

SUPPLEMENTARY MATERIAL

Manuscript Title: Multi-Sensor Approach for Early Crop Disease Detection: Socio-Economic and Ecological Implications

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Table S1: Hardware and software tools in the multi-sensor approach

Category	Model
Hyperspectral sensor	ASD FieldSpec 4 HR spectroradiometer (Exp 1) Headwall Nano-Hyperspec camera mounted on a DJI Matrice 300 drone (Exp 2, 3)
SIF sensor	Ground-based sensor Fluorescence bOX (FLOX) containing two spectrometers: high-spectral resolution QE6500 PRO & FLAME VNIR spectrometer (400-1000 nm)
Thermal Infrared sensor	DJI Zenmuse XT2 camera mounted on a DJI Matrice 210 drone
LiDAR sensor	DJI Zenmuse L1 sensor mounted on a DJI Matrice 300 drone
Data processing softwares	FLIR ResearchIR software Agisoft Metashape photogrammetry software DJI Terra and GeoSLAM Connect

Table S2: Overview of digital transition implications at process-level

Process Dimension	Process-before	Process-after	Implications
Detection Timing	Post-symptom	Pre-symptomatic	Reduced probability of irreversible losses
Monitoring effort	Manual, periodic	Sensor-based, continuous	Labour reallocation
Decision trigger	Experience-based	Data-driven	Lower uncertainty
Intervention strategy	Reactive	More targeted & anticipatory	Potential input savings

Table S3: Costs Incurred and the associated temporal stage

Cost category	Costs	Code	Stage
Operational expenses (OPEX)	Infrastructure maintenance and repairs - hardware (drones, sensors, other devices), software (data processing, field mapping)	5INh 6INs 7MR	These costs emerged during the set-up (S) and implementation (I) stages, and these are typically regarded as substantial upfront capital investments
	Licensing and subscription charges for software and applications	8Lics	They emerged primarily in the operation (O) stage
	Systems upgrading, materials and electricity costs	9Up 10Mat 11E	These are distributed across all the three stages (S,I,O)

Training and human capital costs	Costs for hiring skilled personnel, encompassing instrument technicians and data processing specialists	0SL	These are generated in the set-up (S) and implementation (I) stage of the technology; however, they can extend to the operation (O) stage unless the end-user acquires the required technical and political capabilities.
Coordination and integration costs	Interoperability challenges between different sensor types or software systems, data exchange burdens from processing large volumes of high-resolution imagery and the need to synchronise data collection schedules, all contributed to these costs.	1CC 2CPI	These costs spanned across all three stages of technology implementation (S,I,O) as it required investments in data management infrastructure, software integration and workflow coordination, which are crucial in all stages of the multi-sensor approach development
Transition costs	Transition costs are the expenses due to shifting practices such as time spent in acquisition of new skills and adapting the system for site and time specific data collection	12DS 13Ppr 14Dr 15Dm 16SsD 17Tdc	These are generated in the Set-up (S) and implementation (I) stages, when the researchers try to adapt to new practices of data collection and data management.

Governance and compliance costs	These costs emerged from the need to ensure compliance with the data protection standards, managing and negotiating data-sharing, data ownership contracts and ensuring adherence to regulatory procedures	18Ps 19DS	Privacy and security costs are spread across all the three stages (S,I,O), starting from setting up protocols for secure data exchanges, ensuring compliance to continuous management of risks. Data sharing costs mainly occurred at the operation (O) stage, where the data exchange became mandatory
Risk and uncertainty costs	These costs are due to technology implementation overruns, where projects exceed initial estimates due to misjudged complexity, technical failures or training delays and integration challenges, including system incompatibilities, process misalignments and data inconsistencies	3TRM	They emerged primarily in the implementation (I) and operation (O) stages, when the stakeholders face unforeseen weather challenges during the flight operation

Note: For the detailed information on codes, refer to the Figure A.1

Table S4: Impact distribution across different stakeholder groups

Stakeholder group	Task	Implication
Agri-environmental researcher	Invested in designing experiments & validating sensor outputs	Gained access to high-resolution datasets and new scientific knowledge
Instrument technician	Held the responsibility of calibrating sensors, troubleshooting hardware and ensuring reliable system performance	Developed specialised technical skills
Data processing specialist	Undertaken the workload of cleaning, integrating and analysing complex multi-sensor datasets	Gained expertise in advanced analytics and contributed to decision-making that improved disease management efficiency
Technology provider	Invested in R&D, prototyping and system integration to support the experiment	Benefitted from opportunities to test hardware and software, establish partnerships and demonstrate the applicability of their technologies in real-world scenarios
Public authority	Incurred costs through funding, staff training and integrating remote sensing into policy frameworks	Benefitted from improved monitoring of compliance and evidence-based policymaking

Farmer (If the technology is scaled up)	May incur huge expenses related to infrastructure, data access, time spent learning to use technology or hiring professionals	Benefit from early detection, targeted interventions, reduced crop losses and optimised input use
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Note: The implications were derived by analyzing the tasks, responsibilities, and resource commitments of each stakeholder within the case study and assessing their associated costs, benefits, and capability gains using the CBA framework. Farmer-related implications refer to a potential large-scale deployment scenario.

