The Economic Value of Climate Forecast Precision: Investment Decisions and Risk Management in Agricultural Markets

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Abstract

This paper examines the economic implications of climate forecast precision on agricultural investment decisions and risk management strategies. We develop a theoretical framework analyzing how forecast accuracy influences farmers' planting decisions, input allocation, and market coordination. The analysis demonstrates that improved forecast precision generates substantial economic value through reduced uncertainty and enhanced decision-making capabilities. We explore the relationship between forecast reliability, investment timing, and expected returns under different risk profiles. The model reveals that forecast precision acts as an information good with diminishing marginal returns, creating heterogeneous benefits across farm sizes and crop types. Market failures emerge when forecast information becomes a club good, leading to suboptimal resource allocation. The findings suggest that public provision of high-quality climate forecasts can generate significant welfare gains, particularly for smallholder farmers who face greater constraints in accessing and utilizing forecast information. Policy implications include the design of forecast dissemination systems, investment in forecast infrastructure, and mechanisms to ensure equitable access to climate information services.

Keywords: Climate forecasting; Agricultural economics; Information economics; Risk management; Investment decisions

JEL Classification: Q54; D81; Q12; C53; O13

1 Introduction

Climate forecasts have become increasingly sophisticated over recent decades, with advances in meteorological science and computational capabilities enabling predictions at

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multiple temporal and spatial scales. These forecasts range from seasonal outlooks to multi-decadal projections, each serving distinct roles in economic planning and decision-making. The agricultural sector represents one of the most climate-sensitive domains of economic activity, where production outcomes depend critically on temperature, precipitation, and extreme weather events. Consequently, the ability to anticipate climatic conditions holds substantial economic value for farmers, agribusinesses, and policymakers.

The economic literature on climate information has established that forecast accuracy directly influences welfare through multiple channels. First, improved forecasts enable better timing of agricultural operations, including planting, irrigation, and harvesting decisions. Second, they facilitate optimal input allocation by allowing farmers to adjust fertilizer application, seed selection, and labor deployment based on expected conditions. Third, accurate forecasts support risk management through crop insurance pricing, futures market participation, and diversification strategies. Despite these recognized benefits, the precise economic value of forecast improvements remains inadequately quantified, particularly regarding the distributional implications across different farm types and regions.

This paper contributes to the existing literature by developing a comprehensive theoretical framework that explicitly models the relationship between forecast precision and agricultural investment decisions. Unlike previous studies that focus primarily on ex-post evaluation of forecast benefits, we examine the ex-ante decision-making process under uncertainty, incorporating realistic constraints on information processing and capital availability. Our analysis reveals several important insights regarding the structure of forecast value and its implications for market efficiency.

The theoretical model demonstrates that forecast precision exhibits diminishing marginal returns in value generation. Initial improvements in accuracy yield substantial benefits by reducing fundamental uncertainty about climate outcomes. However, as precision approaches theoretical limits, additional improvements generate progressively smaller gains. This nonlinearity has important implications for optimal investment in forecast infrastructure and suggests that resources may be more efficiently allocated to expanding forecast access rather than pursuing marginal accuracy improvements.

We identify market failures arising from the club-good characteristics of climate forecasts. While forecasts are non-rivalrous in consumption, exclusion is technologically feasible through subscription services or proprietary distribution channels. This creates potential for underproduction relative to the social optimum, as private providers cannot capture the full social value of forecast information. The problem becomes particularly acute for smallholder farmers in developing regions, who face both affordability constraints and limited technical capacity to translate forecasts into actionable decisions.

The analysis also examines coordination problems in agricultural markets where multiple farmers respond simultaneously to common forecast signals, drawing on insights from collective action theory (Holahan and Lubell, 2016). When forecasts predict favorable conditions, widespread planting of particular crops can lead to supply gluts and price declines, potentially negating the benefits of accurate prediction. This strategic interdependence suggests that forecast value depends not only on accuracy but also on the structure of market competition and the degree of crop diversification across the farming population.

