

Economic Value of Weather Forecast Accuracy for Smallholder Crop Decisions: A Decision Framework Under Uncertainty

Ludmila Gonçalves Generoso da Silva*

Laís Ribeiro Pereira†

João Victor Pinho de Almeida‡

Abstract

Weather forecast accuracy represents a critical determinant of agricultural decision-making for smallholder farmers operating under climate uncertainty. This article develops an economic framework to assess the value of forecast precision in crop management decisions, examining how forecast errors translate into opportunity costs and suboptimal resource allocation. Through systematic analysis of existing empirical evidence from multiple agricultural contexts, we demonstrate that forecast accuracy exhibits non-linear economic returns, with threshold effects determining adoption patterns and welfare outcomes. The analysis reveals substantial information asymmetries between large-scale commercial operations and resource-constrained smallholders, generating disparities in adaptive capacity and economic resilience. We identify critical gaps in service delivery models that fail to account for the specific decision environments of smallholder producers, including timing constraints, input availability, and risk preferences. The framework quantifies economic losses from forecast errors across different crop cycles and demonstrates how service reliability affects farmer trust and sustained utilization. Our findings indicate that improving forecast accuracy from moderate to high levels can increase net agricultural income by 15-26 percent for smallholder operations, with effects concentrated during critical decision windows. Policy implications emphasize

*Email: ludygeneroso22@gmail.com

†Email: laispereiraribeiro05@gmail.com

‡Email: joaoalmeida092004@gmail.com

the need for context-specific accuracy standards, investment in last-mile delivery infrastructure, and mechanisms to reduce information access costs for vulnerable producers.

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1 Introduction

Agricultural production under climate variability necessitates continuous decision-making regarding input allocation, crop selection, and timing of field operations. For smallholder farmers, these decisions occur within constrained information environments characterized by limited access to reliable weather forecasts and restricted capacity to absorb economic losses from prediction errors. The economic value of weather information depends fundamentally on forecast accuracy and the extent to which predictions enable superior resource allocation compared to decision-making based on historical climate patterns or indigenous knowledge systems.

Recent systematic evidence demonstrates that 70 percent of African smallholder farmers depend on rainfed agriculture, rendering production outcomes highly sensitive to rainfall variability and temperature extremes (Nyoni et al., 2024). Climate information services have expanded substantially over the past decade, yet adoption rates remain heterogeneous across regions and farmer categories. In West African contexts, approximately 68 percent of smallholders express demand for climate information services, with willingness to pay averaging USD 2.01 for daily forecasts (Ouedraogo et al., 2022). However, these aggregate figures obscure significant variation in service utilization and economic returns across different accuracy levels and delivery mechanisms.

The relationship between forecast precision and agricultural outcomes exhibits critical threshold effects. Empirical validation studies from South Asian agricultural systems demonstrate that seasonal forecast accuracy varies substantially across meteorological parameters, with precipitation forecasts achieving 87-98 percent successful usability, while wind speed predictions range between 44-83 percent (Singh et al., 2022). These accuracy differentials generate corresponding variations in economic returns, with high-precision services enabling net income increases of 17-26 percent for cotton and wheat production systems. The translation of meteorological accuracy into economic value depends on multiple mediating factors, including farmer

response capacity, input market integration, and the alignment between forecast lead times and critical decision windows.

Information asymmetries between large commercial operations and smallholder producers constitute a persistent challenge in agricultural development. Commercial farms typically maintain private meteorological stations, employ agronomists with technical capacity to interpret probabilistic forecasts, and possess financial buffers to absorb occasional forecast errors. In contrast, smallholders rely predominantly on publicly provided information services, often delivered through intermediaries with limited technical capacity to contextualize predictions for specific farming systems. This asymmetry generates differential adaptive capacity, reinforcing existing productivity gaps and economic vulnerabilities.

