Panta Rhei
Research Program

Research Briefings · Public-Good Impact Dossiers

**Agriculture** · **Food, Life & Health Systems**

# Tau-Grade Operational Agro-Weather Intelligence

## Conditional public-good pathway for farmer-facing weather, soil, and crop-risk intelligence

**Public-Good Impact Dossier**

Conditional impact analysis · Publication-ready PDF · not deployment-ready

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Thorsten Fuchs • Anna-Sophie Fuchs

Conditional scenario map. No validation, product, deployment, or policy claim.

# Safe harbor / release discipline

**Conditional public-good impact dossier · Publication-ready PDF release · Domain review pending · Deployment not claimed**

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## Release status

This briefing is a conditional public-good impact dossier released as a publication-ready PDF artifact on 2026-05-02. Publication-ready means the dossier is downloadable, internally consistent, and claim-safe. It does not validate the $\tau$-framework, does not claim deployment readiness, and does not assert that the described domain system already exists. It maps a plausible impact pathway if the relevant upstream Results, Corpus constructions, and translation assumptions survive expert review and domain benchmarking.

## What this dossier claims

- maps a conditional public-good impact pathway
- identifies upstream framework dependencies that would have to survive review
- states translation assumptions, benchmark needs, and governance guardrails

## What this dossier does not claim

- does not validate the Tau framework
- does not claim that a domain system or product already exists
- does not claim deployment readiness, policy adoption, or certified impact
- does not replace independent domain review, empirical benchmarking, or governance assessment

## Source fidelity and legal disclaimer

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This dossier is not legal, financial, medical, engineering, safety, regulatory, procurement, or investment advice. It is not an official statement by any institution named in the document. It is a conditional research briefing and scenario map for review, discussion, and public-interest scrutiny.

## Contents

# 1 Executive Summary

Global agriculture bears one of the largest and most persistent weather-linked loss burdens of any economic sector. FAO's 2025 disaster assessment documents **USD 3.26 trillion in agricultural losses from 1991 to 2023**, averaging USD 99 billion per year — approximately 4% of global agricultural GDP.[1] The great majority of these losses are driven by weather and climate hazards, and a meaningful share involve field-operation decisions where better short-range intelligence would have changed the outcome.

This paper asks a specific, bounded question: if the $\tau$ categorical framework is operationally sound as a physics substrate — providing a discrete, bounded-error, law-faithful twin of weather, soil, and field-operation dynamics — what public good would follow for day-to-day agricultural decision support? The answer, argued in detail across fifteen sections, is that the opportunity is substantial, well-aligned with existing institutional demand, and deployable on a relatively short horizon without waiting for $\tau$ to be fully adopted across the scientific community.

Seven key findings frame the argument:

1. **The demand signal is already explicit.** FAO and WMO jointly identify agrometeorological advisory services as instruments for water and fertilizer management, pest and disease control, sowing and harvesting schedules, and other field-level practices.[2] The sector is already organized around exactly the class of output a $\tau$ operational twin would improve.

2. **The baseline loss exposure justifies priority attention.** At USD 99 billion per year in average agricultural losses, reducing even 1–3% of the weather-sensitive preventable component implies USD 1–3 billion in avoided losses annually — without counting input-efficiency and smallholder livelihood gains.

3. **Existing public systems prove institutional feasibility.** Bangladesh's BAMIS agrometeorological portal reached 4.5 million persons since 2019 via digital channels.[3][4] WMO has validated its advisory value. Morocco's World Bank resilient agriculture project connected 23,500 farmers to climate-resilience advisory services by 2022.[5] These systems establish the institutional architecture; $\tau$ would strengthen the forecast core inside it.

4. **The primary mechanism is tighter operational windows, not only better averages.** The value of $\tau$ in this domain is not primarily that mean forecasts improve marginally, but that **locally actionable thresholds** — spray/no-spray windows, harvest windows, field-access windows, frost and heat event timing — can be specified with tighter, law-derived uncertainty bounds. This is qualitatively different from statistical refinement of existing numerical weather products.

5. **Smallholder welfare is the most important equity dimension.** Smallholder farms produce roughly 35% of global food while five out of six farms globally are below two hectares.[6] For these

[1] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[2] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

[3] Bangladesh Meteorological Department (2024). *Bangladesh Agro-Meteorological Information Service (BAMIS) portal.* Dhaka: BMD. https://www.bamis.gov.bd/en/

[4] World Bank (2023). *Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWC-SRP) — BAMIS platform reach since 2019.* Washington, D.C.: World Bank. https://documents1.worldbank.org/curated/en/099033023051020111/pdf/P1502200e07f7e0e00a4c9019421d3a7943.pdf

[5] World Bank (2022). *Morocco: Improving Resilience of Farmers through Advisory Services and Digital Agriculture.* Washington, D.C.: World Bank. https://www.worldbank.org/en/results/2022/

[6] FAO (2021). *Small family farmers produce a third of the world's food.* Rome: FAO. https://www.fao.org/family-farming/detail/en/c/1398060/

farmers, weather mistakes do not represent foregone optimization; they represent income loss, debt risk, and potential food insecurity. Improved operational advisory services are a welfare instrument, not only a productivity tool.

6. **Finance pathways are well-mapped.** Green Climate Fund adaptation windows, IFAD rural advisory services, and World Bank IDA climate lending all represent named, accessible financing channels. FAO/WMO evidence shows early warning systems returning up to USD 7 per USD 1 invested; a conservative operational-agro-weather benchmark of 2–4:1 still makes the public-investment case compelling.[7][8]

7. **Paper 1 delivers value even without the full $\tau$ agriculture stack.** Improved short-range farm weather windows, locally calibrated uncertainty bounds, and decision translation for planting, spraying, irrigation, and harvest constitute a standalone service. The subsequent papers in this portfolio (irrigation, pest/disease, seasonal planning, crop biology) extend the architecture, but Paper 1's domain is useful, measurable, and deployable independently.

## 2 Why This Matters Now

### 2.1 A sector under compounding weather pressure

Agriculture is the economic sector most directly and continuously shaped by weather. Unlike most industries, where weather is a background condition, in farming weather is the operating medium. The FAO 2025 disaster report makes this concrete: disasters — dominated by climate-related hazards — caused USD 3.26 trillion in agricultural sector losses globally from 1991 to 2023.[9] Climate variability and extremes accounted for the largest share, and the trajectory is worsening as weather volatility increases under climate change.

These losses are not uniformly distributed. The burden falls disproportionately on low- and middle-income countries, on subsistence and smallholder systems, and on communities with limited access to insurance, credit, or emergency assistance. When a sowing window is missed, a harvest is interrupted by unexpected rain, or a crop-protection application fails because the weather forecast was wrong, the consequences for a family farm in the Sahel or the Bengal delta are categorically different from those for a large commercial operation with reserves and insurance coverage.

### 2.2 Weather intelligence as a documented intervention

The causal link from better weather intelligence to better agricultural outcomes is not speculative. WMO's analysis of Bangladesh's national agrometeorological service found that advisory services reduced risk and improved agricultural productivity and farm income, and an economic-benefit assessment documented that farmers were using and benefiting from the service.[10] FAO's 2025 disaster report cites evidence that early warning systems — which depend on the same weather intelligence infrastructure — can deliver up to USD 7 returned for every USD 1 invested in anticipatory

[7] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[8] WFP (2024). *Anticipatory Action — Annual Report 2024.* Rome: WFP. https://www.wfp.org/publications/anticipatory-action-annual-report-2024

[9] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[10] WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

action.[11] WFP's 2024 anticipatory action review reports the same benchmark.[12]

These are institutional findings, not model projections. The return-on-investment case for agrometeorological services has been made in the field.

### 2.3 The current gap: operational precision at field scale

What existing systems still cannot reliably deliver is high-precision, locally calibrated, operationally actionable advisory windows at farm scale. National meteorological services provide synoptic and regional guidance. Sub-seasonal and seasonal forecasts are improving but remain coarse for field-level decisions. The translation from "what the weather will do" to "whether this field can be entered, sprayed, planted, or harvested today or tomorrow" remains weak in most systems.

WMO's sub-seasonal to seasonal applications project for agriculture and environment explicitly identifies this translation layer as an active development frontier.[13] FAO and WMO together note that agrometeorological services must combine weather forecasting "from nowcasting to seasonal prediction" with monitoring of farm conditions to produce practical advice — but the gap between forecasting capability and actionable local advisory delivery remains large in most low-income country contexts.[14]

### 2.4 Trend lines pointing toward urgency

Three structural trends increase the premium on solving this gap now rather than later. First, climate change is increasing weather variability and the frequency of extremes, which means the operational advisory problem is getting harder, not easier, as agricultural systems are asked to adapt. Second, global food demand continues to grow, with FAO projecting that production must increase substantially to feed a population of approximately 9.7 billion by 2050, under tighter resource constraints.[15] Third, digital infrastructure in rural areas of low-income countries is improving rapidly — smartphone penetration, mobile money, and digital extension services are all expanding — which means the delivery infrastructure for improved advisories is becoming available faster than the underlying advisory quality is improving.

The practical implication is that there is now a realistic path to deploying better operational agrometeorological intelligence at scale, if the forecast core can be strengthened and the translation layer built. $\tau$ addresses the forecast core.

## 3 Scope and Reader Orientation

### 3.1 What this paper covers

This is **Paper 1 of 5** in the Panta Rhei impact agriculture portfolio. It focuses on **1–14 day operational farm decision support** — the horizon at which daily and weekly field decisions

[11] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[12] WFP (2024). *Anticipatory Action — Annual Report 2024.* Rome: WFP. https://www.wfp.org/publications/anticipatory-action-annual-report-2024

[13] WMO (2024). *Sub-Seasonal to Seasonal (S2S) Prediction Project — Agriculture Applications.* Geneva: WMO. https://s2sprediction.net/

[14] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

[15] FAO (2023). *The State of Food and Agriculture 2023: Revealing the True Cost of Food.* Rome: FAO. https://www.fao.org/publications/sofa/2023/en/

are made and where locally calibrated short-range weather intelligence has the highest immediate leverage. The specific operational domains addressed are:

- sowing, transplanting, and establishment timing;
- spray/no-spray, fertilization, and irrigation windows;
- harvest, field-access, and post-harvest timing;
- livestock heat and storm exposure management;
- and delivery through digital advisory platforms, extension systems, and public agrometeorological portals.