Our findings have direct relevance for agricultural policy and climate service design. The public-good aspects of climate forecasts provide strong justification for government provision or subsidization, particularly in regions with high agricultural dependence and limited private sector capacity (Zilberman et al., 2018). Furthermore, the heterogeneous value of forecasts across farm types suggests that dissemination strategies should be tailored to different user groups, with particular attention to ensuring that smallholders receive both forecast information and the technical assistance needed to utilize it effectively.

2 Literature Review and Theoretical Background

The economic analysis of climate forecasts intersects multiple research domains, including agricultural economics, information economics, and development studies. Understanding how forecast information influences agricultural decisions requires consideration of both microeconomic decision-making and broader institutional contexts that shape information access and utilization capacity.

The agricultural economics literature has extensively studied decision-making under uncertainty, providing theoretical foundations relevant to forecast value analysis. Within the expected utility framework, forecast precision reduces the variance of subjective probability distributions over climate outcomes, thereby influencing both expected returns and risk exposure. Risk-averse farmers derive additional value from forecasts beyond their mean-prediction accuracy, as reduced uncertainty itself provides utility gains. The relationship between information quality and investment decisions becomes particularly important when farmers face capital constraints or when investments exhibit irreversibility characteristics.

Information economics provides crucial insights into market structure and provision of forecast services. The work on information asymmetry and market failures applies directly to climate forecast markets, where producers may have private information about forecast quality and where buyers face difficulties in assessing accuracy ex-ante. These informational frictions can lead to adverse selection problems and market breakdown, particularly when forecast quality varies across providers. The public-good characteristics of forecasts further complicate private provision, as individual purchasers cannot fully appropriate the social benefits of improved agricultural productivity and food security.

Recent contributions have explored the distributional implications of climate forecast access across different farm types and regions. Returns to forecast information vary significantly across farm sizes, with larger operations better positioned to exploit forecast signals through sophisticated risk management strategies. This heterogeneity raises equity concerns, as smallholder farmers who are most vulnerable to climate variability may derive relatively less benefit from forecast improvements. Such patterns reflect both differences in technical capacity and constraints on access to complementary inputs such as irrigation infrastructure and crop insurance.

The literature on public investment and agricultural development provides important context for understanding forecast value in developing regions. **?** analyze the role of public capital in productivity growth, demonstrating that public investment in infrastructure generates positive externalities for private sector activity. Similarly, public investment in forecast infrastructure can be understood as a form of productive public capital that enhances agricultural productivity through improved information quality. The productivity of such investments depends critically on complementary factors including farmer education, extension services, and access to adaptive technologies.

Studies examining sectoral efficiency in agricultural development offer insights into how forecast improvements might generate differential impacts across regions and farming systems. **?** demonstrates that public investment in agriculture yields significantly larger positive impacts on poverty reduction than investments in non-agricultural sectors in contexts where agriculture dominates rural livelihoods. This finding suggests that forecast improvements specifically targeting smallholder agriculture could generate substantial welfare gains in agricultural economies, provided that farmers possess the capacity to respond to forecast information.

The relationship between public and private capital in agricultural development has implications for understanding how forecast investments interact with farmer resources. **?** examines productivity relationships between public and private capital, showing that effectiveness of public capital varies with existing levels of private capital. Applied to forecast services, this suggests that forecast value depends on farmers' existing capacity to respond to information through adjustments in private investment and management practices. Regions with limited private capital may realize smaller benefits from forecast improvements absent complementary investments in farmer capacity.

Research on public policy and development challenges emphasizes the importance of human capital investments alongside infrastructure development. **?** analyzes the impact of public investments in education and health on economic growth, demonstrating that human capital accumulation drives long-term productivity gains. Similarly, realization of forecast value in agriculture depends on farmer capacity to interpret and utilize climate information, suggesting that forecast dissemination should be accompanied by educational programs and extension services.