The cost structure of forecast errors varies systematically across crop cycles and production systems. Planting decisions based on erroneous rainfall onset predictions can result in complete crop failure for annual crops with narrow establishment windows. Mid-season forecast errors affect input application timing and pest management strategies, generating productivity losses but rarely total failures. Harvest timing decisions based on precipitation forecasts influence grain quality and post-harvest losses, with economic consequences that vary by storage capacity and market access. Understanding these differential cost structures enables more precise targeting of accuracy improvement investments and service delivery enhancements.

This article develops a comprehensive framework for assessing the economic value of weather forecast accuracy in smallholder agricultural contexts. The analysis synthesizes empirical evidence from multiple geographic settings to identify generalizable patterns in the accuracy-adoption-outcomes relationship. We examine how forecast reliability influences farmer trust and sustained service utilization, recognizing that one-time forecast failures can generate persistent skepticism that undermines long-term adoption. The framework incorporates opportunity cost analysis to quantify economic losses from suboptimal decisions under forecast uncertainty, providing a basis for cost-benefit assessment of service improvement investments.

The subsequent analysis proceeds as follows. Section 2 establishes the theoretical foundations of information value in agricultural decision-making, incorporating insights from decision theory under uncertainty and the economics of information. Section 3 examines empirical evidence on the relationship between forecast accuracy and economic returns across diverse agricultural systems. Section 4 analyzes the cost structure of forecast errors, distinguishing between different types of decision mistakes and their economic consequences. Section 5 investigates information asymmetries and structural barriers limiting smallholder access to high-quality fore-

casts. Section 6 discusses policy implications and alternative service delivery models. Section 7 concludes with synthesis of findings and research priorities.

2 Theoretical Framework: Information Value in Agricultural Decision-Making

The economic value of weather forecasts derives from their capacity to reduce decision uncertainty and enable resource allocation that better matches environmental conditions. In agricultural contexts, farmers face sequential decision problems where current choices influence future production possibilities and where production outcomes depend on stochastic weather realizations. Information value arises when forecasts shift the probability distribution over possible weather states in ways that enable welfare-improving adjustments to planned activities.

Consider a simplified decision framework where a farmer must select crop type c from a feasible set C prior to the growing season, with net returns $\pi(c, w)$ depending on the realized weather state $w \in W$. Without forecast information, the farmer maximizes expected utility based on the unconditional probability distribution over weather states:

$$\max_{c \in C} E[U(\pi(c, w))] = \max_{c \in C} \sum_{w \in W} P(w) \cdot U(\pi(c, w)) \quad (1)$$

where $U(\cdot)$ represents the farmer's utility function, typically exhibiting risk aversion for resource-constrained smallholders, and $P(w)$ denotes the unconditional probability of weather state w based on historical climate data or subjective beliefs.

With access to a forecast signal $s \in S$, the farmer updates beliefs about weather realizations according to the conditional probability $P(w|s)$ and selects the crop that maximizes conditional expected utility:

$$\max_{c \in C} E[U(\pi(c, w))|s] = \max_{c \in C} \sum_{w \in W} P(w|s) \cdot U(\pi(c, w)) \quad (2)$$

The value of forecast information can be expressed as the difference in expected utility between decision-making with and without the forecast signal, averaged over all possible forecast realizations:

$$V_{forecast} = E_s \left[\max_{c \in C} E[U(\pi(c, w))|s] \right] - \max_{c \in C} E[U(\pi(c, w))] \quad (3)$$

This formulation reveals that forecast value depends on the informativeness of the signal, represented by the correlation between s and w , and the sensitivity of optimal decisions to weather conditions. Forecasts generate economic value only when they induce decision changes that improve expected outcomes relative to the default strategy.

Forecast accuracy determines the strength of the relationship between signals and realized weather states. A perfectly accurate forecast satisfies $P(w|s) = 1$ for the correct weather state and zero otherwise, while an uninformative forecast leaves beliefs unchanged such that $P(w|s) = P(w)$. Real-world forecasts exhibit intermediate accuracy levels, characterized by metrics such as the probability of detection, false alarm rate, and critical success index. The economic value of accuracy improvements is non-linear, with threshold effects where marginal accuracy gains generate substantial decision improvements in critical ranges but minimal value in other regions.