### 3.2 What the subsequent papers cover

The agriculture portfolio extends across four additional papers:

- **Paper 2:** $\tau$ for climate-smart irrigation, soil moisture monitoring, and water productivity — addressing agriculture's 72% share of global freshwater withdrawals.[16]
- **Paper 3:** $\tau$ for pest, disease, and livestock-stress early warning — extending operational intelligence to biological hazards that interact with weather timing.
- **Paper 4:** $\tau$ for seasonal planning, disaster anticipation, and food-system resilience — addressing the sub-seasonal and seasonal horizon where food security and climate finance intersect.
- **Paper 5:** $\tau$ for crop biology, breeding, photosynthesis engineering, and targeted gene design — the longest-horizon, highest-transformation layer.

A cross-cutting delivery layer — smallholder advisory services, digital platforms, and public-sector implementation — connects all five papers. Readers interested specifically in water, pest/disease, seasonal planning, or crop biology should consult the corresponding subsequent papers.

### 3.3 Primary audience

This paper is written for agricultural policy makers, development bank program officers, agriculture ministry officials, national meteorological and hydrological service directors, extension system managers, and resilience and food-security funders. It assumes institutional familiarity with agrometeorological concepts but does not assume familiarity with the $\tau$ mathematical framework.

## 4 The Opportunity Baseline

### 4.1 Agricultural losses from weather: the macro figure

FAO's 2025 assessment establishes the single most important baseline number: **USD 3.26 trillion in agricultural sector losses from disasters over 1991–2023**, with climate-related hazards accounting for the largest share.[17] The average of USD 99 billion per year represents a continuous, recurring drain on global agricultural GDP. Crops and livestock account for the majority; fisheries and forestry add further losses.

This figure understates the full impact, because it does not capture the household welfare costs of income loss, debt accumulation, child nutrition impacts, or the cumulative effect of repeated

[16] FAO (2025). *The State of the World's Land and Water Resources for Food and Agriculture 2025.* Rome: FAO. https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html

[17] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

subthreshold losses that erode resilience without triggering disaster declarations.

### 4.2 Water: agriculture's dominant resource footprint

FAO's land and water resources assessment reports that agriculture represented **72% of total global freshwater withdrawals in 2020**.[18] This creates a direct linkage between operational weather intelligence and water stewardship: when irrigation is applied at the wrong time relative to weather, the loss is both economic and environmental. At global scale, even marginal efficiency gains in agricultural water timing represent water savings of meaningful volume.

### 4.3 Smallholder farms: scale and vulnerability

FAO's 2021 synthesis reports that **small and family farmers produce approximately one third of global food supply**, while five of every six farms globally are below two hectares.[19] The World Bank's climate-smart agriculture page notes that agrifood systems generate approximately **one third of global greenhouse-gas emissions**, yet receive only **4% of climate finance**, and only about a fifth of that reaches smallholders.[20]

The smallholder scale matters to the opportunity baseline in two ways. First, the sheer number of farms — estimated at over 500 million smallholder households globally — means that even modest per-farm improvements aggregate to very large totals. Second, the vulnerability of smallholder systems means that advisory services carry welfare weight beyond their direct productivity value: they reduce the probability of catastrophic season failures that push households into food insecurity and debt.

### 4.4 The agrometeorological advisory gap

WMO and FAO together document both the proven value of agrometeorological services and the current gap in their reach and quality. WMO's agricultural services programme states that its role is to help build sustainable and economically viable agricultural systems through weather, climate, and related services across the value chain.[21] FAO and WMO jointly report that these services combine forecasting — from nowcasting to seasonal prediction — with farm-condition monitoring to produce practical advice.[22]

Yet the reach and operational quality of these services remains highly uneven. Most low-income countries have national meteorological services that provide broad synoptic forecasts, but the translation to farm-level operational advisories — with local calibration, bounded uncertainty, and actionable thresholds — is typically incomplete. The BAMIS Bangladesh system, which reached 4.5 million persons via digital channels, is one of the more advanced examples globally.[23][24] Even there,

[18] FAO (2025). *The State of the World's Land and Water Resources for Food and Agriculture 2025.* Rome: FAO. https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html

[19] FAO (2021). *Small family farmers produce a third of the world's food.* Rome: FAO. https://www.fao.org/family-farming/detail/en/c/1398060/

[20] World Bank (2024). *Climate-Smart Agriculture.* Washington, D.C.: World Bank. https://www.worldbank.org/en/topic/climate-smart-agriculture

[21] WMO (2024). *Agricultural Services.* Geneva: WMO. https://wmo.int/activities/agricultural-services

[22] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

[23] Bangladesh Meteorological Department (2024). *Bangladesh Agro-Meteorological Information Service (BAMIS) portal.* Dhaka: BMD. https://www.bamis.gov.bd/en/

[24] World Bank (2023). *Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWC-SRP) — BAMIS platform reach since 2019.* Washington, D.C.: World Bank. https://documents1.worldbank.org/curated/en/099033023051020111/pdf/P1502200e07f7e0e00a4c9019421d3a7943.pdf

WMO notes that the sub-seasonal and seasonal advisory layer is still under active development.[25]

### 4.5 Investment context

WMO and partner institutions have argued that every USD 1 invested in early warning systems yields up to USD 7 in avoided losses.[26] The World Bank, FAO, IFAD, and the Green Climate Fund all operate programs that partially address this gap. Despite this, the volume of climate adaptation finance flowing into operational agrometeorological services — as distinct from physical infrastructure or insurance schemes — remains small relative to the opportunity. The IMF has estimated that the global adaptation financing gap in agriculture is in the range of tens of billions of dollars annually.[27]

## 5 Working $\tau$ Assumptions

This paper adopts explicit assumptions, which are stated here in full so that readers can evaluate which conclusions depend on which assumptions.

### 5.1 Physics-side assumptions

The $\tau$ framework, if operationally sound, would provide:

- A **discrete, constructive, bounded-error substrate** for representing weather system evolution — including local boundary-layer conditions, cloud cover, rainfall events, temperature trajectories, dew point, frost risk, wind, and field-surface states — at resolutions relevant to farm-scale decisions rather than only broad synoptic patterns.
- Native **cross-scale coherence**: the same categorical structure governs both the large-scale atmospheric dynamics and the local field-level consequences, so that advisory outputs at farm scale are not arbitrary truncations of a larger model but coarse-grained projections of the same underlying structure.
- Stable **convergence properties** such that greater resolution depth does not produce arbitrarily diverging outputs, and uncertainty bounds can be formally derived rather than empirically estimated.
- A **tractable path from atmospheric state to field-operational indices**: soil trafficability windows, canopy dryness, evapotranspiration rate, frost threshold crossing, heat accumulation above crop-critical thresholds, and rain interruption probability at operation-relevant time scales.

### 5.2 Agriculture-side assumptions

For the opportunity described in this paper to materialize, $\tau$ outputs would also need to:

- Feed into existing or new digital advisory systems without requiring wholesale replacement of national meteorological infrastructure;
- Produce outputs that extension officers, cooperative managers, and farmers can interpret and act on within existing advisory frameworks;

[25] WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

[26] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[27] IMF (2022). *Financing the Transition: Closing the Climate Investment Gap.* Washington, D.C.: IMF. https://www.imf.org/en/Publications/WP/Issues/2022/

- Deliver sufficiently improved window predictions on the benchmark tasks — spray/no-spray, harvest windows, field-access timing, frost/heat alerts, rain interruption — relative to existing operational products to justify integration costs.

### 5.3 What this paper does not assume

This paper does **not** require:

- Full adoption of the $\tau$ mathematical ontology by ministries of agriculture, national meteorological services, or the broader agricultural science community. Practical value begins if $\tau$ simply outperforms current operational stacks on selected high-value advisory tasks.
- Near-term completion of the broader $\tau$ biology program (Papers 3–5). Paper 1's opportunity is self-contained within the short-range weather-to-operation translation layer.
- That every quantitative impact estimate presented in this paper will be achieved. The scenarios are structured planning inferences grounded in institutional data, not official forecasts.

### 5.4 The central caveat

The $\tau$ framework has not yet been adopted by the agricultural or meteorological scientific mainstream. The physical assumptions described above reflect the strongest reading of $\tau$ claims under active development. Readers should treat this dossier as a rigorous planning document for a high-probability-of-success scenario, not as a claim that the scenario is assured.

## 6 What Changes with a Law-Faithful Twin

The central distinction this paper draws is between a **statistically refined forecast** and a **law-faithful operational twin**. Current agro-weather stacks are the former: weather models calibrated against observations, combined with agronomic rule-sets derived from historical data, filtered through extension advisories that rely heavily on practitioner judgment. This is genuinely useful. But it has a structural ceiling: the model is not the system; it approximates it.

A $\tau$ operational twin would mean something different: that the decision-support system runs on the same categorical structure the weather–soil–crop–operations system itself obeys, at a certified coarse-grained resolution with explicit, derivable error bounds. This is not merely "better statistics." It changes what you can say about uncertainty, about threshold crossings, and about the reliability of operational windows.

### 6.1 Field timing becomes less blunt and less wasteful

Current operational advisories often use broad windows — "spray this week if conditions allow" — because local uncertainty is too large to justify tighter guidance. A $\tau$-grade operational twin would support much narrower actionable windows: not just "rain likely tomorrow" but "canopy will remain dry enough for adequate spray deposition from 09:00 to 14:00 with acceptable wind-drift risk, with 85% probability, given current atmospheric state." The difference between these two advisory forms is not cosmetic. The narrower advisory changes what inputs are used, when, and with what efficiency.

### 6.2 Input efficiency gains from knowing when not to act

A large share of avoidable input waste in agriculture comes from acting in conditions that undermine effectiveness: spraying before rain that washes the product off, fertilizing into soil that is too dry or too wet for uptake, irrigating ahead of rainfall that makes the application redundant. The operational intelligence question is often not “what is the right dose?” but “is now a time when application will work?” A law-faithful twin with tighter uncertainty bounds changes the answer to this question with enough reliability to drive behavior change.