The governance dimension of technology provision receives attention in literature on global technology governance. Juma et al. (2001) examines measures needed to ensure that technological advances benefit developing countries, emphasizing the importance of both domestic innovation capacity and international cooperation. Applied to climate forecasts, this framework suggests that effective forecast services require both investment in domestic meteorological capacity and participation in international observational networks and forecast development efforts.

Game-theoretic approaches provide tools for analyzing strategic interactions in agricultural markets with shared information sources. Gilles (2010) develops cooperative game theory frameworks for analyzing networks and hierarchies, offering insights into how farmers might coordinate responses to forecast information. When farmers share common forecasts, their planting decisions become strategically interdependent, creating potential for coordination failures or cooperation opportunities. The structure of these strategic interactions influences the aggregate value of forecast improvements.

Collective action theory offers additional perspectives on coordination challenges in agricultural markets (Holahan and Lubell, 2016). Forecast information creates a form of collective action problem where individual rational responses to common signals may generate socially suboptimal outcomes through excessive correlation in planting decisions. Governance mechanisms that facilitate coordination among farmers while preserving beneficial competition could enhance the social value of forecast improvements.

Economic theory more broadly emphasizes the importance of market incentives and price signals in shaping resource allocation (Dubbink, 2003). Forecast information interacts with market price signals to influence farmer decisions, with the relative importance of forecasts versus prices depending on forecast accuracy, price volatility, and the timing of different decision stages. Understanding these interactions requires integrated analysis of information and market dynamics.

The literature on technology adoption in developing countries highlights barriers that limit uptake of new information sources and practices. Raja and Christiaensen (2017) examines how digital technologies affect labor markets and economic opportunities, noting that technology benefits depend critically on complementary investments in skills and infrastructure. Similar considerations apply to climate forecast utilization, where farmer capacity to interpret probabilistic information and translate forecasts into management adjustments determines realized value.

Despite substantial progress, important gaps remain in the economic literature on climate forecasts. Limited research examines the dynamic aspects of forecast value, including learning effects as users gain experience with forecast interpretation and the evolution of value as climate patterns change. The interaction between climate forecasts and other information sources, such as market price signals and agricultural extension services, also merits further investigation. Additionally, most existing studies focus on seasonal forecasts, with less attention to the economic implications of subseasonal predictions or long-term climate projections.

This paper addresses several gaps by developing a theoretical framework that integrates individual decision-making, market-level outcomes, and distributional effects. By explicitly modeling the relationship between forecast precision and economic value across multiple channels, we provide a foundation for welfare analysis and policy design that accounts for heterogeneity in farmer circumstances and market structures.

3 Theoretical Framework

We develop a stylized model of agricultural investment decisions under climate uncertainty to analyze the economic value of forecast precision. Consider a representative farmer who must decide on input allocation before observing the realized climate state. The farmer's objective is to maximize expected utility, accounting for both returns and risk.

Let $s \in S$ denote the true climate state, drawn from a finite set of possible states. The probability distribution over states is given by $p(s)$, representing the climatological baseline. Before making investment decisions, the farmer observes a forecast signal $f \in F$, which provides imperfect information about the true state. The precision of the forecast is characterized by the conditional probability distribution $q(s|f)$, describing the likelihood of each climate state given the observed signal.

The farmer chooses an investment level $I \geq 0$, which determines input expenditure on seeds, fertilizers, irrigation, and labor. Production outcomes depend on both the investment level and the realized climate state through a production function $Y(I, s)$. We assume this function is increasing and concave in investment for each climate state, reflecting diminishing returns to input application. Importantly, the marginal productivity of investment varies across climate states: favorable conditions enhance the returns to intensive cultivation, while adverse conditions reduce input effectiveness.

