GEORGIA

Transforming Water Management for Resilient Farming

WHITE PAPER

Architectural Innovations in Climate-Resilient Smart Irrigation

The GEORGIA Platform: Bridging Biophysical Modeling, Zero-Trust Federated Learning, and Distributed Ledger Technology

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As the global agricultural sector confronts the compounding challenges of acute water scarcity, aquifer depletion, and extreme climate unpredictability, the demand for precision irrigation systems has surged. The European Green Deal sets ambitious targets for sustainable resource management, yet the adoption of advanced agri-tech remains severely stalled. This stagnation is largely driven by monolithic software architectures that fail to adapt to local conditions, poor semantic interoperability across hardware vendors, and deeply rooted, valid concerns regarding data sovereignty and privacy among farmers.

The GEORGIA Project (Green dEal cOmpliant iRriGation Increasing Europe's Agriculture resilience to drought) directly addresses these critical bottlenecks by introducing a highly decentralized, cloud-native, microservices-based cyber-physical system. This technical white paper details the platform's core architectural innovations designed to overcome both technical and socio-economic barriers. Key breakthroughs include: a Dynamic "Switchboard" Orchestrator that manages a portfolio of containerized, best-of-breed biophysical simulation engines; a Zero-Trust Federated Learning (ZTFL) framework that enables privacy-preserving AI training at the edge; and an *interDLT* hybrid blockchain infrastructure designed for immutable, transparent resource auditing without exposing sensitive operational data.

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1. Socio-Economic Context and Architectural Mandate

The architectural design of the GEORGIA platform is not purely theoretical; it is directly informed by empirical field data and the lived realities of farm managers. A comprehensive requirements elicitation survey (documented in GEORGIA's Deliverable D1.1) involving 164 stakeholders across seven European countries utilized the Problem Confrontation Index (PCI) to quantify the exact barriers to smart irrigation adoption.

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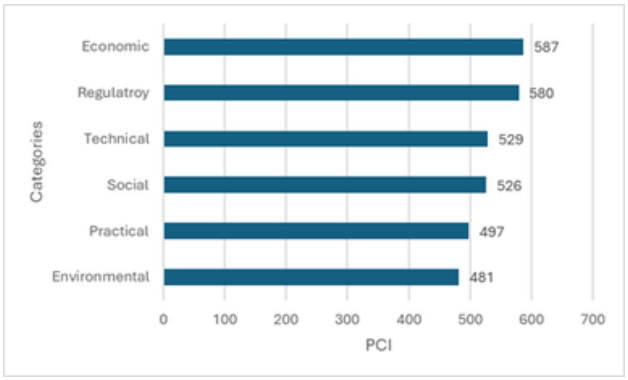
The data revealed a striking paradigm: the primary obstacles preventing the digitization of water management are not environmental or technical feasibility constraints, but rather profound economic and institutional hurdles.

The highest-rated barriers included high initial investment costs (PCI = 712), lack of subsidies (PCI = 619), and a pervasive mistrust in government & institutions (PCI = 540). Farmers operate on notoriously thin margins; the prospect of investing heavily in proprietary, “black-box” systems that lock them into single-vendor ecosystems is economically unviable. Furthermore, stakeholders expressed acute anxiety that sharing high-resolution yield and water usage data to central cloud servers could lead to strict regulatory penalization or market exploitation.



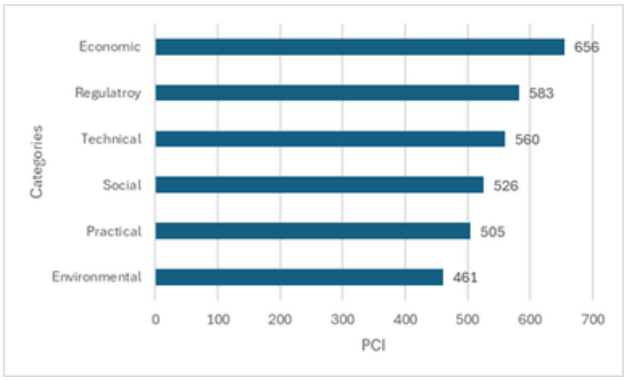


Figure 1: Left: Non-conventional water source and treatment practices: Average PCI per category. Right: Efficient irrigation techniques: Average PCI per category

To successfully overcome these barriers and achieve widespread adoption, the GEORGIA platform's software architecture was mandated to fulfill three strict criteria:

- Hardware-Agnostic Interoperability: It must decouple the data processing intelligence from the physical sensor hardware, lowering investment costs by allowing farmers to use legacy or low-cost commercial off-the-shelf (COTS) sensors.