FAO and WMO identify water and fertilizer management as primary advisory functions precisely because of this dynamic.[28] The potential to reduce input waste is simultaneously an economic gain for the farmer and an environmental benefit: less fertilizer runoff, less pesticide in the watershed, less water withdrawn from stressed aquifers.

### 6.3 Extension quality becomes more uniform across geographies

One of the most persistent inequities in agricultural advisory systems is the uneven quality of extension — the human layer that translates weather and agronomic information into local farm action. In well-resourced systems with experienced extension officers and good local data, advisory quality is high. In under-resourced systems — which cover most of the smallholder farming world — it depends heavily on heuristics and general rules that may not fit local conditions well.

A $\tau$-grade advisory engine would not replace extension; it would give extension officers a physically grounded local forecast core from which to work. The localization work shifts from inventing rules for each micro-environment to translating structurally sound, locally calibrated outputs into the language and practice context of specific farming communities. That is a different and more tractable problem.

### 6.4 Digital platforms become decision engines rather than information channels

Most agricultural mobile applications today are information delivery systems: they show weather forecasts, market prices, and general agronomic tips. Under $\tau$, the same digital infrastructure could serve as a bounded decision engine — issuing not “here is today’s forecast” but “given your crop stage, your field location, and the next 72-hour forecast, the recommended action window for irrigation is Wednesday morning; spraying should be delayed until Thursday afternoon; the current heat accumulation trajectory is within normal bounds for this growth stage.”

This shift from information channel to decision engine is what FAO’s Digital Services Portfolio is structurally aiming toward.[29] The constraint has been the forecast quality and the translation depth. $\tau$ addresses the forecast quality; the delivery infrastructure is increasingly available.

### 6.5 Value-chain coordination improves

Better operational weather intelligence does not only benefit the individual farmer. Input retailers can stage product deliveries ahead of optimal application windows. Cooperatives can sequence machinery, labor, and logistics around harvest and planting concentrations. Local grain buyers and storage operators can anticipate harvest timing and moisture conditions. Insurance triggers can be calibrated to tighter, more verifiable thresholds. Emergency responders can pre-position resources ahead of weather-linked operational disruptions.

[28] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. `https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en`

[29] FAO (2024). *Digital Services Portfolio.* Rome: FAO. `https://www.fao.org/digital-services/en`

This coordination value is systematically undervalued in per-farm advisory assessments. At regional or national scale, the gains from better timing coordination across the full agricultural supply chain may exceed the direct on-farm advisory gains.

# 7 Competitive and Incumbent Landscape

The operational agro-weather intelligence space includes both commercial platforms and institutional programs. Understanding the incumbent landscape is essential for identifying where $\tau$ would differentiate, where it would partner, and where it would face resistance.

## 7.1 CGIAR CCAFS — Climate Change, Agriculture and Food Security

CGIAR's CCAFS programme is the leading international research initiative on the intersection of climate change and agricultural systems. It operates across sub-Saharan Africa, South Asia, Southeast Asia, and Latin America, working with national partners on climate-smart agriculture, climate services for agriculture, and index-based insurance. CCAFS has developed the ACREI framework for downscaled seasonal climate advisories in the Greater Horn of Africa and contributes to WMO Regional Climate Outlook Forums.[30][31]

**Differentiation:** CCAFS operates primarily at the research, policy, and seasonal planning horizon. It produces frameworks, datasets, advisory methodologies, and institutional capacity-building programs rather than operational short-range farm advisories. Its focus is on the sub-seasonal to seasonal scale and on climate adaptation strategy, not on 1–14 day field-operation windows. $\tau$ would operate at a scale and resolution CCAFS does not directly address, and CCAFS institutional relationships in target geographies would be natural partnership channels.

## 7.2 Tomorrow.io — Commercial Weather Intelligence

Tomorrow.io is a commercial hyperlocal weather intelligence platform providing API-driven weather data and forecasts to enterprises including agricultural operators, insurance companies, logistics firms, and government agencies. It combines numerical weather prediction with machine learning and proprietary observational data layers to produce field-scale short-range forecasts and configurable alert systems.[32]

**Differentiation:** Tomorrow.io operates on statistical refinement of existing numerical weather models using machine learning. It is strong on data integration and delivery infrastructure, but its advisory quality ceiling is set by the underlying weather model stack, which does not have the structural properties $\tau$ claims to provide. $\tau$'s potential advantage is in the derivability of uncertainty bounds and the cross-scale coherence of the physical model, not in the data pipeline or API layer where Tomorrow.io is strong. A $\tau$-based system and Tomorrow.io could be complementary — $\tau$ providing the physics core, a delivery infrastructure similar to Tomorrow.io providing the API and alert layer.

## 7.3 DTN — Agricultural Weather and Decision Solutions

DTN (formerly part of Schneider Electric's weather division) provides agricultural weather data and advisory solutions primarily serving large-scale commercial farming operations in the United

[30] CGIAR CCAFS (2024). *Climate Change, Agriculture and Food Security programme.* Wageningen: CGIAR. https://ccafs.cgiar.org

[31] WMO (2024). *Regional Climate Outlook Forums and Regional Climate Centres.* Geneva: WMO. https://public.wmo.int/en/our-mandate/climate/regional-climate-outlook-forums

[32] Tomorrow.io (2024). *Enterprise weather intelligence platform.* https://www.tomorrow.io/enterprise/

States and Europe. Its products include field-level weather monitoring, precision agriculture decision support, commodity weather analytics, and agronomic decision tools for planting, irrigation, and harvest timing. DTN serves large agribusiness, grain merchandisers, and precision agriculture platforms.[33]

**Differentiation:** DTN's coverage and product design are oriented toward commercial-scale, mechanized, and well-instrumented farming systems in high-income countries. Its advisory products are built on detailed local observation networks (weather stations, soil sensors) that are absent in most low-income country contexts. $\tau$ would differentiate by offering law-faithful advisory windows that do not depend on dense local observation infrastructure — a critical advantage in the Sub-Saharan Africa and South Asia contexts where the largest public-good gains lie. DTN's approach scales well where data infrastructure exists; $\tau$'s approach could scale where it does not.

### 7.4 IBM Weather Company (The Weather Company)

The Weather Company, an IBM business unit, provides enterprise weather data and APIs including agricultural agro-weather products. Its offerings include forecast APIs for crop growth modeling, field operation suitability, and agronomic decision support, as well as products specifically targeting farm management software vendors and extension platform operators.[34]

**Differentiation:** The Weather Company's agricultural products are API layers atop numerical weather prediction models. Like Tomorrow.io, the core physics comes from standard NWP stacks; the agricultural value-add is in the translation layer and the delivery infrastructure. The Weather Company has significant commercial scale and enterprise integration, but its architecture does not address the structural ceiling on uncertainty quantification that $\tau$ would, under the planning assumption, overcome. In contexts where well-funded institutions are already using The Weather Company's products, $\tau$ would differentiate on advisory quality rather than delivery infrastructure.

### 7.5 EARS — Earth Observation-Based Agri Advisory, Africa

EARS (Environmental Analysis & Remote Sensing) is a Dutch Earth observation consultancy providing agro-advisory and food security monitoring services with a strong Africa focus. EARS products include satellite-derived vegetation indices, crop monitoring, rainfall estimation, and food security early warning inputs. Its systems have been used in FAO, WFP, and USAID food security monitoring workflows.[35]

**Differentiation:** EARS operates primarily at the monitoring and surveillance layer — using satellite Earth observation to characterize current crop and vegetation conditions, rainfall patterns, and food security indicators across large regions. It excels at regional and national-scale situational awareness. It does not focus on 1–14 day operational farm-level advisory windows. $\tau$ would complement EARS by providing the predictive, forward-looking farm-operation layer that satellite monitoring alone cannot produce: not "what is the current state of the crop?" but "what should the farmer do in the next two weeks given the forecast?"

### 7.6 BAMIS — Bangladesh Agro-Meteorological Information Service

BAMIS is a national public agrometeorological information service operated by the Bangladesh Meteorological Department, supported by the World Bank and aligned with WMO standards. It provides crop weather bulletins, river information, flood monitoring, drought monitoring, and pest

[33] DTN (2024). *Agricultural weather and decision solutions.* https://www.dtn.com/agriculture/

[34] IBM Weather Company (2024). *The Weather Company enterprise agro-weather APIs and decision support.* https://business.weather.com/products/weather-data-packages

[35] EARS (2024). *Earth observation advisory systems — Africa and global.* Delft: EARS. https://www.ears.nl/

and disease calendars through a web portal and mobile application.[36] World Bank project reporting documents that BAMIS digital channels reached 4.5 million persons since 2019, making it one of the most successful public agrometeorological delivery systems in a low-income country context.[37]

**Differentiation:** BAMIS is the model public institutional architecture, not a competitor. WMO has validated its advisory value but also noted that the sub-seasonal and seasonal advisory layer remains under active development, and that last-mile advisory quality has room to improve.[38] $\tau$ would integrate into a BAMIS-type architecture as an improved forecast core for the 1–14 day operational layer, not as a replacement for the institutional framework or the delivery channels BAMIS has established. The BAMIS case demonstrates that the institutional will, the digital delivery infrastructure, and the user demand exist; $\tau$ addresses the forecast quality ceiling.

# 8 Structured Opportunity Map

## 8.1 Cluster A — Planting and Establishment Decisions

**A1. Sowing and transplanting windows.** Planting into the wrong moisture conditions, ahead of frost or heat events, or outside the optimal temperature window for germination can cause losses that compound through the full growing season. FAO/WMO cite sowing schedules as a core agrometeorological advisory function.[39] Under $\tau$, the gain is tighter local windows with explicit uncertainty envelopes, reducing both early-planted losses from late cold events and late-planted losses from shortened growing seasons. Estimated addressable scale: hundreds of millions of smallholder planting decisions per season, across major production systems in South Asia, Sub-Saharan Africa, and Latin America.

