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

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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)

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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.

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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

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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

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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

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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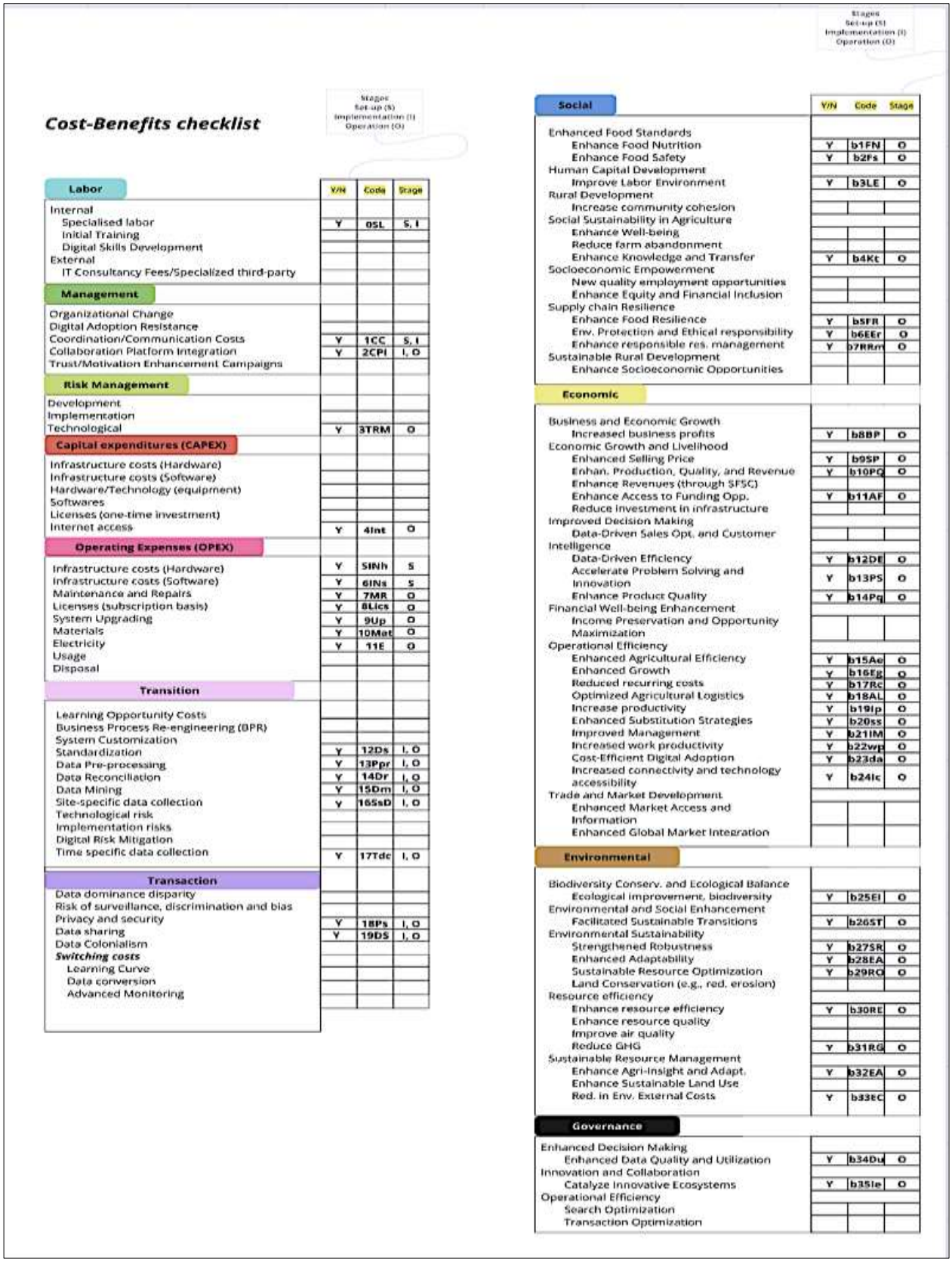

Figure S1: Cost-benefit evaluation of the technology

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