The timing of forecast delivery relative to decision deadlines constitutes an essential dimension of service value. Agricultural decisions exhibit varying degrees of flexibility and lead time requirements. Crop selection for annual systems must occur weeks or months before planting, while irrigation scheduling and pest management allow more proximate adjustments. The value of forecast lead time trades off against accuracy decline for longer prediction horizons. For resource-constrained smallholders, this trade-off is complicated by input procurement constraints that may require longer planning horizons than technically optimal from a pure information perspective.

Risk preferences fundamentally shape the value farmers assign to forecast information. Risk-averse producers value forecasts not only for improving expected returns but also for reducing downside risk and enabling more stable income streams. The variance-reducing effect of forecasts can generate substantial welfare improvements even when effects on mean returns are modest. This risk dimension helps explain observed willingness to pay for forecast services that exceeds the measured impact on average agricultural income. Empirical evidence from Zimbabwe indicates farmers are willing to pay approximately USD 1 per month for seasonal weather forecasts, with aggregate national economic value estimated at USD 53.2 million annually (Manzvera et al., 2024).

Information complementarities between weather forecasts and other agricultural services influence total value creation. Forecasts enable more precise timing of fertilizer application, reducing nutrient losses and improving efficiency. They facilitate integrated pest management by identifying weather windows favorable for in-

tervention. They inform harvest scheduling to minimize quality deterioration and post-harvest losses. When farmers lack access to these complementary inputs and services, the marginal value of forecast improvements diminishes. This complementarity structure implies that forecast service investments should be coordinated with broader agricultural development initiatives to maximize welfare impacts.

The persistence of forecast reliability over time affects farmer learning and trust formation. A single forecast failure can disproportionately damage service credibility, particularly when losses are substantial or when forecasts contradicted farmers' indigenous knowledge systems. Trust rebuilding requires consistent accuracy over extended periods, creating path dependence in service adoption. This dynamic implies that forecast service providers face higher implicit costs of accuracy failures than simple period-by-period loss calculations would suggest. The reputational dimension necessitates conservative service design with explicit uncertainty communication rather than overconfident predictions.

3 Forecast Accuracy and Economic Returns

Empirical evidence from diverse agricultural contexts demonstrates substantial economic returns to forecast accuracy improvements, with magnitudes varying systematically across crop types, decision categories, and farmer resource endowments. Validation studies that compare forecast performance against observed meteorological conditions provide critical evidence on the accuracy-returns relationship and identify where accuracy improvements generate the largest economic impacts.

Field experiments conducted in Punjab agricultural systems during 2013-2018 evaluated medium-range weather forecasts for cotton and wheat production (Singh et al., 2022). Maximum accuracy occurred for precipitation forecasts, which achieved seasonal usability rates between 87-98 percent. Cloud cover predictions reached 65-75 percent usability, while temperature forecasts ranged from 51-72 percent for maximum temperature and 56-67 percent for minimum temperature. Wind speed predictions exhibited the lowest accuracy at 44-83 percent. Farmers who adopted agrometeorological advisory services based on these forecasts achieved additional net returns of Rs. 4,055-1,900 per acre for cotton and Rs. 5,461-5,045 per acre for wheat, representing 17-21 percent profit increases for cotton and 18-26 percent for wheat relative to farmers using traditional decision methods.

The economic benefits of forecast utilization depend critically on the alignment between forecast parameters and decision requirements. Rainfall predictions generate high value for planting timing and variety selection decisions, where precipitation

onset and distribution directly determine optimal strategies. Temperature forecasts influence pest pressure predictions and crop development rates, affecting input timing decisions. Wind speed and humidity forecasts contribute to disease management and irrigation scheduling. The differential accuracy across these parameters implies that comprehensive agricultural decision support requires parameter-specific accuracy standards rather than aggregate forecast quality metrics.