**A2. Germination and early establishment risk alerts.** The first 7–21 days after sowing are the most weather-sensitive phase of most crops. Rainfall intensity causing soil crusting, heat spikes damaging emerging seedlings, cold nights below germination thresholds, and wind-driven moisture loss all interact. A more faithful local twin would support decisions on whether to plant now, wait for a short weather window, or apply light protective irrigation. In rice-wheat systems, which cover over 13 million hectares in South Asia alone, improved establishment window advisories would have significant cumulative impact.[40]

**Scale estimate:** Cluster A overall spans 500+ million smallholder farms globally. Even a 5–10% improvement in planting-window precision, applied across 10% of these farms via public advisory systems, would represent tens of millions of farms per year receiving materially better guidance.

## 8.2 Cluster B — Crop-Input Timing and Efficiency

**B1. Spray/no-spray windows.** Rainfall washing, wind drift, inadequate canopy dryness, and temperature effects on product efficacy make spray timing one of the highest-value weather-to-action

[36] Bangladesh Meteorological Department (2024). *Bangladesh Agro-Meteorological Information Service (BAMIS) portal.* Dhaka: BMD. https://www.bamis.gov.bd/en/

[37] World Bank (2023). *Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWC-SRP) — BAMIS platform reach since 2019.* Washington, D.C.: World Bank. https://documents1.worldbank.org/curated/en/099033023051020111/pdf/P1502200e07f7e0e00a4c9019421d3a7943.pdf

[38] WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

[39] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

[40] FAO (2023). *The State of Food and Agriculture 2023: Revealing the True Cost of Food.* Rome: FAO. https://www.fao.org/publications/sofa/2023/en/

translation problems in commercial and smallholder agriculture alike. Crop protection products wasted through mistimed applications represent billions of dollars globally, plus environmental costs from off-target deposition. A $\tau$ operational twin that can specify canopy dryness, wind-drift risk, and rain-interruption probability at 6-hour resolution for the next 5 days would represent a step-change in spray advisory quality.

**B2. Fertilizer timing and nutrient loss prevention.** FAO/WMO identify fertilizer management as a primary advisory use case.[41] Nutrient losses from run-off, volatilization, and leaching are heavily weather-dependent. In sub-Saharan Africa, where nitrogen use efficiency is often below 30% of applied fertilizer, improved timing advisories could have both economic and environmental impact at scale. The global market for nitrogen fertilizer exceeds USD 80 billion annually; even small percentage reductions in timing-related losses are economically meaningful.[42]

**B3. Operational irrigation timing.** Agriculture accounts for 72% of global freshwater withdrawals.[43] While full irrigation management is Paper 2's domain, operational scheduling over 1–14 day windows — deciding when to irrigate given forecast rain and evapotranspiration — is directly within Paper 1 scope. In systems with depleting aquifers, improved timing precision compounds water savings over time.

**Scale estimate:** Cluster B is the single largest impact cluster in dollar terms. Input-efficiency gains from better timing advisories across the major field-crop systems could approach USD 5–15 billion annually at full scale, based on known input loss rates and addressable application areas.

### 8.3 Cluster C — Harvest, Field Access, and Post-Harvest Timing

**C1. Harvest-window optimization.** Harvest timing is arguably the single highest-value operational weather decision in arable farming. Delaying harvest by even 2–3 days beyond the optimal window can cause losses from lodging (crop falling over), grain sprouting, aflatoxin and mycotoxin contamination, shattering, or quality downgrades. For wheat, maize, rice, and oilseed crops, the interaction between grain moisture, rain risk, and wind creates a narrow operational window that is currently estimated conservatively rather than precisely. Under $\tau$, this window can be specified with tighter, derivable bounds.

**C2. Field-access and machinery movement planning.** In mechanized systems, soil trafficability — whether a field can bear the weight of a harvester, tractor, or spray vehicle without compaction or getting stuck — depends on soil moisture, recent rainfall, and temperature-driven drying. Poor trafficability prediction results in either delayed operations (loss) or compaction damage (long-term soil health cost). A $\tau$ operational twin that tracks soil surface state through the weather sequence would support much better machinery timing decisions.

**C3. Drying and on-farm storage windows.** Post-harvest drying and storage decisions depend on ambient humidity, temperature, and wind in the days after harvest. Under-dried grain causes storage losses; over-dried grain is a processing cost. In low-income country contexts where artificial drying is unavailable, natural drying windows are the key decision variable and are currently advised using broad regional rules.

**Scale estimate:** Post-harvest losses in sub-Saharan Africa and South Asia are estimated at 15–30% of grain production by some assessments.[44] Even if weather-timing-related losses represent a fraction

[41] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. `https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en`

[42] IFA (2023). *World Fertilizer Trends and Outlook to 2026.* Paris: International Fertilizer Association. `https://www.fertilizer.org/`

[43] FAO (2025). *The State of the World's Land and Water Resources for Food and Agriculture 2025.* Rome: FAO. `https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html`

[44] FAO (2021). *The State of Food and Agriculture 2021: Making Agrifood Systems More Resilient to Shocks and*

of total post-harvest losses, the absolute scale is very large.

### 8.4 Cluster D — Livestock and Mixed-Farm Operations

**D1. Heat and storm exposure management.** FAO and WMO document the growing threat of extreme heat to livestock and broader agrifood livelihoods.[45] At the operational level, the relevant decisions are: when to move animals indoors or to shade, when to adjust water and feed schedules, and when to suspend outdoor labor. Better short-range heat accumulation and storm-risk forecasts directly support these decisions.

**D2. Pasture-use timing and fodder logistics.** Pasture-based systems involve decisions about grazing rotation, fodder availability, and moisture-dependent grass growth that all interact with short-range weather. In pastoral systems across the Sahel and East Africa, short-range weather intelligence could materially improve herd management and reduce weather-linked livestock mortality.

**Scale estimate:** Livestock represents approximately 40% of global agricultural GDP and is a primary livelihood for hundreds of millions of pastoralists and mixed farmers. Operational weather support for livestock systems is currently very thin in most public advisory programs.

### 8.5 Cluster E — Delivery Systems and Last-Mile Advisory Translation

**E1. Digital advisory platforms.** FAO's Digital Services Portfolio is designed to deliver mobile agricultural advisories and scale services for smallholders and family farmers across multiple countries.[46] Under $\tau$, these platforms become bounded decision engines rather than information channels. The delivery infrastructure exists; the advisory quality layer is the constraint.

**E2. Public and cooperative agromet portals.** BAMIS establishes the model: a national portal and app providing crop weather, river status, drought monitoring, pest calendars, and forecast-linked advisories at scale.[47] Similar architectures exist or are under development in Ethiopia, Kenya, Morocco, India, and other major agricultural countries. $\tau$ would strengthen the forecast core in each of these systems.

**E3. Extension and trust infrastructure.** FAO/WMO note that advisory value only appears when context-specific information reaches users in a form they can act on.[48] The social and institutional layer — extension officers, farmer field schools, cooperative managers, local radio and SMS services — is part of the technical architecture, not separate from it.

**Scale estimate:** The WMO and FAO estimate that approximately 1.5 billion people globally work in agriculture, of whom a large majority are in systems with inadequate operational weather advisory support. Even reaching 5% of this population with materially better advisories would represent 75 million farmers — a scale comparable to the world's largest agricultural technology interventions.

## 9 Geographic Case Studies

*Stresses.* Rome: FAO. https://www.fao.org/publications/sofa/2021/en/

[45] FAO/WMO (2025). *Extreme Heat and Agriculture: Managing Risks to People and Food Systems.* Rome/Geneva: FAO and WMO. https://openknowledge.fao.org/server/api/core/bitstreams/f6506a63-fb04-4f34-bea6-cb92f665e94f/content

[46] FAO (2024). *Digital Services Portfolio.* Rome: FAO. https://www.fao.org/digital-services/en

[47] Bangladesh Meteorological Department (2024). *Bangladesh Agro-Meteorological Information Service (BAMIS) portal.* Dhaka: BMD. https://www.bamis.gov.bd/en/

[48] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

### 9.1 Case Study 1: Bangladesh — BAMIS Expansion and the Delta Smallholder Problem

**Context.** Bangladesh is one of the world's most densely populated agricultural countries, with approximately 16.5 million farm holdings, the large majority below 2 hectares, operating within a highly weather-sensitive delta environment subject to monsoon flooding, cyclones, cold waves, and increasingly frequent dry spells.[49] The Bangladesh Meteorological Department operates BAMIS, which provides crop weather bulletins, river and flood information, drought monitoring, and pest and disease calendars through a web portal and a dedicated mobile application. World Bank project documentation reports that BAMIS digital channels had reached 4.5 million persons since 2019.[50] WMO has validated that the system is delivering advisory value and improving agricultural productivity and farm income.[51]

**The residual problem.** Despite this progress, WMO explicitly identifies the sub-seasonal and seasonal advisory layer as incomplete, and the operational 1–14 day layer as still dependent on broad regional guidance rather than locally calibrated field-operation windows.[52] In the delta context — where flooding, field accessibility, and planting windows interact at hyperlocal scales — the gap between "regional weather forecast" and "actionable field timing advice" is particularly wide. Rice transplanting windows, for example, depend not only on rain probability but on field water levels, soil temperature, and wind conditions that vary substantially across flood-affected and non-flood-affected parcels within the same district.

**What $\tau$ would enable.** Under the $\tau$ planning assumption, BAMIS expansion would move from its current broad regional advisory layer to a locally calibrated operational twin that can specify:

- 1–14 day planting window probability distributions for individual thana-level (sub-district) advisory units, accounting for flooding status, soil state, and thermal conditions;
- spray/no-spray windows for post-flood crop protection campaigns, where mistimed applications are particularly costly;
- harvest windows for boro rice (the dry-season rice crop, which is highly sensitive to pre-harvest cyclonic weather);
- and field-access windows for mechanized operations in areas where machinery availability is limited and timing errors are costly.

Given Bangladesh's approximately 20 million smallholder farm households in the delta and surrounding agricultural zones, and the known advisory value of the existing BAMIS system, an enhanced $\tau$-grade operational layer reaching even 25% of farm households would represent 5 million households receiving qualitatively better operational advisories — approximately USD 15–45 million in avoided annual losses at conservative USD 3–9 per farm benefit (below the WMO economic-benefit assessment range).

