Demeter - Product Requirements Document

AI-Powered Digital Twin for Smallholder Maize Production

Version: 1.0
Date: February 25, 2026
Team: 3-4 members (Frontend, Backend/Java, AI Engineer, Hardware)

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1. Executive Summary

Demeter is an AI-powered Digital Twin platform that helps smallholder maize farmers in Sub-Saharan Africa predict climate risks and simulate farming decisions before committing resources.

One-Liner

> An AI farm co-pilot that lets farmers test "what-if" scenarios and receive SMS-based decision guidance.

Key Value Proposition

- **Predict** drought stress 7-14 days ahead
- **Simulate** scenarios (dry spells, delayed planting, irrigation changes)
- **Alert** farmers via SMS with actionable recommendations

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2. Problem Statement

- Sub-Saharan Africa loses **$4B+ annually** in maize production due to climate volatility
- Smallholder farmers (80% of food production) make decisions **blind to near-term risks**
- A single misjudged decision during dry spell = **30-50% yield loss**

Target Persona

Amina, 38, Kaduna State, Nigeria - Grows maize on 1.5 hectares - Feature phone, uses mobile money - Rain-fed agriculture - Lost 45% of harvest last season to unexpected dry spell

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3. Solution Overview

```
+------------------------------------------------------------------+
|                           DEMETER FLOW                           |
+------------------------------------------------------------------+
|                                                                  |
|   SENSOR DATA          WEATHER API         SYNTHETIC DATA        |
|       |                     |                    |               |
|       +---------------------+--------------------+               |
|                             |                                    |
|                             v                                    |
|                    +-------------------+                         |
|                    |   JAVA BACKEND    |                         |
|                    |   (Spring Boot)   |                         |
|                    |   - REST API      |                         |
|                    |   - Data Store    |                         |
|                   +--------+---------+                           |
|                            |                                     |
|                            v                                     |
|                   +------------------+                           |
|                   |   ML SERVICE     |                           |
|                   |   (Python)       |                           |
|                   |   - Ensemble     |                           |
|                   |   - Simulation   |                           |
|                   +--------+---------+                           |
|                            |                                     |
|            +---------------+---------------+                     |
|            v               v               v                     |
|       +---------+    +----------+    +----------+               |
|       |DASHBOARD|    |   SMS    |    |   API    |               |
|       |(Next.js)|    |(Africa's |    | Response |               |
|       |         |    | Talking) |    |          |               |
|       +---------+    +----------+    +----------+               |
|                                                                  |
+------------------------------------------------------------------+
```

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4. Core Features

ID	Feature	Priority	Owner
F1	Sensor data ingestion (real + synthetic)	P0	Backend + Hardware
F2	Weather data integration (Open-Meteo)	P0	Backend
F3	ML Ensemble prediction engine	P0	AI Engineer
F4	Scenario simulation API	P0	AI Engineer + Backend
F5	Dashboard with risk visualization	P0	Frontend
F6	SMS alerts via Africa's Talking	P1	Backend
F7	Farm management (CRUD)	P1	Backend + Frontend

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5. ML Ensemble Architecture

```
+------------------------------------------------------------------+
|                      ML ENSEMBLE                                 |
+------------------------------------------------------------------+
|                                                                  |
|  +------------------+  +------------------+  +----------------+  |
|  |  PHYSICS MODEL   |  |  RANDOM FOREST   |  |    LSTM        |  |
|  |  (Water Balance) |  |  (Classifier)    |  |  (Forecaster)  |  |
|  |                  |  |                  |  |                |  |
|  |  Hargreaves ET0  |  |  Stress classes: |  |  14-day        |  |
|  |  FAO-56 Kc       |  |  None/Low/Med/   |  |  rolling       |  |
|  |  Soil deficit    |  |  Severe/Critical |  |  prediction    |  |
|  |                  |  |                  |  |                |  |
|  |  Weight: 0.4     |  |  Weight: 0.35    |  |  Weight: 0.25  |  |
|  +--------+---------+  +--------+---------+  +--------+-------+  |
|           |                     |                     |           |
|           +---------------------+---------------------+           |
|                                 |                                 |
|                                 v                                 |
|                    +--------------------+                         |
|                    |   META-LEARNER     |                         |
|                    |   Weighted Average |                         |
|                    +----------+---------+                         |
|                               |                                   |
|                               v                                   |
|                    +--------------------+                         |
|                    |  OUTPUT            |                         |
|                    |  - Stress Index    |                         |
|                    |  - Risk Category   |                         |
|                    |  - Confidence      |                         |
|                    |  - Recommendation  |                         |
|                    +--------------------+                         |
|                                                                   |
+-------------------------------------------------------------------+
```

Model Inputs

- Soil moisture (%)
- Temperature (C)
- Humidity (%)
- Rainfall (mm) - actual + forecast
- Crop growth stage
- Days since last rain