Comparative analysis from West African contexts reveals that climate information services in Niger and Mali achieved high to moderate forecast accuracy, with Critical Success Index values of 0.7-0.58 and Brier Scores of 0.11-0.43 in Niger, and CSI of 0.94-0.91 with Brier Scores of 0.06-0.25 in Mali (Bizo et al., 2024). These accuracy levels translated into significant economic benefits, with farmers utilizing climate information experiencing average income improvements of FCFA 24,943 per hectare at season start, declining to FCFA 15,355 during the growing period and FCFA 6,204 at season end. The declining income effect across the crop cycle reflects the concentration of high-value decisions early in production, when crop selection, planting timing, and initial input application determine subsequent production trajectories.

Time savings constitute an additional economic benefit that conventional income analysis may underestimate. The West African evidence indicates that climate information utilization reduced labor requirements from 36 hours per hectare at season start to 8 hours during active cultivation (Bizo et al., 2024). For smallholder households facing labor constraints and operating multiple income-generating activities, these time savings enable portfolio diversification and risk reduction beyond the direct agricultural income effects. The value of time savings varies with local wage rates and off-farm opportunity costs, generating heterogeneous returns across different economic contexts.

Simulation studies that integrate seasonal climate forecasts with crop growth models demonstrate how forecast-informed decision-making affects crop selection diversity and income stability. Research from Sri Lankan farming systems shows that farmers utilizing seasonal forecasts select more diversified crop portfolios, generating increases in average agricultural income with particularly notable improvements in drier climate scenarios (Gunda et al., 2017). The diversification effect arises because forecasts enable differentiated responses to predicted conditions rather than single-strategy approaches based on historical averages. In water-scarce environments, forecast-informed farmers shifted toward higher-value crops like onions when predictions indicated favorable moisture conditions, generating substantial income improvements relative to risk-averse default strategies.

The relationship between forecast accuracy and adoption rates exhibits non-linear dynamics with threshold effects. Agent-based modeling of Ethiopian farming communities demonstrates that forecast precision correlates positively with adoption rates and economic benefits, but social dynamics at the community level substantially influence adoption patterns (Alexander and Block, 2022). Peer learning and trust diffusion create adoption cascades when initial users experience positive outcomes, while forecast failures can trigger rapid credibility erosion. These social multiplier effects imply that targeted accuracy improvements for influential farmer networks may generate larger aggregate impacts than uniform but modest accuracy enhancements across all users.

Systematic evidence synthesis across African agricultural contexts reveals that approximately 68 percent of farmers in ECOWAS countries demand climate information services, though actual utilization rates vary substantially with service accessibility and perceived reliability (Ouedraogo et al., 2022). The gap between stated demand and realized adoption reflects multiple barriers including delivery system inadequacies, literacy constraints limiting interpretation capacity, and risk aversion toward new information sources following historical forecast failures. These adoption barriers imply that forecast accuracy improvements alone may generate limited economic impacts without complementary investments in delivery infrastructure and farmer capacity development.

4 Cost of Forecast Errors and Opportunity Costs

Forecast errors generate economic costs through multiple channels, including direct production losses from misallocated inputs, opportunity costs from foregone superior strategies, and transaction costs from adjustment efforts when realized conditions diverge from predictions. The cost structure of forecast mistakes varies systematically across decision types, with irreversible choices exhibiting higher error costs than flexible decisions that permit mid-course corrections.

Planting timing errors represent a high-cost failure category because establishment windows for annual crops are narrow and costly to repeat. A false alarm forecast predicting rainfall onset that fails to materialize can result in seed loss and the need to replant, doubling seed costs and delaying the production cycle. In regions with single rainy seasons, delayed planting reduces total growing period and often necessitates switching to shorter-cycle varieties with lower potential yields. Conversely, missed detection of favorable planting conditions causes farmers to delay unnecessarily, similarly compressing the effective growing season. For smallhold-

ers operating at subsistence margins, these planting failures can precipitate food security crises and debt accumulation.

Mid-season forecast errors affect input application efficiency and pest management outcomes but rarely cause total production failures. Fertilizer application based on erroneous rainfall predictions can result in nutrient leaching if precipitation exceeds forecasts or reduced uptake efficiency if conditions are drier than predicted. These errors reduce fertilizer use efficiency but generate smaller percentage impacts on total production relative to planting failures. Pest and disease management decisions exhibit similar patterns, where forecast errors lead to sub-optimal intervention timing but rarely catastrophic losses. The more gradual cost structure for mid-season decisions provides opportunities for adaptive learning and error correction that are absent for one-time establishment decisions.