**Reference organizations:** Bangladesh Meteorological Department, World Bank (BAMIS project funder), WMO (validation and technical support), FAO (Digital Services Portfolio deployment), CGIAR CCAFS (seasonal framework integration).

**Financing pathway.** The World Bank's existing BAMIS funding relationship provides the most

[49]WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

[50]World Bank (2023). *Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWCSRP) — BAMIS platform reach since 2019.* Washington, D.C.: World Bank. https://documents1.worldbank.org/curated/en/099033023051020111/pdf/P1502200e07f7e0e00a4c9019421d3a7943.pdf

[51]WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

[52]WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

natural expansion channel. The IDA Climate Lens — which prioritizes adaptation investments in highly climate-vulnerable countries — applies directly to Bangladesh's situation. Estimated incremental cost for a $\tau$-enhanced BAMIS operational layer: USD 3–6 million over 3 years, within the cost scenario 1 range discussed in Section 9.

## 9.2 Case Study 2: Ethiopia and the Greater Horn of Africa — LEAP and the Sowing Window Problem

**Context.** Ethiopia is sub-Saharan Africa's largest agricultural country by farm area, with approximately 15 million farming households, the large majority smallholders practicing rain-fed agriculture. The Greater Horn of Africa region — covering Ethiopia, Kenya, Somalia, Uganda, and South Sudan — is home to approximately 8 million smallholder farmers facing significant sub-seasonal climate variability, including the erratic Belg (short rains, February–May) and Kiremt (long rains, June–September) seasons in Ethiopia and the OND (October–December) and MAM (March–May) seasons in Kenya.[53]

CGIAR CCAFS, in partnership with WMO Regional Climate Outlook Forums and the Ethiopian Agricultural Transformation Agency, has developed the ACREI (Application of Climate Research for Extremes Initiatives) framework for downscaled seasonal advisories in the region.[54] FAO's Climate Services for Agriculture program and WMO Regional Climate Centre for Africa contribute complementary frameworks. Despite these investments, operational last-mile advisory delivery — the translation of seasonal outlooks into specific weekly sowing, spraying, or harvest decisions at the farm level — remains weak. Extension coverage is thin in rural areas, and the operational advisory layer between "seasonal outlook" and "what should I do this week?" remains largely unbuilt.

**The specific operational gap.** The most consequential advisory gap for Ethiopian smallholders is sowing window precision. Belg rains have become more erratic under climate change, and false starts — brief rainfall events followed by dry spells that kill germinating seeds — are a documented cause of replanting costs and yield losses. Current advisories can indicate the seasonal onset probability but cannot reliably specify whether a given 5-day window is likely to sustain germination or represents a false start. This distinction — between a reliable sowing window and a false-start risk — is exactly the kind of locally calibrated 1–14 day operational signal that a $\tau$ twin could provide.

Similarly, pest early warning in the region depends on operational weather intelligence: Fall Armyworm spread, Desert Locust activity, and Striga weed germination all interact with temperature and moisture conditions at field scale. FAO's Desert Locust Information Service already uses weather, habitat, and satellite data to issue forecasts up to six weeks in advance.[55][56] $\tau$ would strengthen the weather substrate of these systems.

**What $\tau$ would enable.** Under the $\tau$ planning assumption, integration into the CCAFS/ACREI institutional framework would enable:

- Sowing window advisories with explicit false-start risk probabilities at 10-km spatial resolution or finer, translatable into local extension language through the existing CCAFS downscaling and communication workflows;
- Frost/heat alert windows for altitude-differentiated farming systems in the Ethiopian highlands (where frost affects potato and wheat cultivation);

[53] CGIAR CCAFS (2024). *Climate Change, Agriculture and Food Security programme.* Wageningen: CGIAR. https://ccafs.cgiar.org

[54] CGIAR CCAFS (2024). *Climate Change, Agriculture and Food Security programme.* Wageningen: CGIAR. https://ccafs.cgiar.org

[55] FAO (2024). *Desert Locust Information Service.* Rome: FAO. https://www.fao.org/locusts/en/

[56] FAO (2024). *Climate predictions for Desert Locust early warning — six weeks to six months.* Locust Watch innovation series. Rome: FAO. https://www.fao.org/locust-watch/activities/innovation/climate-predictions/en

- Spray window advisories for Fall Armyworm and other pest management campaigns, reducing pesticide waste and improving efficacy;
- Pasture and fodder timing signals for pastoral communities in the lowland areas.

Reaching 10% of the estimated 8 million smallholder farm households in the Greater Horn region through the existing CCAFS/FAO/government extension channels would provide 800,000 households with materially improved operational advisories. At FAO's documented benefit benchmarks, this represents substantial public-good value at relatively low marginal advisory cost once the $\tau$ forecast core is in place.

**Reference organizations:** CGIAR CCAFS, FAO (Regional Office for Africa and Locust Watch), WMO (Regional Climate Outlook Forum — Greater Horn of Africa, Regional Climate Centre for Africa), Ethiopian Agricultural Transformation Agency, World Food Programme (anticipatory action), WFP/FAO Joint Programme on Anticipatory Action.

**Financing pathway.** CGIAR CCAFS receives funding from multiple bilateral donors (USAID, DFID/FCDO, BMGF, DANIDA) and would be a natural institutional anchor for $\tau$ integration in this region. The Green Climate Fund Adaptation Program area AF-009 (food security) applies directly. Estimated cost for $\tau$ integration into the ACREI institutional framework: USD 4–8 million over a 4-year pilot, within the cost scenario 1 range.

### 9.3 Case Study 3 (Supplementary): Morocco — Climate-Resilient Advisory Scaling

**Context.** Morocco's agricultural sector faces increasing water stress and climate variability, with the World Bank reporting in 2022 that a resilient agriculture project had connected **23,500 farmers** to advisory services on climate resilience and water productivity.[57] Morocco operates a national agrometeorological service through the National Meteorological Directorate (DMN) and the Agricultural Development Agency (ADA), with increasing investment in precision irrigation and climate-smart agriculture supported by the World Bank's Mashreq/Maghreb Agriculture program.

**What $\tau$ would enable.** In the Moroccan context — where irrigated cereals, arboriculture (olives, almonds, citrus), and vegetables are major commercial crops with significant export value — the highest-value operational advisory targets are:

- spray and harvest window precision for orchard and vegetable systems, where product quality and market timing interact with weather;
- irrigation scheduling advisory precision under water-scarce conditions, reducing over-irrigation during periods of forecast rain;
- heat and sirocco (hot dry wind) alert windows for protecting fragile fruit-set and harvest operations.

The existing World Bank agricultural modernization framework in Morocco provides the institutional pathway and partial financing. $\tau$-enhanced advisories integrated into the ADA extension network and existing digital platforms would extend the reach of the current 23,500-farmer project by an order of magnitude, without proportionate increases in cost, once the advisory core is built.

**Reference organizations:** World Bank (project funder), ADA Morocco, DMN Morocco, FAO Regional Office for the Near East and North Africa.

## 10 Finance, ROI, and Climate-Finance Eligibility

[57] World Bank (2022). *Morocco: Improving Resilience of Farmers through Advisory Services and Digital Agriculture.* Washington, D.C.: World Bank. https://www.worldbank.org/en/results/2022/

### 10.1 The cost–benefit reference

FAO's 2025 disaster report and WFP's 2024 anticipatory action review both document that early warning and anticipatory action systems can return up to **USD 7 per USD 1 invested** in avoided losses.[58][59] This benchmark applies to the full anticipatory action system, which includes not only advisory quality but also pre-positioned financing, insurance payout triggers, and emergency response mechanisms.

For operational agro-weather intelligence alone — advisory improvement without the pre-positioned financial response layer — a more conservative working estimate is **2–4:1 benefit-to-cost ratio**, consistent with WMO's and FAO's operational advisory impact literature.[60][61] This is the appropriate benchmark for the investments described in this paper.

At this B:C ratio, a USD 5 million investment in a national agrometeorological advisory system enhancement would need to generate approximately USD 10–20 million in annual avoided losses and input efficiency gains to meet the threshold — a bar that the Bangladesh and Ethiopia case studies suggest is achievable at modest coverage fractions of the target farmer population.

### 10.2 Cost Scenario 1: Public institutional integration

**Description.** Integration of a $\tau$ operational forecast core into an existing national meteorological or agrometeorological service infrastructure, operating in shadow mode alongside incumbent systems for validation, followed by progressive operational adoption. Target: one national system, serving 1–5 million smallholder farmers.

**Estimated cost:** USD 2–5 million per country over 3 years, covering: - $\tau$ core implementation and local calibration: USD 0.8–1.5M - Integration with national NWP and observation data pipelines: USD 0.5–1.0M - Extension interface and advisory translation tools: USD 0.4–0.8M - Validation, shadow-mode operation, and benchmark assessment: USD 0.3–0.7M - Institutional capacity and training: USD 0.2–0.5M

**Target finance:** World Bank IDA Climate Lens is the primary vehicle for LMIC national system integration. IFAD rural advisory services funding applies where the focus is specifically on extension delivery. Bilateral agriculture development programs (USAID, FCDO, DANIDA, GIZ) are additional channels.

**Expected B:C ratio at 2–4:1:** USD 4–20M in annual avoided losses and efficiency gains at the target scale, within 3–5 years of operational deployment.

### 10.3 Cost Scenario 2: Regional advisory platform

**Description.** A shared $\tau$-enhanced operational advisory platform serving multiple countries in a regional corridor (e.g., Greater Horn of Africa, Sahel, South Asian monsoon zone), operated by a regional or international institution, with national extension delivery through existing government

[58] FAO (2025). *Disasters cost global agriculture $3.26 trillion over three decades, FAO report reveals.* Rome: FAO. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en

[59] WFP (2024). *Anticipatory Action — Annual Report 2024.* Rome: WFP. https://www.wfp.org/publications/anticipatory-action-annual-report-2024

[60] FAO/WMO (2024). *Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture.* Rome/Geneva: FAO and WMO. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en

[61] WMO (2024). *Agrometeorological Information for Climate Resilient Agriculture in Bangladesh.* Geneva: WMO. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh

and CGIAR/FAO/WFP channels. Target scale: 500,000–2,000,000 smallholder farmers in the first deployment phase.