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- Privacy by Design: It must enforce strict, mathematically proven data privacy to overcome institutional mistrust, ensuring that raw operational data never leaves the farm boundary without explicit, cryptographic consent.

- Explainable Economic Value: It must move beyond abstract scientific metrics to provide highly accurate, explainable economic optimizations that clearly demonstrate a return on investment (ROI) for every drop of water saved.

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2. Data Ingestion and Semantic Interoperability

The GEORGIA Data Acquisition Layer acts as the sensory nervous system of the platform. Given the fragmented nature of the agricultural Internet of Things (IoT) market, GEORGIA utilizes an advanced “Adaptor Pattern” at the edge to decouple data collection from downstream processing.

To prevent vendor lock-in and ensure semantic interoperability across broader European data spaces, the ingestion layer standardizes all incoming telemetry (transmitted via MQTT, LoRaWAN, or HTTP REST) to the strict GEORGIA Data Model. This model inherits directly from the AgriDataValue (ADV) and the DEMETER Agriculture Information Model (AIM).

- Context Broker and Semantic Normalization: Raw payloads from diverse manufacturers are inherently messy (e.g., Vendor A might output {temp_c: 24}, while Vendor B outputs {Temperature: 24}). The GEORGIA Context Broker utilizes JSON-LD (Linked Data) to map all incoming telemetry to the standardized “sosa:Observation” ontology. This ensures that every individual data point (such as volumetric water content or electrical conductivity) is strictly bound to its spatial and temporal metadata (sensor depth, GPS coordinates, standardized UTC timestamps).

- Asynchronous Message Bus: Once normalized, payloads are published to a high-throughput, asynchronous event bus powered by Apache Kafka / RabbitMQ. This decoupling is critical for rural environments; it buffers data during intermittent connectivity drops and ensures that sudden spikes in sensor traffic do not overwhelm or degrade the performance of the downstream simulation engines.

- Polyglot Persistence Architecture: Recognizing that agricultural data is highly heterogeneous, GEORGIA avoids the single-database approach. Data is routed to purpose-built, optimized stores:

    - PostgreSQL(TimescaleDB plugin): Utilized for time-series sensor data. Its hyper-table architecture allows for lightning-fast temporal aggregations (e.g., calculating daily temperature averages from minute-by-minute sensor pings).

    - PostGIS: Dedicated to geospatial boundaries, enabling complex topological queries (e.g., intersecting field polygons with regional watershed maps).

    - Object Data Lake: Utilized for unstructured, high-volume binary data, such as multispectral orthomosaics from drones or Sentinel-2 satellite tiles.

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3. The “Switchboard” Orchestrator and Containerised Simulation Core

A fundamental limitation of legacy Farm Management Information Systems (FMIS) is their reliance on a single, generalized biophysical model. A model optimized for simulating the canopy development of row crops will inevitably fail to capture the complex hydraulic realities, deep root systems, and perennial nature of citrus orchards or vineyards.

