may be voluntary, whereas drainage, stations, and roads require cost sharing. **Figure 2** links infrastructure, insurer decisions, and plot action; warnings do not guarantee zero loss.

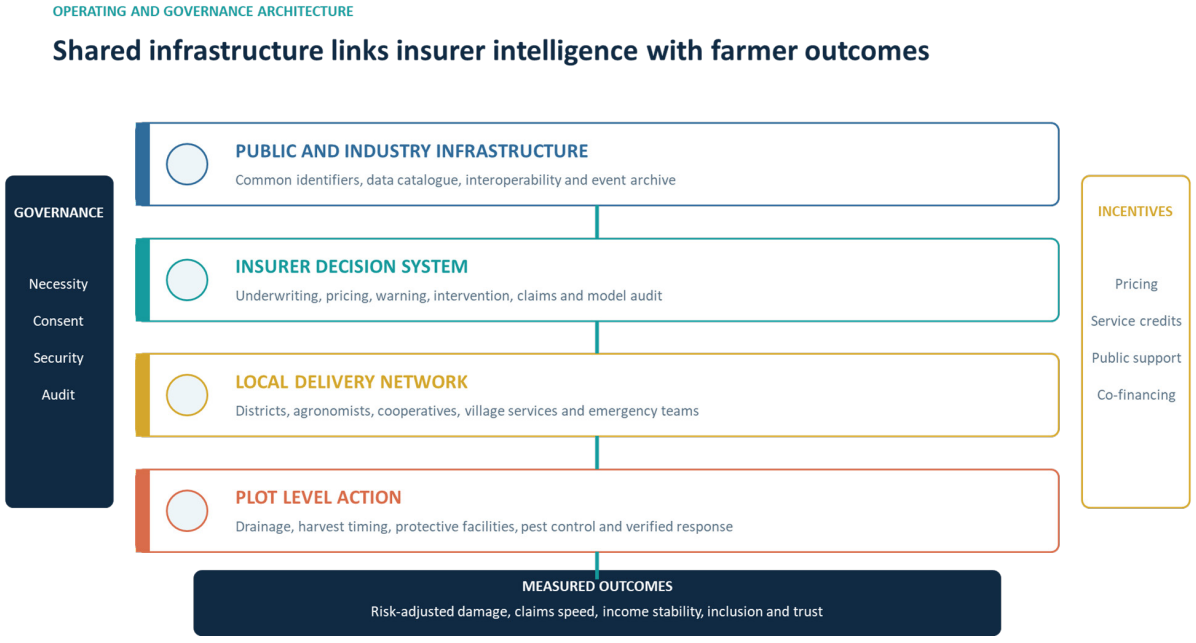

Figure 2. Operating and governance framework for mountainous agricultural-insurance risk reduction. Source: Authors' conceptualization based on the policy and governance requirements in the literature [1–3, 6, 22]

4. Operating mechanism and governance

4.1. Allocation of roles and accountability

Municipal authorities should set data and evaluation standards; local governments should support parcel verification and disputes. Insurers remain accountable for products, models, services, claims, and consumer protection; providers remain responsible for contracted performance. Farmers retain rights to information, correction, choice, and appeal. Government should support shared foundations without directing individual decisions.

Business responsibility cannot be outsourced, technical responsibility must be traceable, and public responsibility should focus on shared infrastructure. Data use requires necessity, authorization, security, retention limits, and audits. Provider contracts should specify ownership, documentation, service levels, incidents, and exit arrangements.

4.2. Contractual and financial incentives

Annual contracts may underfund prevention because benefits are uncertain and shared. Incentives can combine renewal benefits for verified measures, public payments tied to risk-adjusted loss and welfare, and co-financing for monitoring, drainage, and pest surveillance. Eligibility and verification rules should be disclosed. Performance must be measured against credible weather-adjusted baselines.