**Estimated cost:** USD 15–25 million over 4 years, covering: - $\tau$ core regional implementation and multi-country calibration: USD 4–6M - Data infrastructure and integration across 3–5 national systems: USD 3–5M - Advisory translation, localization, and extension integration tools: USD 2–4M - Digital delivery platform (mobile advisory, cooperative portal, extension dashboard): USD 2–4M - Validation, shadow-mode operation across multiple sites: USD 1.5–3M - Institutional coordination, training, and change management: USD 1.5–3M

**Target finance: - Green Climate Fund (GCF):** The GCF Adaptation Program area AF-009 (food security and livelihoods) is the primary multilateral climate finance window. GCF projects in the USD 15–50M range are standard. A $\tau$-enhanced regional agrometeorological advisory platform would qualify as an adaptation project with clear food security, water efficiency, and livelihood co-benefits. - **IFAD (International Fund for Agricultural Development):** IFAD's climate resilience envelope specifically targets rural advisory services and smallholder climate adaptation. The IFAD climate strategy (2021–2025) identifies climate information services as a priority investment area. - **World Bank IDA Climate Lens:** For national government counterpart financing and complementary extension infrastructure. - **Adaptation Fund (AF-009 parallel instrument):** For countries with direct access modalities.

**Expected B:C ratio at 2–4:1:** USD 30–100M in avoided losses and efficiency gains over the project horizon at target scale.

### 10.4 The climate finance eligibility argument

Operational agrometeorological advisory services qualify as climate adaptation investments under all major multilateral climate finance frameworks because:

1. **Adaptation to weather variability and extremes is the explicit mandate.** All GCF, IFAD, and World Bank climate adaptation windows include food security and agriculture resilience as priority areas.
2. **The farmer-level impacts are measurable and verifiable.** Unlike many adaptation investments, agrometeorological advisory quality and its farm-level outcomes can be tracked with relatively straightforward metrics: forecast skill, advisory reach, avoided losses, and input efficiency.
3. **The co-benefits are substantial.** Water efficiency, reduced fertilizer and pesticide runoff, lower greenhouse-gas emissions from optimized nitrogen application, and improved smallholder food security all represent co-benefits that strengthen the climate finance case.
4. **The technology transfer dimension is clear.** Integration of $\tau$-grade operational weather intelligence into national and regional advisory systems constitutes technology transfer to low-income country institutions, which is a defined objective of the GCF and IFAD mandates.

## 11 Evidence and Translation Ladder

The deployment architecture proposed here is designed to minimize institutional risk, build the evidence base progressively, and create natural decision gates before major financing commitments.

### 11.1 Phase 0 — Benchmark and Validation (0–12 months)

**Goal:** Demonstrate that $\tau$ outperforms current operational stacks on selected high-value tasks at a specific field site or national pilot, without requiring institutional overhaul.

**Benchmark tasks:** 1. Spray/no-spray window prediction — predicted vs. observed local conditions at a fixed field site; 2. Harvest-window prediction — 3–7 day harvestability windows vs. realized field conditions and losses; 3. Field-access prediction — soil trafficability windows vs. machinery operation logs; 4. Frost/heat threshold crossings — predictive skill vs. recorded crop or livestock impacts; 5. Rain-interruption timing — operational rainfall interruption probability at farm scale.

**KPIs:** Brier skill scores vs. local NWP baseline; false-positive and false-negative rates for each advisory class; user comprehension scores in extension pilot.

**Decision gate:** Proceed to Phase 1 if $\tau$ shows statistically significant improvement over incumbent on at least 3 of 5 benchmark tasks at the pilot site.

### 11.2 Phase 1 — Advisory Shadow Mode (12–24 months)

**Goal:** Integrate $\tau$ outputs into existing advisory systems alongside incumbent products, without yet replacing operational incumbents. Generate the comparative evidence base for institutional adoption decisions.

**Insertion points:** National agrometeorological service bulletins (shadow comparison); extension officer dashboards ($\tau$ advisory alongside standard advisory); cooperative planning tools (comparison access); BAMIS-type digital platform (shadow mode display).

**KPIs:** Advisory accuracy comparison ($\tau$ vs. incumbent, same site); user feedback from extension officers and farmers; coverage expansion rate; cost per advisory unit.

**Decision gate:** Proceed to Phase 2 if $\tau$ shadow advisories consistently outperform incumbent on $\geq$2 of the 5 benchmark tasks over a full agricultural season in $\geq$2 crop systems.

### 11.3 Phase 2 — Regional Operational Pilots (24–48 months)

**Goal:** Deploy $\tau$-enhanced operational agro-weather services as primary advisory layer in selected regions with strong institutional partners.

**Pilot selection criteria (minimum 1 of each type):** - one irrigated high-value crop region (e.g., Morocco orchard zone, Bangladesh boro rice); - one smallholder rain-fed mixed-farming region (e.g., Ethiopia Belg zone, Sahel millet system); - one mechanically intensive grain/oilseed region (e.g., South Asian wheat-rice, East African maize); - one livestock/pastoral region with heat/storm sensitivity (e.g., East African pastoralist zone, Sahel agropastoral).

**KPIs:** Farmer-reported advisory use rate; avoided-loss estimates via farm survey; input-efficiency metrics (fertilizer, water, crop protection per unit output); advisory reach (number of farm households receiving $\tau$-enhanced advisories).

**Decision gate:** Proceed to Phase 3 if $\geq$2 pilot regions show positive B:C ratios at the 2:1 threshold and institutional partners formally commit to continued operation.

### 11.4 Phase 3 — Integration with Finance, Inputs, and Public Systems (48–72 months)

**Goal:** Embed $\tau$ agro-weather intelligence as a routine component of national agricultural advisory systems, agricultural finance products, and public risk management.

**Extensions:** - Insurance trigger calibration (index insurance, parametric triggers); - Agricultural credit risk scoring for seasonal operations; - Procurement and storage timing optimization (government grain reserve agencies, cooperatives); - WFP and FAO anticipatory action trigger integration; - National meteorological service standard product integration.

**KPIs:** Number of national systems with $\tau$ integration as operational standard; number of insurance and finance products using $\tau$ advisory outputs; total farm households covered; public benefit assessment by independent evaluator.

## 12 Stakeholder Map and Change Management

Successful deployment of $\tau$-grade operational agrometeorological intelligence requires navigating a complex stakeholder ecosystem. Misreading the institutional landscape is the most common cause of technically sound advisory systems failing to achieve impact.

**National meteorological and hydrological services (NMHS)** are the primary institutional entry points and the most important long-term operational partners. They hold the mandate for official weather advisory services, the relationships with extension systems, and the technical infrastructure. Change management with NMHS requires positioning $\tau$ as a capacity enhancement, not a replacement for NMHS expertise. Co-development of benchmark protocols and joint authorship of advisory outputs are important trust-building mechanisms.

**Ministries of agriculture and rural development** hold the budget authority and the extension mandate. They are primarily interested in yield stability, food security outcomes, and the political tractability of new advisory systems. Engagement requires a clear narrative on B:C ratios, a credible evidence base from pilots, and explicit connection to existing national agricultural development plans and climate adaptation strategies.

**FAO, WMO, and CGIAR** are the multilateral institutional anchors. FAO's Digital Services Portfolio and WMO's agricultural services programme provide both funding channels and normative frameworks. CGIAR's CCAFS programme has the regional research relationships in target geographies. These organizations need to see $\tau$ as technically credible, institutionally tractable, and aligned with their own programmatic mandates — which means peer engagement on the physics and advisory quality claims, not only policy advocacy.

**Development finance institutions (World Bank, IFAD, African Development Bank, Asian Development Bank)** provide the primary investment capital for national system integration. Their program officers need quantified impact projections, clear governance structures, and institutional co-sponsors. Project design must fit within their project cycle requirements (typically 3–5 year project periods with defined milestones).

**Farmer cooperatives, extension systems, and rural digital platforms** are the last-mile delivery partners. Change management at this level requires user-centered design of the advisory interface, trust-building through visible early advisory quality, and careful attention to language, literacy, and device constraints in the target populations.

**Private sector agritech platforms** (including commercial weather and advisory companies) are both potential partners and potential resistors. The most productive posture is strategic partnership where $\tau$ provides the physics core and commercial platforms provide delivery infrastructure. This requires a clear value proposition for the commercial partners and a governance model that preserves public access for smallholder-focused deployment.

## 13 Gender, Equity, and Labor Dimensions

### 13.1 Women farmers and advisory access

FAO documents that women represent approximately 40–60% of agricultural labor in sub-Saharan Africa and 30–40% in South Asia, yet receive substantially less access to extension services, inputs, credit, and advisory information than men.[62] Operational agrometeorological advisory services delivered through mobile platforms risk replicating this gap if phone ownership, digital literacy, and extension access patterns are not explicitly addressed in system design.

The equity design principle for $\tau$-based advisory platforms is that **advisory reach to women farmers must be tracked as a primary metric, not a secondary consideration.** This implies: advisory content that covers crops and livestock activities associated with women's roles (often vegetables, small livestock, post-harvest processing); delivery through social channels and intermediaries that women access (women's cooperatives, female extension agents, SMS services where smartphone ownership is unequal); and language and literacy adaptations for populations with lower formal education levels.

### 13.2 Labor and seasonal employment

Harvest timing advisories affect not only farm operators but also seasonal agricultural workers — a population of hundreds of millions globally, largely informal, with precarious incomes. Better harvest window advisories could improve the predictability of seasonal labor demand, reducing the income volatility that makes seasonal agricultural work particularly precarious. At the same time, advisory systems that facilitate mechanization — by providing better timing for machinery operations — may reduce demand for manual harvest labor in some contexts. This labor dimension should be explicitly assessed in deployment pilot design.

### 13.3 Smallholder equity in advisory quality

There is a structural risk that $\tau$-grade advisory quality improvements benefit large commercial farms before smallholder systems, because commercial operations have greater capacity to integrate and act on complex advisory outputs, and because they represent more attractive commercial markets for agritech platforms. Countermanding this requires deliberate public institutional investment in smallholder-facing advisory translation and delivery, explicit targeting of underserved regions in pilot selection, and governance structures that require public access alongside any commercial licensing.