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Stages: Set-up (S) Implementation (I) Operation (O)			
Cost-Benefits checklist			
Stages: Set-up (S) Implementation (I) Operation (O)			
Labor	V/N	Code	Stage
Internal			
Specialised labor	Y	0SL	S, I
Initial Training			
Digital Skills Development			
External			
IT Consultancy Fees/Specialized third-party			
Management			
Organizational Change			
Digital Adoption Resistance			
Coordination/Communication Costs	Y	1CC	S, I
Collaboration Platform Integration	Y	2CPI	I, O
Trust/Motivation Enhancement Campaigns			
Risk Management			
Development			
Implementation			
Technological	Y	3TRM	O
Capital expenditures (CAPEX)			
Infrastructure costs (Hardware)			
Infrastructure costs (Software)			
Hardware/Technology (equipment)			
Softwares			
Licenses (one-time investment)			
Internet access	Y	4Int	O
Operating Expenses (OPEX)			
Infrastructure costs (Hardware)	Y	5INh	S
Infrastructure costs (Software)	Y	6INs	S
Maintenance and Repairs	Y	7MR	O
Licenses (subscription basis)	Y	8Lic	O
System Upgrading	Y	9Up	O
Materials	Y	10Mat	O
Electricity	Y	11E	O
Usage			
Disposal			
Transition			
Learning Opportunity Costs			
Business Process Re-engineering (BPR)			
System Customization			
Standardization	Y	12Ds	I, O
Data Pre-processing	Y	13Ppr	I, O
Data Reconciliation	Y	14Dr	I, O
Data Mining	Y	15Dm	I, O
Site-specific data collection	Y	16sD	I, O
Technological risk			
Implementation risks			
Digital Risk Mitigation			
Time specific data collection	Y	17Tdc	I, O
Transaction			
Data dominance disparity			
Risk of surveillance, discrimination and bias			
Privacy and security	Y	18Ps	I, O
Data sharing	Y	19DS	I, O
Data Colonialism			
Switching costs			
Learning Curve			
Data conversion			
Advanced Monitoring			
Stages: Set-up (S) Implementation (I) Operation (O)			
Social	V/N	Code	Stage
Enhanced Food Standards			
Enhance Food Nutrition	Y	b1FN	O
Enhance Food Safety	Y	b2Fs	O
Human Capital Development			
Improve Labor Environment	Y	b3LE	O
Rural Development			
Increase community cohesion			
Social Sustainability in Agriculture			
Enhance Well-being			
Reduce farm abandonment			
Enhance Knowledge and Transfer	Y	b4Kt	O
Socioeconomic Empowerment			
New quality employment opportunities			
Enhance Equity and Financial Inclusion			
Supply chain Resilience			
Enhance Food Resilience	Y	b5FR	O
Env. Protection and Ethical responsibility	Y	b6ER	O
Enhance responsible res. management	Y	b7RRm	O
Sustainable Rural Development			
Enhance Socioeconomic Opportunities			
Economic			
Business and Economic Growth			
Increased business profits	Y	b8BP	O
Economic Growth and Livelihood			
Enhanced Selling Price	Y	b9SP	O
Enhance Production, Quality, and Revenue	Y	b10PQ	O
Enhance Revenues (through SFSC)			
Enhance Access to Funding Opp.	Y	b11AF	O
Reduce investment in infrastructure			
Improved Decision Making			
Data-Driven Sales Opt. and Customer Intelligence			
Data-Driven Efficiency	Y	b12DE	O
Accelerate Problem Solving and Innovation	Y	b13PS	O
Enhance Product Quality	Y	b14Pq	O
Financial Well-being Enhancement			
Income Preservation and Opportunity Maximization			
Operational Efficiency			
Enhanced Agricultural Efficiency	Y	b15Ae	O
Enhanced Growth	Y	b16Eg	O
Reduced recurring costs	Y	b17RC	O
Optimized Agricultural Logistics	Y	b18AL	O
Increase productivity	Y	b19Ip	O
Enhanced Substitution Strategies	Y	b20ss	O
Improved Management	Y	b21IM	O
Increased work productivity	Y	b22wp	O
Cost-Efficient Digital Adoption	Y	b23da	O
Increased connectivity and technology accessibility	Y	b24lc	O
Trade and Market Development			
Enhanced Market Access and Information			
Enhanced Global Market Integration			
Environmental			
Biodiversity Conserv. and Ecological Balance			
Ecological improvement, biodiversity	Y	b25Ei	O
Environmental and Social Enhancement			
Facilitated Sustainable Transitions	Y	b26ST	O
Environmental Sustainability			
Strengthened Robustness	Y	b27SR	O
Enhanced Adaptability	Y	b28EA	O
Sustainable Resource Optimization	Y	b29RO	O
Land Conservation (e.g., red. erosion)			
Resource efficiency			
Enhance resource efficiency	Y	b30RE	O
Enhance resource quality			
Improve air quality			
Reduce GHG	Y	b31RG	O
Sustainable Resource Management			
Enhance Agri-Insight and Adapt.	Y	b32EA	O
Enhance Sustainable Land Use			
Red. in Env. External Costs	Y	b33EC	O
Governance			
Enhanced Decision Making			
Enhanced Data Quality and Utilization	Y	b34Du	O
Innovation and Collaboration			
Catalyze Innovative Ecosystems	Y	b35Ie	O
Operational Efficiency			
Search Optimization			
Transaction Optimization			

Figure S1: Cost-benefit evaluation of the technology

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