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A Circular Data Economy Architecture for Precision Agriculture: Responsible Reuse of Farm Data Across Production, Sustainability Reporting, Finance, and Insurance

Lukas Weber^{1*}, Sophie Janssen², Jonas Richter¹, Elena Fischer³

Abstract

Precision agriculture generates expanding volumes of sensor, machinery, remote-sensing, weather, soil, crop, livestock, operational, input-use, resource-use, and farm-management data. Although these data are commonly collected for immediate production purposes, they may also support sustainability reporting, environmental accountability, agricultural finance, insurance, and risk assessment. Such secondary use creates the possibility of a circular data economy in which curated farm data are responsibly reused across several applications and subsequently improved through feedback. This article proposes an original conceptual architecture for organizing these reuse pathways while preventing circularity from becoming uncontrolled extraction, opaque scoring, or unequal value capture. The architecture connects farm data generation and collection with quality and provenance review, metadata curation, consent and purpose limitation, data stewardship, interoperability, production analytics, sustainability reporting, finance and insurance applications, farmer protection, auditability, and feedback updating. It distinguishes analytical usefulness from implementation readiness and places governance gates before each consequential reuse pathway. Production reuse is treated as conditional decision support rather than a productivity guarantee; sustainability reuse is treated as bounded evidence rather than automatic reporting accuracy; and finance or insurance reuse is subject to data-quality, bias, fairness, transparency, and dispute requirements. The principal contribution is a structured circular data economy architecture that clarifies how agricultural data may circulate across domains while preserving farmer agency, contextual integrity, accountability, and explicit legal, financial, insurance, and deployment boundaries.

Keywords Precision agriculture, Data governance, Circular data economy, Farm data reuse, Sustainability reporting, Agricultural finance

*Correspondence:

Lukas Weber

lukas.weber@uni-stuttgart.de

¹ Department of Circular Data Economy and Agriculture, Faculty of Agriculture, University of Stuttgart, Stuttgart, Germany

² Department of Responsible Farm Data Reuse, Faculty of Agricultural Sciences, Eindhoven University of Technology, Eindhoven, Netherlands

³ Department of Sustainability Reporting and Agricultural Finance, Faculty of Agriculture, University of Basel, Basel, Switzerland

Introduction

Precision agriculture increasingly depends on interconnected processes through which farm observations are generated, transferred, processed, analysed, and translated into decision-relevant information. These processes may involve sensors, agricultural machinery, remote-sensing platforms, weather services, farm-management systems, advisory tools,

analytics providers, and other actors operating across an agricultural data chain. The value of farm data therefore does not arise solely from the act of collection. It depends on whether data retain sufficient quality, context, interoperability, and analytical relevance as they move between technical systems and organizational settings. Smart-farming research has shown that agricultural big-data applications are embedded in broader configurations of technologies, stakeholders, business relationships, and governance arrangements rather than functioning as isolated analytical tools [1].

A circular data economy extends this observation by asking how farm data generated for one legitimate purpose may be responsibly reused for another. Circularity in this context does not mean unrestricted replication or perpetual commercial exploitation. It refers to governed movement through a sequence of generation, validation, curation, authorized reuse, value creation, accountability, and feedback updating. The arrangement is socio-technical because its operation depends not only on databases and analytical models but also on institutions, professional roles, farmer capabilities, organizational incentives, and unequal distributions of knowledge and power. Research on digital agriculture has accordingly emphasized that technological change must be examined through social, institutional, ethical, and innovation-system perspectives alongside its technical performance [2].

The possibility of secondary reuse creates both opportunities and unresolved tensions. Farm data initially collected to support irrigation, nutrient management, disease monitoring, machinery operation, or crop forecasting may later be requested for sustainability indicators, supply-chain documentation, financial analysis, insurance design, or agricultural risk assessment. However, the existence of data does not establish that a proposed reuse is authorized, reliable, proportionate, or beneficial to the farmer. Agricultural big-data scholarship has identified continuing questions concerning ownership, privacy, security, access, control, aggregation, and the economic distribution of data-derived value [3]. These questions become especially consequential when farm data influence external assessments that may affect access to services, commercial relationships, environmental scrutiny, or perceived risk.