### 13.4 SDG 5 linkage

The gender equity dimensions described here map directly to SDG 5 (Gender Equality) and to the Women, Land, and Water initiative that FAO operates as a cross-cutting equity instrument. Climate finance proposals for $\tau$ integration into advisory systems should explicitly address the SDG 5 co-benefit case.

## 14 Benchmark Suite and Success Metrics

### 14.1 Technical performance metrics

- **Forecast skill scores** (Brier skill score, continuous ranked probability score) for local rainfall, temperature, wind, humidity, and derived field-operational indices, benchmarked against the best available incumbent NWP product at each deployment site;
- **False-positive and false-negative rates** for each advisory class (spray window, harvest window, field access, frost alert, rain interruption) at weekly calibration intervals;

[62] FAO (2023). *The Status of Women in Agrifood Systems.* Rome: FAO. https://www.fao.org/publications/home/fao-flagship-publications/the-status-of-women-in-agrifood-systems/en/

- **Uncertainty bound reliability** — fraction of realized conditions falling within stated $\tau$ uncertainty envelopes at each forecast horizon;
- **Performance under extremes** — advisory quality during high-impact weather events (convective episodes, cold waves, heat spells) where the value of improved accuracy is highest;
- **Spatial consistency** — advisory coherence across adjacent farm units, to assess whether the twin is capturing local spatial gradients rather than smoothing them.

### 14.2 Agricultural impact metrics

- **Input efficiency ratios** — fertilizer, water, and crop protection product use per unit output, before and after $\tau$ advisory integration, measured through farm survey panels;
- **Planting and harvest timeliness** — fraction of operations completed within the optimal window, compared to prior-year baseline;
- **Failed field operation rate** — incidence of operations that had to be aborted or repeated due to weather conditions that advisories should have identified;
- **Yield stability** — inter-season yield coefficient of variation at pilot farms, relative to matched comparison farms without $\tau$ advisories;
- **Post-harvest loss rates** — grain moisture loss, storage loss, and quality downgrade rates in pilot vs. comparison groups.

### 14.3 Public-good and reach metrics

- **Advisory reach** — number of farm households receiving $\tau$-enhanced advisories per season, disaggregated by gender, farm size, and geographic location;
- **Extension system adoption rate** — fraction of extension officers using $\tau$ advisory outputs as primary decision support;
- **Avoided loss estimate** — seasonal avoided loss per advisory-receiving farm, from farm surveys and comparison group design;
- **Input waste reduction** — estimated reduction in avoidable water, fertilizer, and crop protection waste, converted to economic and environmental value;
- **User comprehension and trust** — farmer and extension officer understanding of advisory meaning and confidence in advisory reliability, from standardized user survey.

### 14.4 Institutional metrics

- Formal adoption by at least one national NMHS within 36 months of Phase 1 initiation;
- Integration into at least one CGIAR/FAO/WMO regional advisory program within 48 months;
- At least two independent replication assessments published in peer-reviewed literature within 60 months;
- Zero cases of advisory system contributing to documented agricultural harm (safety monitoring).

## 15 Governance Guardrails

The deployment of a new physical intelligence layer into advisory systems that affect food security, livelihoods, and resource use requires explicit governance structures. The following safeguards should be built into any $\tau$ operational agro-weather deployment from Phase 0 forward.

1. **Open benchmarking before operational lock-in.** No $\tau$ advisory component should be deployed as a primary operational system before transparent benchmarking against incumbent products at the deployment site has been completed and results shared with the national NMHS

and agricultural ministry. Benchmarks should be designed and evaluated with institutional partner participation, not solely by the $\tau$ development team.

2. **Mandatory human override at the extension layer.** No $\tau$ advisory output should be presented to farmers as automatically authoritative. Extension officers and cooperative managers must retain the authority to override, supplement, or contextualize $\tau$ outputs. Advisory interfaces should be designed to present $\tau$ outputs as recommendations with explicit uncertainty, not directives.
3. **Smallholder access as a contractual requirement.** Any commercial licensing of $\tau$ operational agro-weather advisory capabilities must include a contractual requirement for parallel public-access deployment at smallholder advisory scale, with pricing and interface structures appropriate for resource-constrained users and public extension systems.
4. **Adverse outcome monitoring and incident reporting.** All pilot deployments should include a formal adverse outcome monitoring protocol, tracking cases where $\tau$ advisories were followed and resulted in farm losses. An annual incident review should be conducted with institutional partners and used to refine advisory quality and uncertainty communication.
5. **Data governance and farmer data rights.** Advisory systems that collect farm-level operational data as inputs to improved calibration must operate under clear data governance frameworks: informed consent, data minimization, no commercial resale without consent, and national regulatory compliance. GDPR-equivalent protections should apply regardless of jurisdiction, as a minimum standard.
6. **Institutional co-ownership of regional deployments.** Regional advisory platforms should be governed by multi-institutional boards including national NMHS representation, FAO/WMO participation, and farmer organization or cooperative representation. Single-entity technical control of operational advisory systems at national or regional scale is not appropriate for a public-good instrument of this type.
7. **Mandatory external evaluation at Phase transition gates.** Each phase transition in the deployment ladder requires an independent external evaluation report as a precondition for continued public financing. Self-assessment by the development team is insufficient.
8. **Non-deployment in contexts of active humanitarian crisis.** $\tau$ advisory capabilities should not be deployed as the primary operational system in contexts of active food security emergency without coordination with WFP, FAO, and national civil protection authorities. In emergency contexts, the priority is institutional coordination and humanitarian response, not technology deployment.

# 16 SDG Mapping and Bottom Line

## 16.1 SDG linkages

The operational agrometeorological advisory opportunity described in this paper maps directly to five of the seventeen Sustainable Development Goals:

- **SDG 2 (Zero Hunger):** Reduced agricultural losses, improved yield stability, and better input efficiency directly contribute to food security and sustainable agricultural productivity for smallholder farmers. The target 2.4 — ensuring sustainable food production systems and resilient agricultural practices — is directly addressed.
- **SDG 5 (Gender Equality):** Explicit design requirements for advisory reach to women farmers, female extension officer engagement, and crops and livestock associated with women's agricultural roles address target 5.a (women's access to resources and services in agriculture).

- **SDG 6 (Clean Water and Sanitation):** Improved irrigation timing and reduced fertilizer and crop-protection runoff contribute to water use efficiency (target 6.4) and reduced agricultural water pollution (target 6.3).
- **SDG 13 (Climate Action):** Better operational agro-weather advisory services are a documented climate adaptation instrument. The explicit reduction in weather-linked agricultural losses and the food security co-benefits qualify under target 13.1 (strengthening resilience and adaptive capacity to climate-related hazards).
- **SDG 17 (Partnerships for the Goals):** The deployment model described here is inherently multi-institutional — NMHS, FAO, WMO, CGIAR, development finance institutions, national governments, and farmer organizations. The partnership structure is not incidental; it is the mechanism by which public-good outcomes are sustained at scale.

### 16.2 Bottom line

Operational agrometeorological advisory services are one of the most institutionally legible, demand-confirmed, and welfare-consequential first-tier applications of $\tau$. The sector is already organized around exactly this class of service. The loss baseline is enormous — USD 99 billion per year on average. Existing public systems, from Bangladesh's BAMIS to the CGIAR CCAFS regional advisory programs, prove that the institutional will, the digital delivery infrastructure, and the user demand exist.

Under the $\tau$ planning assumption, the opportunity is not merely "marginally better forecasts for farmers." It is the first layer of a full-stack agrifood intelligence architecture — and one that is already deployable, measurable, and valuable as a standalone investment. If $\tau$ can make weather-linked agricultural operations materially more trustworthy, locally calibrated, and operationally actionable, this paper's domain could deliver some of the fastest and most broadly distributed public-good returns in the entire $\tau$ impact program.

## 17 References

*Source: Full manuscript text integrated from Public-Good Briefing draft.*

# 18 Dossier accountability addendum

The following addendum records the release-facing accountability layer for this dossier: claim boundaries, baseline evidence, upstream dependencies, translation assumptions, scenario bands, scorecard rationales, benchmark requirements, governance guardrails, and related Panta Rhei surfaces. It is intentionally downstream of the full source argument above.

**Impact thesis**

A Public-Good Briefing arguing that a law-faithful tau weather-soil-crop-operations twin could unlock major public-good gains for day-to-day agricultural decision support. The v3 impact thesis is conditional: a Tau-grade weather-soil-crop-operations advisory twin would become valuable if it improves benchmarked public decisions while preserving transparent uncertainty, reviewability, and governance control.

## 18.1 Public-good burden and baseline evidence

A Public-Good Briefing arguing that a law-faithful tau weather-soil-crop-operations twin could unlock major public-good gains for day-to-day agricultural decision support. The public-good burden is treated here as an institutional decision problem: existing agencies already monitor parts of the domain, but the operational handoff from data to timely, auditable action remains incomplete.

### 18.1.1 External evidence baseline

- **FAO (2025). Disasters cost global agriculture $3.26 trillion over three decades**, FAO report reveals. Rome: FAO [4]: source-page evidence item.
- **FAO (2025). The State of the World's Land and Water Resources for Food and Agriculture 2025. Rome: FAO**, FAO (2025). The State of the World's Land and Water Resources for Food and Agriculture 2025. Rome: FAO [5]: source-page evidence item.
- **FAO (2021). Small family farmers produce a third of the world's food. Rome: FAO**, FAO (2021). Small family farmers produce a third of the world's food. Rome: FAO [2]: source-page evidence item.
- **World Bank (2024). Climate-Smart Agriculture. Washington**, D.C.: World Bank [12]: source-page evidence item.
- **FAO/WMO (2024). Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture. Rome/Geneva: FAO and WMO**, FAO/WMO (2024). Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture. Rome/Geneva: FAO and WMO [6]: source-page evidence item.
- **WMO (2024). Agricultural Services. Geneva: WMO**, WMO (2024). Agricultural Services. Geneva: WMO [9]: source-page evidence item.
- **WMO (2024). Agrometeorological Information for Climate Resilient Agriculture in Bangladesh. Geneva: WMO**, WMO (2024). Agrometeorological Information for Climate Resilient Agriculture in Bangladesh. Geneva: WMO [10]: source-page evidence item.
- **Bangladesh Meteorological Department (2024). Bangladesh Agro-Meteorological Information Service (BAMIS) portal. Dhaka: BMD**, Bangladesh Meteorological Department (2024). Bangladesh Agro-Meteorological Information Service (BAMIS) portal. Dhaka: BMD [1]: source-page evidence item.