The opportunity cost of forecast errors can exceed the direct loss from the chosen strategy when errors cause farmers to reject superior alternatives. Consider a farmer choosing between a high-value drought-sensitive crop and a lower-value drought-tolerant alternative. A forecast incorrectly predicting adequate rainfall may induce selection of the drought-sensitive option, which fails when actual conditions are dry. The relevant economic loss includes not only the reduced income from the failed crop but also the foregone returns from the drought-tolerant alternative that would have succeeded. This opportunity cost dimension implies that the welfare impact of forecast errors depends on the range of available alternatives and the difference in returns across strategies.

Risk-averse farmers may adopt conservative strategies that sacrifice expected returns to reduce variance, with forecast errors exacerbating these risk premiums. If farmers perceive forecast reliability as uncertain, they may partially discount predictions and maintain risk-reducing practices even when forecasts suggest these are unnecessary. This behavior generates implicit costs from foregone income improvements that accurate and trusted forecasts would enable. The magnitude of this risk premium varies with farmer wealth and access to risk management instruments like crop insurance. Wealthier farmers with better risk-bearing capacity can more fully exploit forecast information, while resource-constrained smallholders may continue conservative practices despite access to accurate predictions.

Empirical evidence on the distribution of forecast error costs across farmer categories reveals systematic inequalities. Smallholders typically operate with limited financial buffers and restricted access to credit, making them vulnerable to forecast failure impacts that would be absorbed more easily by larger operations. Extension service access varies inversely with farm size in many contexts, reducing smallholder

capacity to interpret forecast uncertainty and develop contingency plans. These structural disadvantages imply that identical forecast accuracy levels generate differential economic impacts across the farm size distribution, with smallholders experiencing disproportionate costs from prediction errors.

The cumulative effect of repeated forecast errors extends beyond individual season losses through impacts on farmer trust and long-term service adoption. Systematic reviews of climate information service effectiveness demonstrate mixed results in quantifying benefits, with some studies showing positive impacts while others find effects difficult to measure (Chisadza et al., 2020). This heterogeneity reflects in part the legacy effects of historical forecast failures, which create persistent skepticism that reduces current service utilization even after accuracy improvements. Rebuilding trust following forecast failures requires sustained periods of reliable performance, generating path dependence in service effectiveness that standard period-by-period analysis overlooks.

Transaction costs associated with forecast-based decision adjustments can reduce net economic benefits, particularly for smallholders with limited market access and information channels. Responding to forecast signals often requires securing inputs on short notice, potentially at premium prices if usual supply channels are unavailable. Coordinating with buyers for alternative crop deliveries or adjusting harvest timing to meet market windows adds coordination costs. These transaction frictions reduce the net value of forecast-induced decision changes, with effects concentrated among farmers with weak market integration and limited social networks for information sharing and input access.

5 Information Asymmetries and Access Barriers

Substantial information asymmetries exist between large commercial agricultural operations and smallholder producers, creating disparities in adaptive capacity and economic resilience under climate variability. These asymmetries arise from differential access to forecast technologies, varying capacity to interpret probabilistic predictions, and unequal ability to act on forecast information through resource mobilization and market engagement.

Commercial farms frequently maintain private meteorological monitoring systems that provide farm-specific observations and enable validation of public forecast services. These resources support sophisticated decision support systems that integrate weather predictions with crop models, soil moisture sensors, and pest surveillance networks. In contrast, smallholders rely almost exclusively on publicly

provided forecast services, often delivered through generic broadcast channels that lack localization to specific microclimates and farming systems. This monitoring gap generates corresponding differences in forecast accuracy at the field level, with commercial operations accessing superior information even when regional forecast quality is nominally equal.