4.3. Evaluation and causal identification

Evaluation should cover models, operations, losses, welfare, and governance through recall, calibration, lead time, verification error, claims speed, risk-adjusted damage, uptake, income volatility, consent, appeals, and drift. Prediction without action is not risk reduction; lower payouts caused by invalid claim restriction are not

success.

Phased rollout enables matched difference-in-differences evaluation after pre-trend checks. Synthetic control, event studies, and interviews can supplement small or uneven samples. Reports should disclose model versions, samples, extreme-event treatment, and uncertainty. Independent evaluation reduces implementer-assessor conflicts.

Table 2. Evaluation indicators for intelligent risk-reduction pilots

Dimension	Representative indicators	Comparator	Interpretive caution
Model	Hazard recall, probability calibration, lead time, cross-zone error	Historical back-test, baseline model, out-of-area validation	Do not report aggregate accuracy alone
Operations	Verification error, inspection time, disputes, unit cost	Pre-pilot period, untreated area, manual process	Efficiency must not weaken due process
Loss reduction	Damage rate, tail loss, payout volatility, uptake	Similar plots or phased-rollout control	Control for hazard intensity and crop mix
Farmer welfare	Net income volatility, out-of-pocket cost, satisfaction, renewal	Farm size, age, and digital-capability groups	Monitor digital exclusion and cost shifting
Governance	Consent, human review, appeal time, drift alerts	Policy thresholds, audit logs, complaints	Monitor model drift and third-party risk

5. A Chongqing implementation pathway

5.1. Build a municipal agricultural-insurance data infrastructure

A common plot identifier should link policies with production, weather, resource, forestry, disaster, and emergency data. Rather than centralizing all raw data, a governed catalogue, interfaces, and privacy-preserving computation can enable controlled use. Shared definitions and a ground-verified event archive support training and audit.

5.2. Pilot by terrain and industry

Chongqing needs models for low-hill crop zones, mid-elevation citrus and preserved-mustard zones, and high-mountain medicinal-crop zones. Pilots should combine material hazard, insurable value, feasible action, and accessible data. Citrus may target heat, drought, cold, and disease; preserved mustard tuber, waterlogging, and cold; medicinal crops, slope hydrology, and temperature-humidity stress. **Figure 3** and **Table 3** provide scale baselines, not insured value or hazard severity. Each pilot needs verified samples, a hazard baseline, service protocols, and a comparison group. Expansion should follow validation of the data-to-action loop.