The conceptual problem is therefore not simply how to extract more value from agricultural data, but how to organize reuse without detaching data from their original context or transferring disproportionate risk to farmers. Digital agricultural development must be assessed in relation to people, production, and environmental consequences rather than through technological capability alone [4]. This article addresses that problem by proposing a circular data economy architecture for precision agriculture. The architecture connects farm data generation with production analytics, sustainability reporting, environmental accountability, finance, insurance, and risk assessment while embedding data-quality controls, provenance, consent, purpose limitation, interoperability, privacy, auditability, fairness review, farmer protection, and feedback mechanisms. It is presented as a conceptual contribution for structuring responsible reuse and future empirical investigation, not as an implemented marketplace, legal standard, financial decision system, insurance product, reporting framework, or deployment-ready technical design.

Farm Data as a Circular Economic Resource

Farm data become a circular economic resource when their value can be renewed through carefully governed reuse rather than exhausted after a single production decision. This potential begins with diverse data-generating activities, including field sensing, machinery operation, satellite or drone observation, weather measurement, soil assessment, crop and livestock monitoring, input application, energy and water use, harvest recording, and farm-management documentation. Raw observations, however, are not automatically reusable assets. They must be transformed through cleaning, contextualization, validation, integration, analysis, and communication before they can support a legitimate secondary purpose. The agricultural data-value literature shows that value creation occurs through staged processes in which data are collected, transformed, combined, interpreted, and connected to decisions or services [5]. A circular architecture must therefore represent data value as conditional on quality, context, stewardship, and application fitness.

The economic value created from farm data must also be distinguished from the value captured by particular actors. A farmer may generate the underlying observations, while machinery manufacturers, platform providers, analytics firms, supply-chain organizations, financial actors, insurers, or public institutions possess greater capacity to aggregate and

operationalize them. Digitalization can alter both how value is produced and who is positioned to appropriate it within an agricultural value chain [6]. Consequently, increased data reuse does not necessarily translate into greater farmer benefit. It may instead increase dependency on proprietary infrastructure, reduce bargaining power, create switching costs, or allow downstream actors to obtain recurring value from data for which farmers receive little control, transparency, or compensation. Fair value distribution must therefore be treated as a governance question rather than assumed to follow from technological participation.

Data-sharing platforms and intermediaries can make circular reuse technically and organizationally possible by coordinating transfers, formats, permissions, service relationships, and analytical functions. They may reduce fragmentation and connect farm information to production services, sustainability applications, public programs, financial analysis, insurance, or supply-chain systems. Research on agricultural data-sharing platforms demonstrates that intermediaries can create value by linking participants and enabling data combinations that would be difficult for isolated actors to assemble [7]. Nevertheless, platform-mediated coordination does not itself establish interoperability, fairness, accountability, or farmer control. The intermediary's role must be bounded by transparent access conditions, purpose-specific authorization, portability, provenance obligations, security controls, and limits on onward disclosure or incompatible secondary use.

Farm participation is particularly sensitive to whether data use is understandable and whether farmers perceive that benefits and responsibilities are distributed credibly. Data stewardship should therefore include accessible explanations of what is collected, who receives it, why it is reused, how long it is retained, what analytical or institutional consequences may follow, and how errors or objections can be addressed. Farmer consent should not be reduced to a one-time acceptance of broad terms that permit indefinite function expansion. It should be specific enough to distinguish production support from sustainability, finance, insurance, and risk-scoring applications. Evidence from smart-farming research links farmer trust to transparency concerning downstream data use and to credible arrangements for benefit sharing [8]. A circular data economy must consequently preserve farmer agency through participation, control, review, withdrawal where feasible, dispute mechanisms, and explicit recognition that data circulation does not guarantee farmer benefit.

Production Analytics and Data Reuse

Production analytics represent the most immediate reuse pathway because many precision-agriculture data are generated to understand farm conditions and support operational decisions. Sensor observations may describe soil moisture, temperature, animal behaviour, machinery status, storage conditions, or environmental variables. Machine records can document field operations, fuel use, task timing, application rates, and equipment performance. Remote-sensing, weather, soil, crop, livestock, input-use, operational, and farm-management data can be combined to support classification, anomaly detection, forecasting, monitoring, and decision-support functions. Reviews of machine learning in agriculture demonstrate that such methods have been applied across crop production, water management, livestock systems, disease recognition, and farm-management tasks [9]. More advanced deep-learning techniques expand image- and sensor-based analytical capacity, but their validity remains dependent on dataset suitability, model design, and rigorous evaluation rather than architecture complexity alone [10].