The capacity to interpret probabilistic forecasts varies systematically with educational attainment and technical training. Seasonal climate forecasts typically present information in probabilistic terms, describing the likelihood of different rainfall or temperature scenarios rather than deterministic predictions. Effectively utilizing these forecasts requires understanding probability concepts and translating ensemble predictions into risk-weighted decision strategies. Systematic evidence demonstrates that education emerges as a significant determinant of climate forecast access and utilization, with primary, secondary, and tertiary education increasing adoption probabilities at statistically significant levels (Oyekale, 2017).

Gender dimensions of information access create additional disparities within smallholder farming populations. Systematic review evidence from Sub-Saharan Africa reveals that female farmers exhibit adoption rates of 40-55 percent for climate-smart agricultural practices compared to 55-70 percent for male farmers (Mnukwa et al., 2025). These gender gaps reflect differential access to extension services, literacy rates, and control over productive resources needed to implement forecast-informed strategies. In many agricultural contexts, women perform the majority of farm labor but exercise limited decision authority over crop selection and input use, reducing their capacity to act on forecast information even when accessible.

Resource constraints limit smallholder ability to respond to forecast signals through input procurement and management adjustments. High initial costs of improved seeds, fertilizers, and irrigation equipment reduce adoption of climate-smart practices by approximately 65 percent among resource-poor farmers (Mnukwa et al., 2025). Credit access improves adoption rates by 45 percent, indicating that financial constraints rather than information alone often constitute the binding barrier to forecast utilization. These capital market imperfections imply that forecast service improvements must be accompanied by complementary interventions addressing input affordability and credit access to achieve full welfare potential.

Extension service availability exhibits strong spatial and socioeconomic gradients that exacerbate information asymmetries. Extension access increases adoption of climate-smart agricultural practices by 2.8 times according to systematic meta-analysis (Mnukwa et al., 2025). However, extension coverage varies dramatically across regions and farm size categories, with remote areas and small-scale producers

receiving limited service access. This extension gap reduces smallholder capacity to contextualize regional forecasts for specific farming systems and develop appropriate response strategies. Scaling extension services to reach currently underserved populations requires substantial public investment and institutional reforms to improve service provider incentives.

Geographic isolation compounds information access challenges through limited infrastructure for forecast delivery. Smallholder farmers in remote areas often lack reliable electricity, internet connectivity, and mobile phone coverage necessary for accessing digital forecast services. Radio remains the most prevalent information channel in many rural contexts, but generic radio forecasts provide limited spatial resolution and timing precision for farm-level decisions. Evidence from Malawi indicates that farmers in the Ndau ethnic group and those in remote areas show significant reluctance to pay for forecast services, reflecting both access barriers and skepticism regarding service relevance ([Manzvera et al., 2024](#)).

Land tenure insecurity creates misaligned incentives for long-term agricultural investments, reducing the effective value of climate forecasts that enable multi-year planning. Secure land tenure improves long-term investment by approximately 60 percent ([Mnukwa et al., 2025](#)), facilitating adoption of soil conservation practices, perennial crops, and infrastructure improvements that enhance climate resilience. Smallholders with insecure tenure rights discount the future more heavily and prioritize short-term survival over optimal long-run strategies, reducing the private value of forecast information regarding multi-year climate patterns even when these forecasts are accurate and accessible.

The interaction between multiple access barriers creates cumulative disadvantages that simple additive models underestimate. Farmers facing simultaneous constraints in education, financial resources, extension access, and market integration experience compounded difficulties in forecast utilization. These overlapping barriers generate threshold effects where marginal improvements in single dimensions produce limited impacts unless complementary constraints are simultaneously addressed. Policy interventions must therefore adopt integrated approaches that tackle multiple barriers concurrently rather than sequential reforms addressing constraints in isolation.

6 Policy Implications and Service Delivery Models

Effective climate information service delivery for smallholder farmers requires institutional designs that address the specific decision environments, resource constraints, and information needs of this heterogeneous population. Evidence from diverse agricultural contexts reveals substantial variation in service effectiveness, indicating that forecast accuracy alone is insufficient for welfare improvement without appropriate delivery mechanisms and complementary support systems.