The farmer's profit in state s is given by:

$$\pi(I, s) = pY(I, s) - I \tag{1}$$

where p denotes the output price. For tractability, we assume the price is exogenous to individual farmer decisions, though we later consider market equilibrium effects when analyzing aggregate outcomes. The farmer's expected utility before observing the forecast is:

$$EU_0 = \sum_{s \in S} p(s)u(\pi(I, s)) \tag{2}$$

where $u(\cdot)$ is a von Neumann-Morgenstern utility function exhibiting risk aversion, specifically $u' > 0$ and $u'' < 0$. After observing forecast signal f, the farmer updates beliefs according to Bayes' rule and chooses investment to maximize:

$$EU_f = \sum_{s \in S} q(s|f)u(\pi(I, s)) \tag{3}$$

The value of the forecast equals the difference in expected utility between the information and no-information cases, converted to monetary terms through the risk premium. To characterize forecast precision more explicitly, we introduce a parameter $\theta \in [0, 1]$ measuring accuracy. A perfectly precise forecast has $\theta = 1$, meaning $q(s|f) = 1$ when the forecast correctly identifies the true state. A completely uninformative forecast has $\theta = 0$, implying $q(s|f) = p(s)$ regardless of the signal. Intermediate values reflect varying degrees of accuracy, with higher θ corresponding to more precise forecasts.

The optimal investment decision depends on forecast precision through two channels. First, more accurate forecasts shift the posterior distribution $q(s|f)$ toward states consistent with the signal, altering expected returns to different investment levels. Second, increased precision reduces residual uncertainty conditional on the forecast, potentially affecting the risk premium demanded by risk-averse farmers. Both channels influence the value of improved forecasts, though their relative importance varies with the degree of risk aversion and the structure of returns across climate states.

Consider the marginal value of forecast precision, defined as:

$$\frac{\partial EU_f}{\partial \theta} \tag{4}$$

This marginal value is positive whenever the forecast provides any information about climate states, reflecting the benefits of reduced uncertainty. However, the marginal value declines as precision increases, exhibiting diminishing returns. Intuitively, the first increments of forecast accuracy resolve the most fundamental uncertainties about climate outcomes, while subsequent improvements provide increasingly refined distinctions between similar states.

The heterogeneity of forecast value across farmers arises from several sources. Farmers operating in regions with high climate variability derive greater benefits from forecast precision, as the reduction in uncertainty is more substantial. Similarly, farmers cultivating crops with strong sensitivity to specific climate variables obtain larger gains from forecasts targeting those variables. Farm size also matters: larger operations can spread the fixed costs of acquiring and interpreting forecast information across more extensive production, increasing the per-hectare value of improved precision.

Capital constraints introduce an additional dimension of heterogeneity. Farmers with limited access to credit face restrictions on their ability to adjust investments in response to forecast signals. When favorable forecasts indicate opportunities for intensive cultivation, constrained farmers cannot fully exploit these signals due to inability to finance increased input purchases. This creates a wedge between the potential value of forecast information and its realized benefits, with the gap largest for farmers facing tight credit constraints.

Market-level outcomes depend on the distribution of forecast access and the correlation of farmers' responses to common signals. When all farmers observe the same forecast and adjust production similarly, aggregate supply responds to forecast signals. If forecasts predict favorable conditions, coordinated increases in planting can generate supply gluts that depress prices. Conversely, forecasts of adverse conditions trigger coordinated reductions in planting, potentially creating supply shortfalls. These price effects feed back into individual farmer decisions, creating strategic complementarities that amplify forecast responses.

Let aggregate output be:

$$Q = \int Y(I_i, s)di \tag{5}$$

where the integral is taken over all farmers i. Market clearing requires that price adjusts such that:

$$p(Q) = D(Q) \tag{6}$$

where $D(\cdot)$ is the inverse demand function. When forecast precision improves and farmers respond by adjusting investments systematically, the resulting changes in aggregate output induce price movements that affect all producers.

The coordination problem becomes particularly severe when farmers cannot differentiate their crop choices effectively. In regions where agro-ecological conditions permit only a narrow range of crops, forecast-induced coordination failures may substantially diminish forecast value. Conversely, regions with greater crop diversity and flexibility in planting decisions allow farmers to specialize in niches less affected by coordination problems, preserving more of the potential value from forecast improvements.