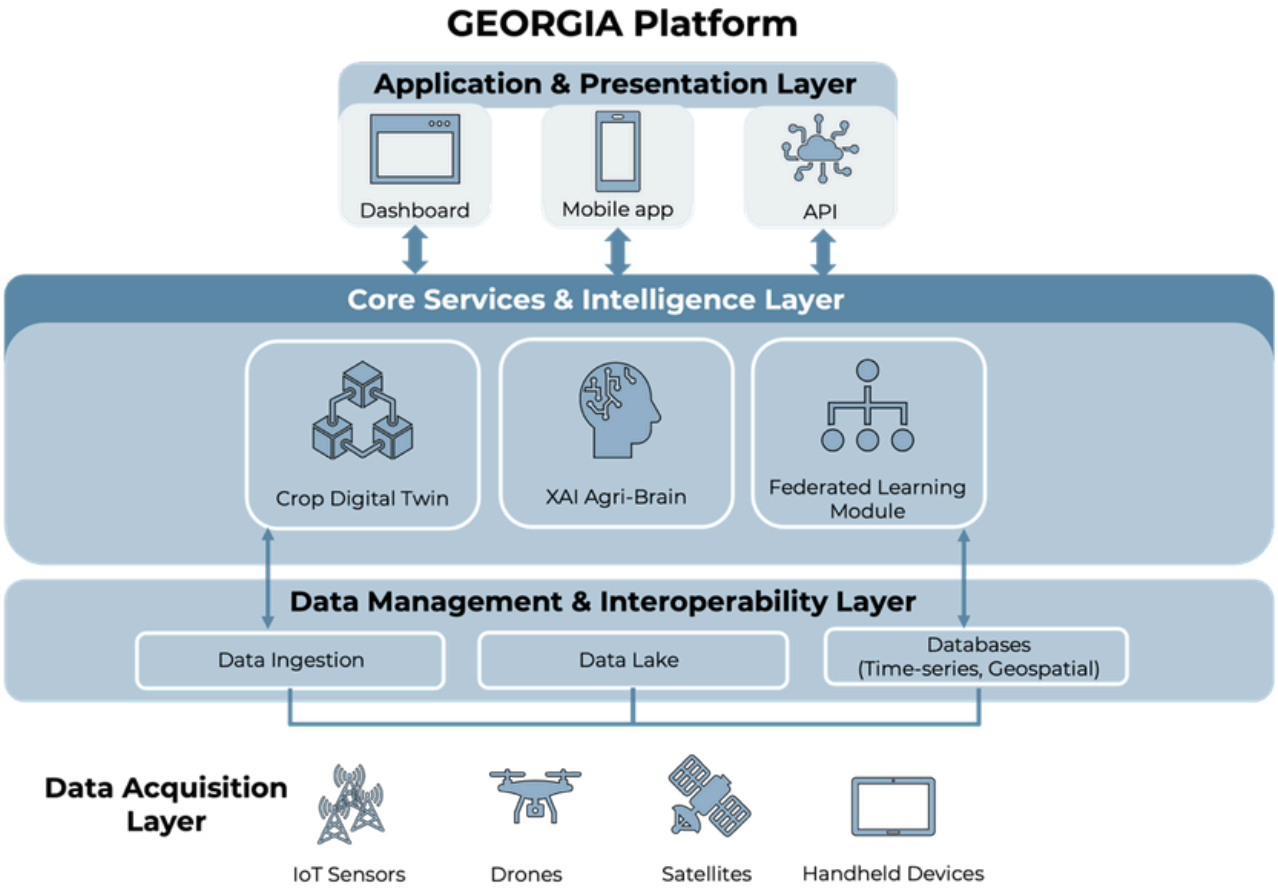

Figure 2: Architecture of the GEORGIA Platform - High-level diagram

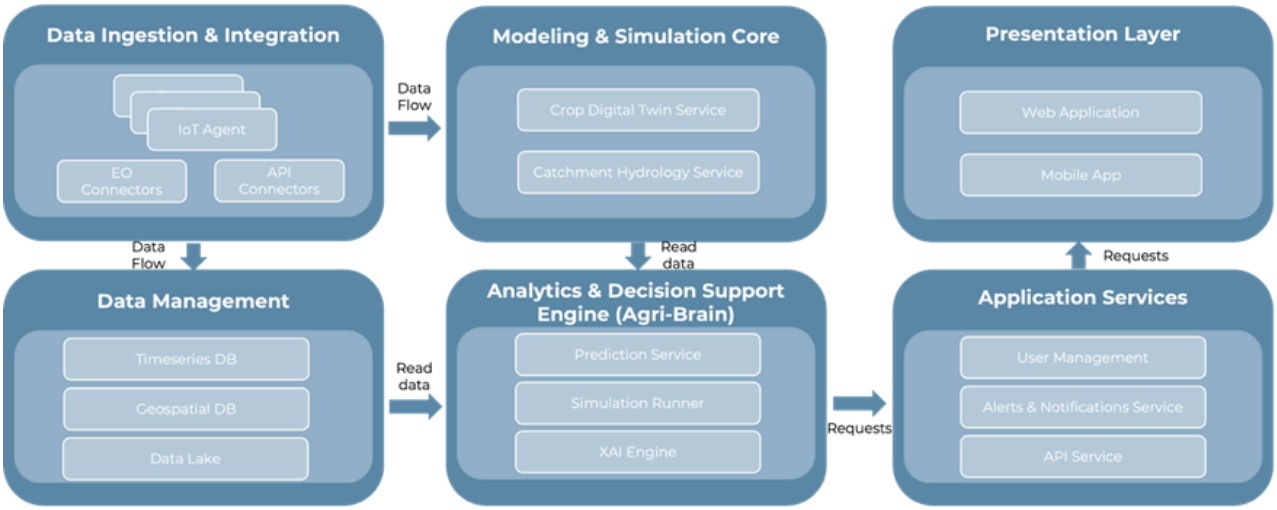

Figure 3: Architecture of the GEORGIA Platform- Functional view diagram

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GEORGIA solves this architectural bottleneck via a Dynamic "Switchboard" Orchestrator. Implemented as a highly concurrent, stateless Python/Django microservice deployed within an auto-scaling Kubernetes (K8s) cluster, the Orchestrator functions as an intelligent traffic controller. It parses incoming JSON-LD simulation requests and dynamically routes the computational job to highly specialized, containerized worker nodes based on metadata such as the cropSpecies and specific soil typologies.

Instead of forcing one model to do everything, the platform leverages a containerized "Best-of-Breed" engine stack. To guarantee scientific validity, each physics engine operates within an isolated Docker pod. This encapsulation prevents devastating dependency conflicts (e.g., clashes between modern Python libraries, .NET runtimes, and legacy Fortran binaries) and allows resource allocation to be tuned per engine:

- AquaCrop (Arboriculture & Vegetables): Developed by the FAO, AquaCrop is highly adept at simulating yield response to water (Steduto et al., 2009). The Orchestrator routes Citrus and Olive requests here to focus heavily on water productivity and hydraulic accuracy, bypassing complex biological parameters that are often unavailable or highly variable for tree crops.

- APSIM (Cereals): For crops like wheat, the Agricultural Production Systems sIMulator (Holzworth et al., 2014) is unmatched. It leverages superior capabilities in simulating nitrogen cycling, protein accumulation, and complex residue management logic.

- DSSAT (Fruiting Vegetables): Tomatoes and similar crops are routed to the Decision Support System for Agrotechnology Transfer (Jones et al., 2003). DSSAT provides detailed physiological stress modeling, specifically capturing phenological sensitivity to heat shock during flowering—a key determinant of fruit set and yield.