Context-specific accuracy standards should guide forecast service development rather than generic quality metrics that ignore decision requirements. Different agricultural decisions exhibit varying sensitivity to forecast errors, with irreversible choices like crop selection requiring higher accuracy thresholds than flexible mid-season adjustments. Planting timing decisions demand precise predictions of rainfall onset within narrow windows, while fertilizer application timing permits broader ranges. Service providers should prioritize accuracy improvements for high-stakes decisions where errors generate largest economic losses, accepting lower precision for decisions where farmers can adapt based on evolving conditions.

Last-mile delivery infrastructure investments constitute a critical complement to forecast accuracy improvements. High-quality regional forecasts generate limited value if smallholders cannot access predictions in timely and interpretable formats. Expansion of mobile phone coverage and radio broadcast infrastructure extends forecast reach to remote populations. Community-based information intermediaries can translate technical forecasts into actionable recommendations contextualized for local farming systems. Systematic reviews indicate that despite growing research attention to climate information services since 2010, significant challenges persist in forecast interpretation and adoption of anticipatory adaptation techniques ([Madhuri, 2025](#)).

Co-production approaches that engage farmers in forecast development and validation processes improve service relevance and build trust. Participatory forecast design incorporates farmer knowledge of local climate patterns, integrates indigenous prediction methods with scientific forecasts, and tailors information presentation to farmer decision frameworks. Evidence demonstrates that farmers combine scientific climate information with indigenous knowledge systems, with mixed results on the measurability of benefits ([Chisadza et al., 2020](#)). Formal integration of these knowledge systems through co-production can enhance forecast credibility and utilization while preserving valuable local observations that improve prediction accuracy for

specific microclimates.

Subsidized access to forecast services may be justified on equity grounds to reduce information asymmetries between commercial operations and smallholders. While willingness to pay studies indicate smallholders value forecast services at approximately USD 1-2 per month, this represents a significant expense for households at subsistence margins. Public provision or subsidized delivery ensures that forecast access does not stratify along income lines, preventing information inequalities from exacerbating existing productivity gaps. The public good characteristics of meteorological observations and modeling infrastructure provide additional economic rationale for government financing rather than full cost recovery models that exclude poor households.

Bundling climate information services with complementary agricultural support systems can enhance total value creation and improve cost-effectiveness of delivery investments. Integrated packages combining forecasts with extension advice, input supply credit, and market linkages address multiple barriers simultaneously and exploit complementarities between information and implementation capacity. Evidence from multiple contexts demonstrates that forecast value depends critically on access to inputs and markets that enable appropriate responses. Standalone forecast services generate limited impacts when farmers lack resources to adjust practices based on predictions.

Quality assurance systems that track forecast accuracy and communicate uncertainty transparently can improve farmer trust and appropriate utilization. Public disclosure of verification statistics enables farmers to assess service reliability and calibrate their dependence on predictions. Explicit communication of forecast uncertainty through probability distributions or confidence intervals helps farmers develop appropriate decision strategies rather than treating predictions as deterministic. However, research indicates that few studies associate accuracy variables with different forecast types across agricultural cycles, representing a knowledge gap that limits service optimization ([Madhuri, 2023](#)).

Institutional coordination between meteorological services, agricultural extension agencies, and development organizations can reduce fragmentation and improve service coherence. Effective climate information delivery requires technical capacity in atmospheric science, agronomy, economics, and communication. No single organization typically possesses all these competencies, necessitating collaboration across institutional boundaries. Coordination mechanisms that align incentives, share data, and integrate expertise can overcome institutional silos that fragment service delivery and reduce effectiveness.

Investment in farmer education regarding forecast interpretation and uncertainty management represents a high-return complement to forecast accuracy improvements. Even highly accurate forecasts generate limited value if users cannot translate probabilistic information into risk-weighted decisions. Training programs that build capacity for probability interpretation, scenario planning, and contingency development enable farmers to extract greater value from existing forecast services while also improving their capacity to manage climate risks more broadly beyond forecast dependence.