4 Economic Analysis of Forecast Precision

The economic value of improved forecast precision manifests through multiple channels, each with distinct characteristics and policy implications. We analyze these channels systematically, beginning with direct effects on agricultural productivity and proceeding to broader market and distributional consequences.

Enhanced forecast precision increases agricultural productivity by enabling better matching between production practices and realized climate conditions. When farmers can accurately anticipate weather patterns, they optimize planting dates, select appropriate crop varieties, and adjust input applications accordingly. These micro-level optimizations aggregate to substantial productivity gains at regional and national scales. The magnitude of productivity improvements depends on the sensitivity of crops to climate variables and the flexibility of farming systems to respond to forecast information.

The risk reduction channel provides an independent source of value from forecast improvements. Even holding expected productivity constant, reduced uncertainty about future climate states benefits risk-averse farmers by narrowing the range of possible outcomes. This value is particularly significant for decisions involving substantial downside risk, such as investments in irrigation infrastructure or high-input cultivation systems vulnerable to weather shocks. The willingness to pay for risk reduction varies across farmers based on risk preferences and existing risk management options, including crop insurance and diversification possibilities.

Resource allocation efficiency improves with forecast precision through better intertemporal and spatial distribution of inputs. Forecasts enable farmers to deploy scarce resources, particularly water and labor, when and where they yield highest returns. During years when forecasts predict drought, farmers can prioritize irrigation for high-value crops and adjust planting to conserve water. Conversely, forecasts of abundant rainfall allow expansion of rain-fed cultivation and reallocation of irrigation capacity to other uses. These reallocation benefits are especially valuable in regions with tight resource constraints.

Market coordination represents a more complex channel through which forecast precision affects welfare. On one hand, forecasts facilitate market coordination by providing common information that aligns planting decisions with expected demand and price conditions. On the other hand, excessive coordination can amplify supply volatility when all farmers respond similarly to forecast signals. The net effect depends on the correlation structure of forecast errors across regions and crops, as well as the elasticity of demand for agricultural products.

The distributional consequences of forecast precision warrant careful analysis. If forecast access and utilization capacity are distributed unevenly across the farming population, improvements in forecast accuracy may exacerbate existing inequalities. Large commercial farmers with sophisticated information systems and flexible production capabilities can extract substantial value from precise forecasts, while smallholders lacking technical capacity or capital access realize smaller benefits. This pattern suggests that forecast improvements alone, without complementary investments in farmer capacity and infrastructure, may widen the productivity gap between large and small operations, as observed in studies of sectoral efficiency (**?**).

Geographic disparities in forecast value arise from spatial variation in forecast skill and climate predictability. Certain regions exhibit stronger teleconnections to large-scale climate drivers, enabling more accurate seasonal forecasts. Farmers in these regions derive greater benefits from forecast improvements relative to those in areas where climate dynamics are dominated by local processes with limited predictability. This geographic heterogeneity implies that optimal investment in forecast infrastructure should account for spatial variation in potential returns, similar to considerations in public capital investment decisions (**?**).

The temporal structure of forecast value reflects differences in prediction horizons and decision timescales. Subseasonal forecasts covering periods of two weeks to two months prove valuable for tactical decisions including irrigation scheduling and pest management. Seasonal forecasts spanning three to six months inform strategic choices such as crop selection and major input purchases. Multi-year climate projections guide long-term investments in farm infrastructure and perennial crop cultivation. Each temporal scale serves distinct economic functions, and the value of improved precision varies across these scales based on the irreversibility and capital intensity of associated decisions.

Forecast precision interacts with other agricultural policies and market institutions in ways that amplify or diminish its economic value. Price support programs and crop insurance schemes affect farmers' risk exposure and investment incentives, thereby altering the marginal value of forecast information. When government policies stabilize output prices or guarantee minimum incomes, the value of forecasts for risk management declines. Conversely, policies that expose farmers to greater market risk increase the value of information that helps manage that risk, consistent with broader frameworks for sustainable development (Zilberman et al., 2018).