Model Outputs

- `stress_index`: 0-100
- `risk_category`: None | Low | Moderate | Severe | Critical
- `confidence`: 0-1
- `days_to_critical`: integer
- `recommendation`: string

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6. Tech Stack

Layer	Technology	Owner
Frontend	Next.js 14 + TypeScript + Tailwind + Recharts	Frontend Dev
Backend API	Java 17 + Spring Boot 3	Backend Dev
ML Service	Python 3.11 + FastAPI + scikit-learn + TensorFlow	AI Engineer
Database	PostgreSQL	Backend Dev
Hardware	ESP32 + DHT22 + Soil Moisture Sensor	Hardware Engineer
Weather API	Open-Meteo (free)	Backend Dev
SMS	Africa's Talking	Backend Dev
Hosting	Vercel (FE) + Railway (BE + ML)	All

7. API Contracts

7.1 Sensor Data Ingestion

```
POST /api/v1/sensor-data
{
  "farm_id": "uuid",
  "soil_moisture": 45.2,
  "temperature": 32.5,
  "humidity": 65.0,
  "timestamp": "2026-02-25T10:30:00Z"
}
```

7.2 Get Prediction

```
GET /api/v1/farms/{farm_id}/prediction

Response:
{
  "farm_id": "uuid",
  "stress_index": 72,
  "risk_category": "SEVERE",
  "confidence": 0.85,
  "days_to_critical": 4,
  "recommendation": "Irrigate 25mm within 3 days",
  "forecast": [
    {"day": 1, "stress": 72},
    {"day": 2, "stress": 76},
    ...
  ]
}
```

7.3 Run Simulation

```
POST /api/v1/farms/{farm_id}/simulate
{
  "scenario": "DRY_WEEK",
  "parameters": {
    "duration_days": 14,
    "rainfall_mm": 0
  }
}

Response:
{
  "baseline": {"stress_index": 45, "yield_impact": 0},
  "simulated": {"stress_index": 82, "yield_impact": -35},
  "recommendation": "Irrigate 25mm before day 3 to avoid critical stress"
}
```

7.4 Send SMS Alert

```
POST /api/v1/alerts/sms
```

```
{
  "farm_id": "uuid",
  "phone": "+2348012345678",
  "language": "en"  // or "ha" for Hausa
}
```

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8. Database Schema

```
+------------------------------------------------------------------+
|                         DATABASE SCHEMA                          |
+------------------------------------------------------------------+
|                                                                  |
|  +----------------+         +----------------+                   |
|  |     FARMS      |         |  SENSOR_DATA   |                   |
|  +----------------+         +----------------+                   |
|  | id (PK)        |----+    | id (PK)        |                   |
|  | name           |    |    | farm_id (FK)   |<----+             |
|  | location       |    |    | soil_moisture  |     |             |
|  | size_hectares  |    |    | temperature    |     |             |
|  | crop_type      |    |    | humidity       |     |             |
|  | planting_date  |    |    | timestamp      |     |             |
|  | growth_stage   |    |    +----------------+     |             |
|  | owner_phone    |    |                          |             |
|  | created_at     |    |    +----------------+     |             |
|  +----------------+    |    |  PREDICTIONS   |     |             |
|                        |    +----------------+     |             |
|                        |    | id (PK)        |     |             |
|                        +--->| farm_id (FK)   |     |             |
|                             | stress_index   |     |             |
|                             | risk_category  |     |             |
|                             | confidence     |     |             |
|                             | recommendation |     |             |
|                             | created_at     |     |             |
|                             +----------------+     |             |
|                                                    |             |
|  +----------------+         +----------------+     |             |
|  |  SIMULATIONS   |         |    ALERTS      |     |             |
|  +----------------+         +----------------+     |             |
|  | id (PK)        |         | id (PK)        |     |             |
|  | farm_id (FK)   |<--------| farm_id (FK)   |-----+             |
|  | scenario_type  |         | alert_type     |                   |
|  | parameters     |         | message        |                   |
|  | baseline       |         | sent_at        |                   |
|  | result         |         | status         |                   |
|  | created_at     |         +----------------+                   |
|  +----------------+                                              |
|                                                                  |
+------------------------------------------------------------------+
```

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9. Simulation Scenarios

Scenario	Parameters	Use Case
`DRY_WEEK`	duration_days, rainfall_mm=0	"What if no rain for 14 days?"
`DELAYED_PLANTING`	delay_days	"What if I plant 2 weeks late?"
`IRRIGATION_TEST`	irrigation_mm	"What if I irrigate 20mm now?"
`CUSTOM`	Any overrides	Free-form scenario

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10. Hardware Specification

Components

- **MCU:** ESP32 DevKit (~$5)
- **Temp/Humidity:** DHT22 (~$3)
- **Soil Moisture:** Capacitive sensor (~$2)
- **Power:** 5V USB or solar panel