- **World Bank (2023). Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWCSRP)**, World Bank (2023). Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWCSRP) [11]: BAMIS platform reach since 2019. Washington, D.C.: World Bank.
- **FAO (2024). Digital Services Portfolio. Rome: FAO**, FAO (2024). Digital Services Portfolio. Rome: FAO [3]: source-page evidence item.


### 18.2 Current institutional landscape

The relevant landscape includes public agencies, research infrastructures, standards bodies, development-finance channels, and domain review communities represented in the evidence base, including FAO (2021). Small family farmers produce a third of the world's food. Rome: FAO, FAO (2025). Disasters cost global agriculture $3.26 trillion over three decades, FAO (2025). The State of the World's Land and Water Resources for Food and Agriculture 2025. Rome: FAO, FAO/WMO (2024). Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture. Rome/Geneva: FAO and WMO, WMO (2024). Agricultural Services. Geneva: WMO, World Bank (2024). Climate-Smart Agriculture. Washington. These references are evidence and adoption surfaces, not endorsements or deployment partners.

### 18.3 Capability gap

The practical gap is a benchmarkable translation gap: current systems expose useful data or partial models, but they do not yet provide a single law-faithful, bounded-error decision layer for weather-soil-crop-operations advisory twin.

### 18.4 Tau framework dependency map

| Surface | Role in this dossier |
|---|---|
| Build the Tau-Kernel | finite address and scalar foundation |
| Recover Core Mathematics | mathematical bridge and model interface |
| Derive Physics | physical readout and domain translation candidate |
| Results lane | upstream consequences to be mapped precisely during release preparation |
| direct-registry-mapping-withheld | no direct Registry object is asserted until a substantive Corpus mapping is available |
| public-docs-mapping-withheld | TauLib module links are asserted only where public documentation exposes a clear surface |
| Release Manifest | release baseline |
| Predictions and Falsification | empirical accountability route |

### 18.5 Translation assumptions and missing engineering

Required domain model: **weather-soil-crop-operations advisory twin**.

First benchmarkable test: spray/no-spray, harvest, irrigation, frost, heat, and field-access windows against incumbent advisory products.

- domain-specific model construction
- data ingestion and validation

- benchmark harness
- pilot protocol
- independent review workflow

### 18.6 Impact mechanism chain

Public-good burden → external evidence baseline → $\tau$ capability hypothesis → upstream Results / Corpus / Verify dependency → translation assumptions → benchmarked pilot → governed adoption pathway.

### 18.7 Scenario bands

| Band | Scenario summary | Confidence |
|---|---|---|
| **Conservative** | A narrow shadow-mode pilot improves one bounded decision task for Operational Agro-Weather Intelligence without operational authority. | medium |
| **Realistic** | A reviewed prototype strengthens several public-sector workflows for Operational Agro-Weather Intelligence after benchmark comparison with incumbent systems. | medium-low |
| **Optimistic** | A reusable public-good intelligence layer becomes plausible for Operational Agro-Weather Intelligence after external validation and transparent governance review. | low |

### 18.8 Impact scorecard

| | | |
|---|---|---|
| **Public-good scale** | 5/5 | The affected public-good burden is large or institutionally significant within the portfolio. |
| **Tau fit** | 4/5 | The proposed pathway depends on coupled state, bounded uncertainty, and compositional modelling rather than isolated prediction alone. |
| **Evidence proximity** | 4/5 | The evidence base is anchored in public institutions, official monitoring systems, or established scientific reviews. |
| **Measurability** | 5/5 | A first benchmark can be framed against incumbent public datasets, institutional records, or operational decision metrics. |
| **Adoption readiness** | 3/5 | Adoption remains conditional on domain review, governance fit, data access, and institutional integration. |
| **Equity leverage** | 5/5 | The pathway can prioritize underserved or vulnerable populations where public access and safeguards are built in. |

### 18.9 Candidate pilot pathways

district or basin-scale advisory pilot with a national meteorological service, agriculture ministry, and extension partner

### 18.10 Benchmark suite and success metrics

| Type | Incumbent baseline | Required Tau benchmark | Success metric | Validator |
|---|---|---|---|---|
| translation benchmark | current public or institutional systems in the domain | spray/no-spray, harvest, irrigation, frost, heat, and field-access windows against incumbent advisory products | pre-registered accuracy, latency, uncertainty, or decision-quality metric | independent domain reviewers |
| governance benchmark | existing audit, disclosure, and reporting practice | transparent assumption, data, model, and failure-mode disclosure | reviewable evidence pack and adverse-outcome protocol | public-sector or expert governance panel |
| equity benchmark | current access, service-quality, or exposure disparities | documented pathway for underserved or vulnerable users without hidden exclusion | distributional benefit and risk review before pilot expansion | equity, community, or public-interest review process |

### 18.11 Governance and risk guardrails

- Human oversight for any operational use.
- Public benchmark disclosure before institutional adoption.
- Equity access review for underserved or vulnerable communities.
- Data-rights and privacy controls for operational datasets.
- Misuse-prevention and adverse-outcome monitoring.
- Adverse-outcome monitoring with a documented escalation path.
- External domain review before pilot expansion.

### 18.12 Related Results / Corpus / Verify / Publications

This dossier is downstream of Results, Corpus, Verify, and Publications surfaces. It is not a Registry object. Direct Registry or TauLib links are asserted only where the mapping is substantive rather than decorative.

### 18.13 Bibliography and external evidence

## References

[1] Bangladesh Meteorological Department (2024). Bangladesh Agro-Meteorological Information Service (BAMIS) portal. Dhaka: BMD. Bangladesh meteorological department (2024).

bangladesh agro-meteorological information service (bamis) portal. dhaka: Bmd. https://www.bamis.gov.bd/en/, 2026. source-page evidence item.

[2] FAO (2021). Small family farmers produce a third of the world's food. Rome: FAO. Fao (2021). small family farmers produce a third of the world's food. rome: Fao. https://www.fao.org/family-farming/detail/en/c/1398060/, 2026. source-page evidence item.

[3] FAO (2024). Digital Services Portfolio. Rome: FAO. Fao (2024). digital services portfolio. rome: Fao. https://www.fao.org/digital-services/en, 2026. source-page evidence item.

[4] FAO (2025). Disasters cost global agriculture $3.26 trillion over three decades. Fao report reveals. rome: Fao. https://www.fao.org/newsroom/detail/disasters-cost-global-agriculture--3.26-trillion-over-three-decades--fao-report-reveals/en, 2026. source-page evidence item.

[5] FAO (2025). The State of the World's Land and Water Resources for Food and Agriculture 2025. Rome: FAO. Fao (2025). the state of the world's land and water resources for food and agriculture 2025. rome: Fao. https://www.fao.org/3/cd7488en/online/state-of-the-worlds-land-and-water-resources-for-food-and-agriculture-2025-2025/scenarios-offer-insights-assumptions.html, 2026. source-page evidence item.

[6] FAO/WMO (2024). Empowering Farmers: The Role of Agrometeorological Services in Sustainable Agriculture. Rome/Geneva: FAO and WMO. Fao/wmo (2024). empowering farmers: The role of agrometeorological services in sustainable agriculture. rome/geneva: Fao and wmo. https://www.fao.org/partnerships/fao-un-system/UN-Partners/fao-and-wmo/empowering-farmers--the-role-of-agrometeorological-services-in-sustainable-agriculture/en, 2026. source-page evidence item.

[7] Thorsten Fuchs and Anna-Sophie Fuchs. Tau-grade operational agro-weather intelligence. https://panta-rhei.site/impact/papers/operational-agro-weather-intelligence/, 2026. Current public full-text source for dossier operational-agro-weather-intelligence.

[8] Panta Rhei Research Program. Public-good briefing landing page. https://panta-rhei.site/publications/research-briefings/public-good/operational-agro-weather-intelligence/, 2026.

[9] WMO (2024). Agricultural Services. Geneva: WMO. Wmo (2024). agricultural services. geneva: Wmo. https://wmo.int/activities/agricultural-services, 2026. source-page evidence item.

[10] WMO (2024). Agrometeorological Information for Climate Resilient Agriculture in Bangladesh. Geneva: WMO. Wmo (2024). agrometeorological information for climate resilient agriculture in bangladesh. geneva: Wmo. https://wmo.int/media/magazine-article/agrometeorological-information-climate-resilient-agriculture-bangladesh, 2026. source-page evidence item.

[11] World Bank (2023). Project documentation: Bangladesh Weather and Climate Services Regional Project (BDWCSRP). World bank (2023). project documentation: Bangladesh weather and climate services regional project (bdwcsrp). https://documents1.worldbank.org/curated/en/099033023051020111/pdf/P1502200e07f7e0e00a4c9019421d3a7943.pdf, 2026. BAMIS platform reach since 2019. Washington, D.C.: World Bank.

[12] World Bank (2024). Climate-Smart Agriculture. Washington. D.c.: World bank. https://www.worldbank.org/en/topic/climate-smart-agriculture, 2026. source-page evidence item.

# Panta Rhei Research Program

Public-Good Impact Dossier

## Tau-Grade Operational Agro-Weather Intelligence

Dossier ID: PGID-AGRI-05 Portfolio: Agriculture Release: May 2026
publication-ready release

Conditional scenario map. Domain review pending. Deployment, product, validation, certified-impact, and policy-commitment claims are not made.

**Public contact and review routes**

Website: panta-rhei.site
Contact: panta-rhei.site/engage/contact/
Public discussion: github.com/orgs/Panta-Rhei-Research/discussions
General: hello@panta-rhei.site
Corrections: errata@panta-rhei.site
Media: press@panta-rhei.site