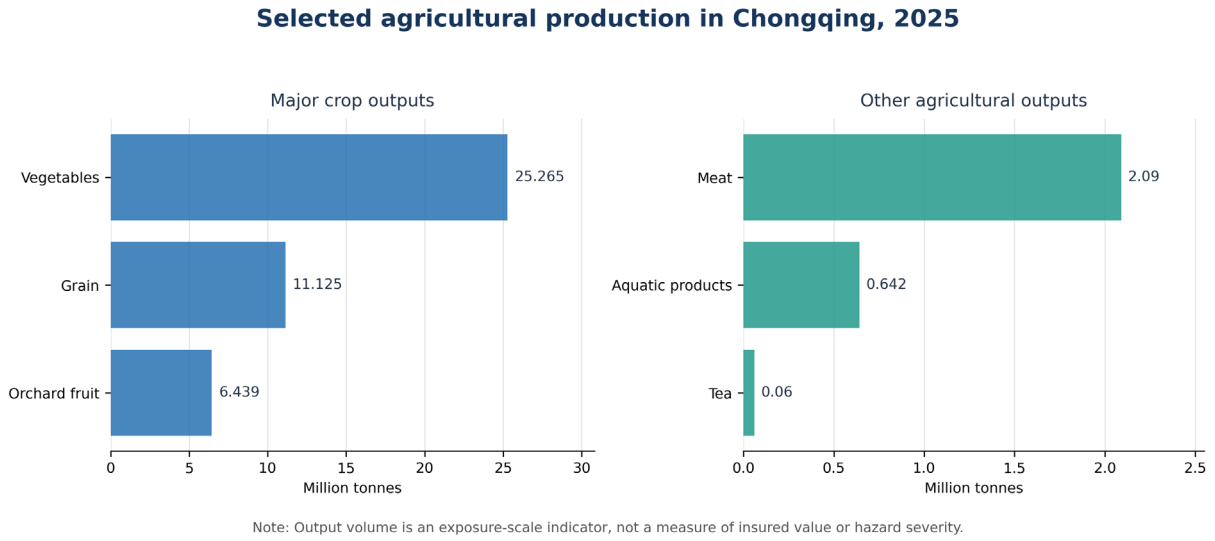

Figure 3. Selected agricultural production in Chongqing, 2025. Source: Authors' calculations and visualization using the 2025 Chongqing statistical communiqué [5]

Table 3. Evidence-based baseline for Chongqing pilot design

Indicator	Verified value	Reference period	Implication for design
Terrain structure	Mountain 75.33%; hills 15.60%; combined 90.93%	First geographical census, released 2017	Terrain-aware zoning is a baseline requirement, not an optional refinement [4].
Primary-sector value added	CNY 212.414 billion; real growth 3.7%	2025 (preliminary)	Agricultural continuity has material regional economic significance [5].
Selected crop outputs	Vegetables 25.265 Mt; grain 11.1247 Mt; orchard fruit 6.439 Mt	2025	Pilot selection should consider exposure scale alongside hazard and intervention feasibility [5].
Central premium subsidy	CNY 560 million, including CNY 93.63 million for local specialties	2024 allocation	Existing public finance can support outcome-based risk-reduction incentives [26].
Recent insurance support	Agricultural-insurance payouts > CNY 2.3 billion; fiscal subsidies > CNY 2.0 billion	Most recent two years reported as of January 2025	The programme scale justifies formal evaluation of prevention, claims and farmer welfare [26].

Note: Mt = million tonnes. Values retain the units and qualifiers used by the cited sources; ">" denotes "more than"

5.3. Develop an insurance technology agronomy and emergency service package

Insurance can anchor warnings, agronomic advice, mechanized services, and emergency capacity. Alerts and training may serve general risks; field advice and inspections may serve higher risks; severe events may trigger harvesting, transport, drainage, protection, or relocation. Published eligibility, content, frequency, channels, and responsibilities distinguish substantive service from nominal spending.

5.4. Incorporate risk reduction into public and insurer performance

Chongqing received CNY 560 million in central premium subsidies in 2024, including CNY 93.63 million for local specialties; recent reporting also recorded more than CNY 2.3 billion in payouts and CNY 2.0 billion in fiscal subsidies [26]. Evaluation should add risk-adjusted loss reduction to coverage, claims, and complaints. Public funds should prioritize shared data, monitoring, and smallholder access, while procurement requires

portability, interfaces, documentation, and exit terms.

5.5. Establish model audit and farmer-rights safeguards

Governance requires pre-deployment validation, live monitoring, and post-event review of representativeness, extreme scenarios, asymmetric errors, missing data, drift, and adverse-decision patterns. Model cards should state geography, data period, performance, limits, and review triggers. Material changes require versioning and revalidation; logs should separate recommendations from human decisions. Farmers need access, correction, offline objections, and timely escalation.

6. Conclusions and research agenda

Technology reduces mountain agricultural risk only when plot data, terrain-aware models, explanations, interventions, contract incentives, and evaluation form one accountable chain. Multi-source data require confidence labels, ground samples, and human review; model outputs cannot replace contracts or mandatory adjustment. Chongqing should combine shared infrastructure with targeted pilots, integrated services, counterfactual evaluation, and model audit.

Future research should build multi-hazard crop panels, compare statistical, machine-learning, and process-based models across terrain, and use phased pilots to identify effects on damage, payouts, investment, and income. Experiments should test how explanations, incentives, and appeals affect uptake and trust. Accuracy, net benefit, and fairness require joint evaluation.

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Disclosure statement

The authors declare no conflict of interest.

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