7 Conclusion

Weather forecast accuracy represents a critical determinant of agricultural welfare for smallholder farmers operating under climate uncertainty and resource constraints. This analysis demonstrates that the economic value of forecast information depends on complex interactions between prediction precision, farmer decision environments, resource access, and institutional delivery mechanisms. Improvements in forecast accuracy generate substantial economic returns when farmers possess the capacity to act on predictions through appropriate input adjustments and management changes, with empirical evidence indicating net income increases of 15-26 percent for high-quality forecast users compared to traditional decision methods.

The relationship between forecast accuracy and economic outcomes exhibits non-linear dynamics with important threshold effects. Modest accuracy improvements in critical ranges generate disproportionate welfare gains, while marginal enhancements in already high-performing systems yield limited additional benefits. This non-linearity implies that accuracy improvement investments should target parameters and timeframes that currently perform below decision-relevant thresholds rather than pursuing uniform enhancement across all forecast dimensions. Precipitation onset predictions and extreme event warnings emerge as particularly high-value targets given their influence on irreversible planting decisions and disaster preparedness strategies.

Forecast errors impose economic costs through multiple channels beyond simple production losses, including opportunity costs from foregone superior strategies, risk premiums from uncertainty, and trust erosion that reduces long-term service utilization. The cost structure varies systematically across decision types, with irreversible choices exhibiting much higher sensitivity to prediction errors than flexible adjustments permitting mid-course corrections. Smallholder farmers with limited financial buffers and weak market access experience disproportionate impacts from forecast

failures, exacerbating existing vulnerabilities and potentially widening inequality between commercial operations and resource-constrained producers.

Substantial information asymmetries persist between large-scale agricultural enterprises and smallholder farmers, reflecting differential access to monitoring technologies, varying capacity to interpret probabilistic forecasts, and unequal ability to mobilize resources in response to predictions. These asymmetries generate disparities in adaptive capacity that compound over time, as farmers with superior information implement more effective climate risk management strategies that improve their competitive position. Addressing these inequalities requires explicit policy interventions to ensure smallholder access to high-quality forecasts rather than assuming that general service provision automatically reaches all agricultural populations.

Service delivery mechanisms critically mediate the translation of forecast accuracy into realized economic benefits. Technical forecast quality represents a necessary but insufficient condition for welfare improvement, requiring complementary investments in last-mile infrastructure, farmer capacity development, and integration with input supply and market systems. Co-production approaches that engage farmers in forecast development enhance service relevance and build trust, while bundled delivery models that combine forecasts with extension advice and input credit address multiple constraints simultaneously.

The findings indicate several priority areas for policy action and research investment. First, context-specific accuracy standards should replace generic quality metrics, recognizing that different agricultural decisions require varying precision levels and that error costs differ systematically across farming systems. Second, subsidized forecast access may be justified on equity grounds to prevent information asymmetries from reinforcing existing inequalities, particularly given the public good characteristics of meteorological infrastructure. Third, institutional coordination mechanisms should align the capabilities of meteorological services, agricultural extension agencies, and development organizations to deliver integrated climate information systems rather than fragmented standalone services.

Future research should address critical knowledge gaps regarding the dynamic evolution of forecast value over multi-year timeframes, accounting for farmer learning, trust formation, and cumulative impacts of accuracy improvements. Systematic investigation of how forecast services interact with other climate adaptation strategies would clarify complementarities and potential substitution effects. Analysis of cost-effective delivery mechanisms for reaching remote and marginalized farming populations remains a priority given persistent gaps in service coverage. Finally, exploration of how forecast information influences within-household decision dynam-

ics and gender-differentiated agricultural strategies would enhance understanding of welfare distribution effects and inform more inclusive service design.

The economic case for investing in improved weather forecast accuracy and delivery systems for smallholder agriculture is compelling, with potential returns substantially exceeding costs when services are appropriately designed and integrated with complementary support systems. Realizing this potential requires moving beyond narrow technical focus on prediction accuracy toward holistic approaches that address the multiple barriers limiting smallholder capacity to access and utilize climate information effectively.

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