- PCSE/WOFOST (Root Crops): Potato simulations are routed to the Python Crop Simulation Environment (de Wit et al., 2019) for specialized biomass partitioning and tuber development modeling, which are critical for predicting harvest quality and size grading.

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By decoupling data collection from processing, the system ensures that digital interventions are firmly grounded in physical reality and scientific rigor.

To maintain absolute scientific validity during continuous software updates, the CI/CD pipeline incorporates a “Golden Gate” mechanism. Every developer code commit triggers automated, headless tests against a verified, historical “Golden Dataset”. If a code change (such as updating a wrapper library) causes a simulation's root mean square error (RMSE) for yield or biomass to deviate beyond a strict, pre-defined threshold against known agronomic baselines, the CI/CD pipeline halts, and the build fails automatically. This guarantees that software optimizations never compromise biophysical accuracy.

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4. Practical Agronomy: Executing Smart Irrigation Scenarios

The true value of the GEORGIA platform lies in its “Agri-Brain”—the analytics and decision support engine that translates the biophysical simulations of the CDT into highly specialized, actionable scenarios.

The platform's Simulation Runner actively instantiates parallel variations of the digital twin to run “What-If” analyses, generating recommendations across diverse agronomic challenges.

Scenario A: Economic Optimisation (Profit-Driven)

- The Challenge: Farmers must maximize the economic margin per cubic meter of water applied, trading off the cost of pumping energy against potential yield losses

- The Science: The Simulation Runner executes parallel variations of the digital twin (e.g., applying 70%, 85%, and 100% of crop evapotranspiration, ET_c). It converts the agronomic outputs (yield) into an economic objective function, factoring in water costs and projected crop revenue based on quality-related price effects.

- Actionable Output: “Recommendation: Reduce irrigation by 15%. This will lower yield by only 2% but reduce energy and water costs by 20%, maximizing net profit”.