Wiring Diagram

```
ESP32 DevKit
+----------------------+
|                      |
|  GPIO4  <------------ DHT22 Data
|  GPIO32 <------------ Soil Moisture Analog
|  3.3V   ----------->  Sensor VCC
|  GND    ----------->  Sensor GND
|                      |
|  WiFi ------------->  Cloud API
|                      |
+----------------------+
```

Data Transmission

- Read sensors every **5 minutes**
- POST to `/api/v1/sensor-data`
- Retry with exponential backoff on failure

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11. Dashboard Wireframe

```
+------------------------------------------------------------------+
|  DEMETER                                    [Amina's Farm v]     |
+------------------------------------------------------------------+
|                                                                  |
|  +-----------------------------+  +--------------------------+   |
|  |     CURRENT RISK            |  |    7-DAY FORECAST        |   |
|  |                             |  |                          |   |
|  |         +-----+             |  |    ------------------    |   |
|  |         | 72  |             |  |   /                  \   |   |
|  |         |     |             |  |  /                    \  |   |
|  |         +-----+             |  | /                      \ |   |
|  |        SEVERE               |  |--------------------------+   |
|  |                             |  | M  T  W  T  F  S  S      |   |
|  |  Days to Critical: 4        |  |                          |   |
|  +-----------------------------+  +--------------------------+   |
|                                                                  |
|  +-----------------------------+  +--------------------------+   |
|  |     SENSOR DATA             |  |    SIMULATION            |   |
|  |                             |  |                          |   |
|  |  Soil Moisture: 32%         |  |  [Dry Week      v]       |   |
|  |  Temperature:   34C         |  |                          |   |
|  |  Humidity:      45%         |  |  Duration: [14] days     |   |
|  |  Last Rain:     5 days ago  |  |                          |   |
|  |                             |  |  [Run Simulation]        |   |
|  +-----------------------------+  +--------------------------+   |
|                                                                  |
|  +----------------------------------------------------------+   |
|  |  RECOMMENDATION                                          |   |
|  |                                                          |   |
|  |  ! Irrigate 25mm within 3 days to avoid 35% yield loss   |   |
|  |                                                          |   |
|  |  [Send SMS Alert]                                        |   |
|  +----------------------------------------------------------+   |
|                                                                  |
+------------------------------------------------------------------+
```

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12. Team Responsibilities

Member	Role	Deliverables
Frontend Dev	Dashboard	Next.js app, charts, simulation UI
Backend Dev (Java)	API + Integration	Spring Boot API, DB, Africa's Talking, Open-Meteo
AI Engineer	ML Service	Python FastAPI, ensemble models, simulation engine
Hardware Engineer	IoT	ESP32 firmware, synthetic data generator

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13. Demo Script (5-7 min)

1. **Hook (30s):** "Amina lost 45% of her maize last season. What if she could have seen it coming?"
2. **Dashboard Tour (1 min):** Show current farm health, sensor data
3. **Simulation Demo (2 min):**
   - Click "Simulate Dry Week (14 days)"
   - Watch stress index climb from 45 to 82
   - Show "Critical in 4 days" warning
4. **SMS Alert (30s):** Send alert, show message on phone
5. **Architecture (30s):** Quick diagram slide
6. **Scale Story (1 min):** "One farm to Platform to Insurance data"
7. **Close (30s):** "Demeter gives farmers foresight. Help us scale it."

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14. Success Metrics

Metric	Target
Sensor to Prediction latency	< 5 seconds
Prediction accuracy (vs FAO baseline)	+/- 15%
Simulation response time	< 2 seconds
SMS delivery success	> 95%

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15. External Services

Service	Purpose	Signup
Open-Meteo	Weather data	No API key needed
Africa's Talking	SMS	https://africastalking.com (free sandbox)
Railway	Backend hosting	https://railway.app
Vercel	Frontend hosting	https://vercel.com

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16. Risk Mitigation

Risk	Mitigation
Hardware fails during demo	Synthetic data generator as fallback
ML model inaccurate	Physics model provides baseline guarantee
API rate limits	Cache weather data, batch requests
SMS not delivered	Show SMS in dashboard as backup

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17. Project Structure

```
demeter/
|-- README.md
|-- PRD.md
|-- backend/                    # Java Spring Boot
|   |-- src/main/java/
|   |-- pom.xml
|   +-- ...
|-- ml-service/                 # Python FastAPI
|   |-- app/
|   |   |-- main.py
|   |   |-- models/
|   |   |   |-- water_balance.py
|   |   |   |-- random_forest.py
|   |   |   |-- lstm.py
|   |   |   +-- ensemble.py
|   |   |-- simulation/
|   |   +-- synthetic/
|   |-- requirements.txt
|   +-- ...
|-- frontend/                   # Next.js
|   |-- src/
|   |-- package.json
|   +-- ...
+-- hardware/                   # ESP32 Arduino
    |-- demeter_sensor/
    |   +-- demeter_sensor.ino
    +-- ...
```

Let's build this and win!