The complementarity between forecast precision and adaptive capacity deserves emphasis. Farmers' ability to respond to forecast information depends on access to flexible inputs, credit availability, and technical knowledge. Regions with well-developed input markets and extension services realize greater benefits from forecast improvements than those with limited adaptive capacity. This complementarity suggests that investments in forecast accuracy should be coordinated with broader agricultural development programs that enhance farmers' responsiveness to information.

International dimensions introduce additional complexity to forecast value analysis. When agricultural markets are globally integrated, domestic forecast improvements affect international competitiveness and trade patterns. Countries with superior forecast capabilities can gain strategic advantages in agricultural production, potentially shifting comparative advantage patterns. However, these benefits may be partially offset by terms-of-trade effects if increased domestic production depresses world prices for exported commodities.

Climate change alters the baseline uncertainty against which forecast value is measured. As climate patterns shift and extreme events become more frequent, the reduction in uncertainty provided by accurate forecasts becomes increasingly valuable. However, climate change may also reduce forecast skill if historical relationships between climate drivers and local weather patterns break down. This tension between increasing uncertainty and potentially declining predictability complicates long-term planning for climate service investments.

The market structure for forecast provision affects the realization of potential economic benefits. Private provision of forecasts may lead to underproduction relative to the social optimum due to inability to capture full social benefits through pricing mechanisms. Public provision addresses this market failure but raises questions about service quality and responsiveness to user needs. Hybrid models involving public-private partnerships offer potential advantages by combining public investment in foundational infrastructure with private sector innovation in service delivery and customization.

5 Institutional Design

The economic analysis of forecast precision generates several important implications for agricultural policy and institutional design of climate services. We discuss these implications across multiple dimensions, including public investment priorities, dissemination strategies, and complementary programs to enhance forecast utilization.

Public investment in forecast infrastructure merits strong justification based on the public-good characteristics of climate information and the substantial social returns to forecast accuracy. The inability of private markets to capture full social benefits through pricing mechanisms leads to underinvestment in forecast production absent government intervention. National meteorological services play a central role in maintaining observational networks, developing forecast models, and disseminating basic climate information. This form of public investment can be understood as productive public capital that generates positive externalities for agricultural productivity (?).

Cost-benefit analysis of forecast infrastructure investments should account for heterogeneous impacts across different farmer groups and regions. Returns to public investment in forecast capacity will be highest in regions with substantial climate variability, large agricultural sectors, and sufficient farmer capacity to utilize forecast information effectively. Evidence from sectoral investment analysis suggests that in agricultural economies, investments targeting agricultural productivity can generate particularly large welfare gains (?). This principle extends to forecast infrastructure when forecasts primarily serve agricultural decision-making.

The design of forecast dissemination systems should account for heterogeneity in user needs and capacities. Farmers require forecast information in formats accessible to their education levels and compatible with their decision-making processes. This necessitates translation of technical forecast products into actionable recommendations, often requiring collaboration between meteorologists and agricultural extension specialists. Mobile technology offers promising channels for reaching smallholder farmers in remote areas, though issues of digital literacy and network coverage require attention, as highlighted in studies of technology adoption (Raja and Christiaensen, 2017).

Capacity building programs represent essential complements to forecast provision. Farmers need training in forecast interpretation, statistical concepts of probability and uncertainty, and strategies for incorporating forecast information into farm planning. Extension services play crucial roles in facilitating this learning process through demonstrations, farmer field schools, and peer-to-peer learning networks. Investment in extension capacity should accompany efforts to improve forecast accuracy to ensure that technical advances translate into realized economic benefits, consistent with findings on human capital investment (?).

Integration of forecast information with existing agricultural advisory services enhances utilization effectiveness. When extension agents incorporate forecast updates into their regular communications with farmers, the information gains credibility and relevance. This integration also enables contextualization of forecasts within broader agronomic guidance, helping farmers understand how to adjust specific practices based on expected conditions. Institutional mechanisms for coordination between meteorological services and agricultural agencies facilitate such integration.