Scenario C: Salinity Leaching Management (Root-Zone EC Control)

- The Challenge: In Mediterranean coastal areas, high salinity levels in soil and irrigation water cause severe plant stress. Standard models often lack the physics to model complex salt transport in the vadose zone.

- The Science: GEORGIA integrates HYDRUS-1D (Šimůnek et al., 2008) as a specialized forensic worker. When IoT sensors detect soil Electrical Conductivity (EC) exceeding crop-specific thresholds, the engine solves the Richards equation for variably saturated flow and the convection-dispersion equation for solute transport.

- Actionable Output: “Root-zone EC critical. Schedule a targeted leaching fraction (LF) of 15% over the next two irrigation events. Postpone if heavy rain is imminent to avoid waterlogging”.

Scenario E: Heat Shock Mitigation

- The Challenge: Extreme heat spikes can cause irreversible damage to sensitive phenological stages, such as flower abortion in tomatoes.

- The Science: Relying on hyper-local weather correction models (adjusting global GFS forecasts using local micro-climate history), the platform anticipates temperatures exceeding crop heat-stress thresholds.

- Actionable Output: “Heatwave alert: Proactively trigger short evaporative cooling cycles via micro-sprinklers during peak heat (13:00-15:00). Cut-off enforced if Relative Humidity (RH) > 60% to prevent fungal outbreaks”.

Scenario P: PDO Quality Preservation (Santorini “Kouloura” Vines)

- The Challenge: Preserving the Protected Designation of Origin (PDO)

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typicity and organoleptic profile of Santorini Assyrtiko wines. These rely on traditional dry-farmed regimes in highly vulnerable, sandy soils, meaning excess water destroys wine quality, but too little kills the vine.

- The Science: Utilizing AquaCrop's robustness in water-driven yield modeling, the system computes a "Winter Recharge Deficit" based on historical Earth Observation (EO) baselines.

- Actionable Output: “Winter recharge deficit detected. Apply 10 mm net in two small events to restore the root-zone to the ‘Recharge Band’ before budbreak. Summer rainfed mode maintained; rescue irrigation locked unless canopy crosses Quality-Safe Minimum”.

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5. Privacy-Preserving AI: Zero-Trust Federated Learning (ZTFL)

To directly address the sector's stringent data sovereignty requirements and the very real physical limitations of rural broadband (where uploading gigabytes of drone imagery is often impossible), the GEORGIA platform implements a robust Edge-Driven Federated Learning architecture. Instead of moving sensitive, high-resolution datasets to a central cloud repository, the system intelligently moves the machine learning computational workload to the edge.

5.1 Cryptographic Architecture and Threat Mitigation

The ZTFL framework enforces a zero-trust security model, applying multiple layers of advanced cryptographic protection to prevent data leakage, man-in-the-middle attacks, and reverse-engineering of localized models:

- Local Training at the Edge: The Edge Gateway (a local computing node

installed at the farm) processes raw data locally to compute mathematical gradients (the vector of weight updates required to minimize error). The raw yield data, proprietary management practices, and high-resolution imagery never leave the farm's local area network.

- Homomorphic Encryption (HE): Before any transmission occurs, the local model weights are encrypted client-side using the CKKS (Cheon-Kim-Kim-Song) scheme via the TenSEAL library. Homomorphic encryption is a breakthrough capability that allows mathematical operations to be performed directly on ciphertexts.

- Post-Quantum Signatures: To guarantee the authenticity of the payload and future-proof the network against "harvest now, decrypt later" quantum computing attacks, every exchange between the edge and the cloud is verified using the Crystals' Dilithium digital signature scheme (implemented via the liboqs-python library).

- Secure Aggregation: The Cloud Aggregation Server receives these encrypted payloads. Because of the Homomorphic Encryption, the server can mathematically aggregate the encrypted gradients into a new, improved Global Model without ever possessing the decryption keys. This makes it mathematically impossible for the cloud provider, regulators, or malicious actors to reverse-engineer an individual farm's data from the global model.