Access to complementary inputs and services determines farmers' capacity to respond to forecast information. Credit programs that provide financing for forecast-contingent investments enable farmers to exploit opportunities identified by accurate predictions.

Input supply chains must be sufficiently responsive to deliver appropriate seeds, fertilizers, and other materials when forecasts indicate conditions favorable for intensive cultivation. Infrastructure including irrigation systems and storage facilities enhances the value of forecasts by expanding the set of feasible responses to different climate scenarios.

Insurance market development benefits from improved forecast precision while also enhancing forecast value for farmers. Index-based insurance products linked to observable weather variables reduce basis risk when forecasts are accurate. Insurers can adjust premium structures based on seasonal forecasts, improving market efficiency. However, regulators must carefully consider the interaction between forecast availability and insurance market function to prevent adverse selection problems when farmers possess superior information about upcoming conditions.

International cooperation in forecast development and dissemination generates positive externalities that individual countries cannot fully capture. Climate systems transcend national boundaries, and forecast skill often depends on observations from multiple countries and regions. Global observational networks and forecast model development benefit from international collaboration and data sharing (Juma et al., 2001). Development assistance for forecast infrastructure in low-income countries yields returns not only for recipient nations but also for global agricultural stability and food security.

The institutional arrangements for forecast provision should balance public and private sector roles according to comparative advantages. Public agencies typically maintain core infrastructure including observational networks and basic forecast production. Private sector firms can add value through customized forecast products, specialized services for particular crops or regions, and innovative dissemination channels. Regulatory frameworks should encourage competition and innovation in value-added services while ensuring that basic forecast information remains freely available as a public good, consistent with economic theory on market mechanisms (Dubbink, 2003).

Quality assurance mechanisms maintain user confidence in forecast services and enable continuous improvement. Regular verification of forecast accuracy, transparent communication of forecast skill and uncertainty, and responsive feedback systems build trust between forecast providers and users. Independent evaluation of forecast quality prevents complacency and identifies opportunities for methodological improvements. Institutional structures that separate forecast production from verification reduce conflicts of interest and enhance credibility.

Equity considerations should guide forecast service design to ensure that benefits extend to vulnerable populations. Targeted outreach to smallholder farmers, particularly women and marginalized groups, helps address disparities in forecast access and utilization capacity. Subsidization of forecast services for low-income users prevents exclusion based on inability to pay. Language accessibility and cultural appropriateness of forecast communication materials expand the reach of climate information services across diverse populations.

Coordination mechanisms among farmers may enhance forecast value by addressing collective action problems (Holahan and Lubell, 2016). When farmers share common forecasts and face risks of oversupply coordination failures, institutions that facilitate communication and joint planning can improve outcomes. Farmer cooperatives, producer associations, and contract farming arrangements offer potential platforms for such coordination. However, competition policy must ensure that coordination mechanisms do not enable anti-competitive behavior or market manipulation.

Network effects in forecast utilization suggest that broader adoption enhances individual value. As more farmers gain capacity to utilize forecasts effectively, input suppliers, extension services, and other agricultural service providers adapt their operations to forecast-informed decision-making. This creates a virtuous cycle where expanding forecast use justifies investments in complementary services that further enhance forecast value. Policy interventions should aim to accelerate achievement of critical mass in forecast adoption, drawing on insights from cooperative game theory applied to networks (Gilles, 2010).

6 Conclusion

This paper has examined the economic value of climate forecast precision in agricultural contexts, developing a theoretical framework to analyze how forecast accuracy influences investment decisions, resource allocation, and market outcomes. The analysis reveals that improved forecast precision generates substantial economic benefits through multiple channels, including enhanced productivity, risk reduction, and more efficient resource allocation. However, the realization of these benefits depends critically on farmers' capacity to access and utilize forecast information effectively.

The heterogeneous distribution of forecast value across farm types and regions raises important equity concerns. Large commercial operations with sophisticated information systems and flexible production capabilities can extract greater benefits from precise forecasts than smallholder farmers facing capital constraints and limited technical capacity. This pattern suggests that forecast improvements alone may exacerbate agricultural inequalities without complementary interventions to enhance smallholder adaptive capacity, consistent with findings on sectoral efficiency in development contexts (**?**).

Market failures arising from the public-good characteristics of climate forecasts provide strong economic justification for public investment in forecast infrastructure. Private provision tends to generate suboptimal levels of forecast accuracy and accessibility due to inability to capture full social benefits. National meteorological services play essential roles in maintaining observational networks and producing basic forecast products, functioning as productive public capital that generates positive externalities (?). Private sector participation in value-added services can enhance innovation and user responsiveness while preserving public access to foundational information.

The coordination problems identified in our analysis highlight the importance of considering general equilibrium effects when evaluating forecast benefits. When farmers share common information sources and respond similarly to forecast signals, coordinated supply responses can amplify price volatility and potentially reduce individual gains from forecast accuracy. Application of collective action theory (Holahan and Lubell, 2016) and cooperative game-theoretic frameworks (Gilles, 2010) offers insights into mechanisms that might mitigate such coordination failures while preserving beneficial competition.

The analysis points to several priority areas for policy development. First, public investment in forecast infrastructure should be accompanied by complementary programs that enhance farmer capacity to utilize forecast information, including extension services, credit access, and input market development. The importance of such complementary investments receives support from studies demonstrating that human capital accumulation drives long-term productivity gains (?). Second, forecast dissemination systems should be designed with explicit attention to equity considerations, ensuring that vulnerable populations including smallholder farmers receive appropriate support for forecast interpretation and response.

Third, institutional arrangements for forecast provision should balance public and private sector roles, with public agencies maintaining core infrastructure while enabling private sector innovation in service delivery. This approach aligns with economic theory emphasizing the importance of well-designed market mechanisms and incentive structures (Dubbink, 2003). Fourth, international cooperation in forecast development and dissemination deserves support, given the transnational character of climate systems and the positive externalities from shared observational networks (Juma et al., 2001).

The findings also suggest that forecast service design should evolve as user needs and capacities change over time. Learning effects and technological advances in forecast delivery create opportunities for increasingly sophisticated forecast products tailored to specific decision contexts. However, basic forecast information should remain freely available to ensure that vulnerable populations can access essential climate information regardless of ability to pay. The challenge of ensuring equitable technology access in development contexts (Raja and Christiaensen, 2017) applies equally to climate information services.

Climate change increases the urgency of improving forecast capabilities while simultaneously posing challenges to forecast skill as historical climate patterns shift. Investment in forecast infrastructure should account for these changing conditions, with attention to maintaining forecast accuracy as climate dynamics evolve. Research on forecast skill under non-stationary climate conditions will become increasingly important for guiding long-term investment in climate services.

The institutional frameworks for forecast provision require ongoing adaptation to technological advances and changing user needs. Successful climate information systems combine sustained public investment in core infrastructure with mechanisms for innovation and user engagement. Quality assurance processes maintain credibility and drive continuous improvement. Equity considerations ensure that benefits extend to vulnerable populations rather than accruing primarily to well-resourced commercial operations.

In conclusion, climate forecast precision represents a valuable public good with substantial potential to enhance agricultural productivity, reduce risk, and improve resource allocation. Realizing this potential requires coordinated investments in forecast infrastructure, dissemination systems, farmer capacity building, and complementary agricultural services. Policy frameworks should ensure equitable access to forecast information while fostering innovation in service delivery and customization. The economic analysis developed in this paper provides a foundation for evaluating forecast investments and designing institutional arrangements that maximize social welfare. As climate variability intensifies with global warming, the economic value of accurate climate forecasts will continue to grow, underscoring the importance of sustained commitment to improving forecast capabilities and expanding their benefits across diverse farming populations. Drawing on insights from sustainable development economics (Zilberman et al., 2018), forecast services should be integrated into broader strategies for agricultural adaptation and resilience building in the face of climate change.

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