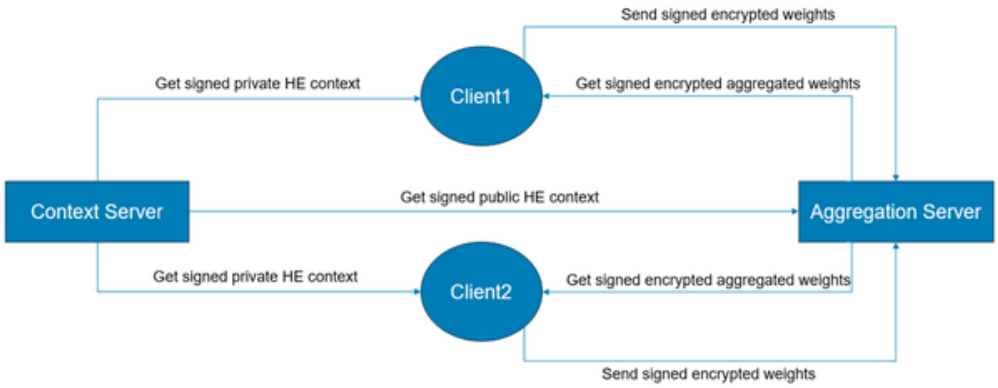

Figure 4: Core components of the proposed ZTFL framework showing the three main entities: Aggregation Server, Clients, and Encryption Context Server, along with their secure communication channels

5.2 Immutable Trust via the interDLT

Optimizing regional water usage requires strict adherence to regulatory quotas established by Water Authorities. However, enforcing these quotas usually requires farmers to submit their private operational logs to a central database, a process heavily resisted due to privacy concerns. To ensure total transparency for regulators without compromising the confidentiality of the farmers, GEORGIA integrates a specialized Distributed Ledger Technology (DLT) component.

The platform relies on a private, on-premise infrastructure based on the goQuorum stack. It utilizes the IBFT (Istanbul Byzantine Fault Tolerance) consensus mechanism. IBFT is specifically chosen because it offers immediate block finality and high throughput without the massive energy consumption or variable “gas fees” associated with Proof-of-Work networks. Smart contracts deployed on this private ledger automatically facilitate the secure recording of water quotas, daily consumptions, and automated irrigation actuations.

To preclude any possibility of historical revisionism by internal actors and to provide irrefutable proof of data integrity to external auditors, the platform employs a hybrid cryptographic bridge:

- A dedicated Relayer Service periodically scans the private Quorum ledger for newly minted blocks containing validated actuation logs (e.g., “Irrigation Event #1024: 50mm Consumed”).

- Instead of transmitting these individual, sensitive transactions to a public chain (which would violate privacy and incur massive transaction fees), the Relayer aggregates them into a cryptographic Merkle Tree.

- The Merkle Root (a single, mathematically unique cryptographic digest representing thousands of private transactions) is submitted as an anchoring transaction to a public blockchain (e.g., Ethereum Mainnet or the Sepolia testnet).

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This hybrid approach represents a profound leap forward. It guarantees that seasonal water quotas are mathematically auditable by third parties. An auditor can hash a farmer's local log and trace it up the Merkle Tree to the public root; if the private data was altered retroactively, the hashes will fail to align. Thus, compliance is proven irrefutably, while the daily operational strategies and raw consumption data remain entirely private.

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6. Bridging the Gap: Explainable AI (XAI)

The sophisticated outputs generated by the biophysical simulation models and the federated machine learning pipelines are synthesized by the GEORGIA "Agri-Brain" into specific, actionable smart irrigation scenarios. The Simulation Runner component continuously instantiates parallel variations of the digital twins to conduct predictive "What-If" analyses.

Examples of these specialized scenarios include:

- Regulated Deficit Irrigation (RDI): Intentionally inducing mild, calculated water stress outside of sensitive phenological windows to save water without impacting final yield.

- Heat Shock Mitigation: Proactively triggering sub-daily, micro-sprinkler evaporative cooling cycles when hyper-local AI weather models predict temperatures exceeding critical thresholds, strictly bounded by relative humidity to prevent fungal outbreaks.

- PDO Quality Preservation: Modeling winter recharge deficits to apply precise, minimal supplemental irrigation to traditional dry-farmed vineyards (e.g., Santorini Assyrtiko), ensuring vine survival while preserving the moderate water stress necessary for high-quality terroir expression.

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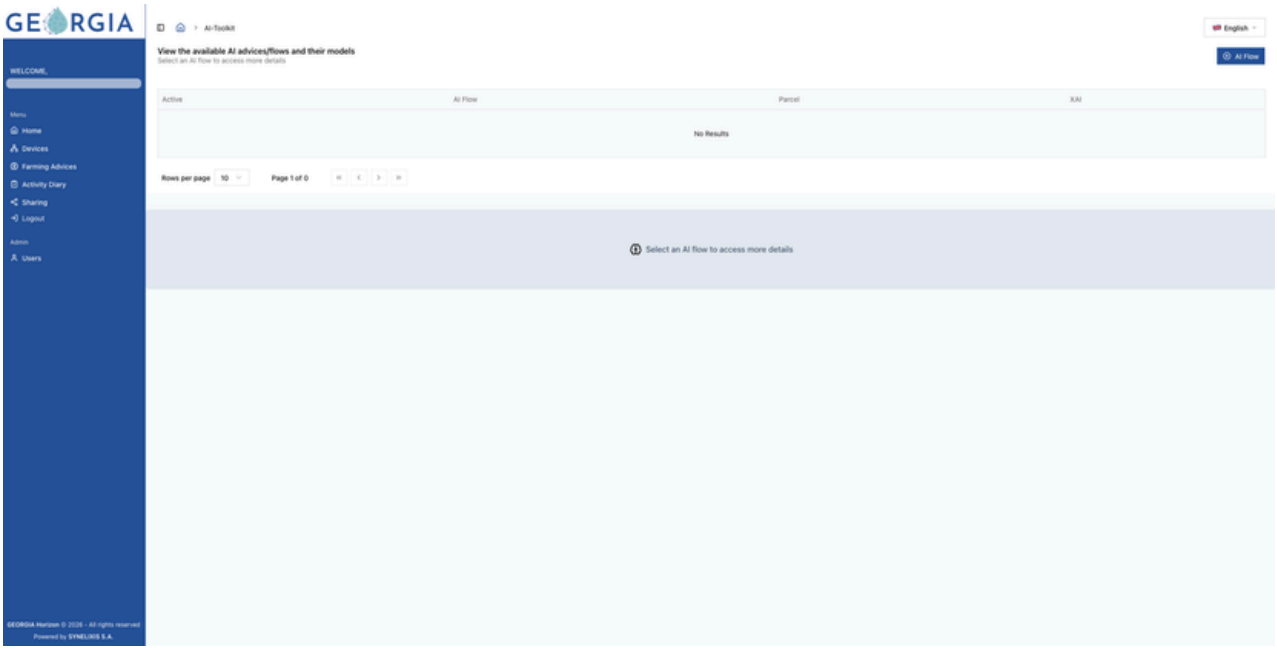

Figure 5: Farming Advice page

Even with robust physics engines and secure blockchains, human operators will routinely ignore an algorithm's advice if it operates as an opaque “black box”. To foster high user adoption, the platform ensures that every automated decision is transparent and interpretable.

Integrating advanced XAI toolkits (such as SHapley Additive exPlanations - SHAP, and LIME), the system mathematically calculates the exact marginal contribution of each input feature to a specific algorithmic recommendation. This raw data is then fed into a Natural Language Generation (NLG) engine within the Web Application.

Instead of presenting the farmer with a confusing probability matrix or a blunt command, the dashboard translates the data into highly readable, contextual justifications. For example, rather than simply stating, “Command: Irrigate 25mm,” the NLG engine outputs: “Recommendation: Irrigate 25mm tomorrow morning. Justification: Soil moisture in the critical 30cm root zone has dropped below the target threshold (contributed +45% to decision), and the 72-hour forecast indicates a high probability of severe heat stress during flowering (contributed +35% to decision)”.

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7. Conclusion

The GEORGIA platform demonstrates that advancing agricultural resilience in the face of climate change requires significantly more than generalized software overlays or simple IoT dashboards. By architecting a platform that dynamically orchestrates specialized biophysical engines, runs proactive agronomic scenarios, secures sensitive operational data through post-quantum federated learning, anchors regulatory trust in a hybrid blockchain, and translates complex probabilities into explainable human insights, the project establishes a highly scalable, scientifically rigorous blueprint for the "Digital Future Farm." Through this multi-layered approach, GEORGIA proves that technology and agroecology can align to make every drop of water count.

For more information on our pilots and technical progress, visit georgia-horizon.eu.

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