Remote-sensing reuse illustrates both the scale of the opportunity and the importance of application-specific controls. Satellite, airborne, or drone-derived observations may contribute to crop-condition assessment, stress detection, field mapping, soil or water analysis, and spatial management. Yet imagery may be affected by atmospheric conditions, sensor resolution, cloud cover, temporal gaps, field size, mixed pixels, crop stage, and insufficient ground observations. Remote-sensing reviews in precision agriculture emphasize that spatial and temporal resolution, calibration, preprocessing, and field validation materially affect the reliability of analytical outputs [11]. Circular reuse may become more iterative when updated observations are connected to digital farm representations, simulation models, and management feedback. Digital-twin concepts illustrate how observations, models, scenarios, and operational responses may form a continuing

update loop, although agricultural digital twins remain a developing concept rather than a universally validated production system [12].

Data reuse across production functions also requires preservation of meaning. A yield value without information on crop identity, field boundary, measurement method, harvest timing, moisture correction, or monitor calibration may be unsuitable for comparison or modeling. Similarly, input-use records require reliable product identities, units, rates, spatial locations, timing, and application context. Water-use estimates require distinctions between withdrawal, application, consumption, and modeled demand. Livestock observations may require animal identification, welfare context, sensor limitations, and restrictions on intrusive monitoring. Crop-data management research shows that increasingly connected agricultural systems depend on coordinated acquisition, storage, integration, interoperability, and contextual data management [13]. Metadata and provenance must therefore accompany reused information so that analysts can determine what each variable represents, how it was generated, and whether it remains fit for the new purpose.

Within the proposed architecture, production analytics form a governed application layer rather than an unrestricted destination for all available data. Data must first pass quality, provenance, authorization, and interoperability checks. Analytical outputs should be presented as bounded evidence, alerts, scenarios, classifications, or decision-support options with documented uncertainty and assumptions. Farm optimization may be included where an objective, constraints, trade-offs, and validation conditions are explicit, but optimization should not be represented as a guaranteed improvement in productivity, profitability, environmental performance, or farmer welfare. Human judgment remains necessary because analytical models may omit local knowledge, operational constraints, crop history, unusual weather, farmer priorities, or emerging conditions. Feedback updating should incorporate observed outcomes, farmer corrections, model errors, and contextual changes through controlled versioning rather than unmonitored automated learning. The production pathway therefore closes a circular loop only when new evidence improves data and models without converting uncertain predictions into compulsory or autonomous farm actions.

Sustainability Reporting and Environmental Accountability

Farm data may also be reused to organize evidence concerning resource use, environmental pressures, and sustainability-related practices. Relevant inputs can include irrigation volumes, nutrient and pesticide applications, machinery fuel use, electricity consumption, soil observations, crop cover, field operations, emissions-related activity data, environmental measurements, and climate-risk information. Smart-farming technologies may support more precise observation and management of agricultural resources, but their sustainability implications depend on how they are implemented, interpreted, and evaluated [14]. The availability of fine-grained data should therefore be understood as an opportunity to strengthen evidence rather than as proof that a farm, technology, or reporting process is sustainable.

A sustainability-reporting reuse pathway must translate operational and environmental observations into indicators with explicit definitions, boundaries, units, methods, and uncertainty. Digital agriculture can support sustainable-system design by integrating field data, models, management information, and scenario analysis [15]. Nevertheless, sustainability evidence is rarely complete, and individual indicators may represent only selected dimensions of a complex farming system. Water-use data, for example, may not capture source scarcity or ecological effects. Nutrient-use indicators may not reveal nutrient availability, losses, soil conditions, or crop requirements. Pesticide-use records may document applications without establishing ecosystem or health outcomes. Soil-health and biodiversity claims require appropriate sampling, baselines, temporal coverage, and scientifically justified indicators rather than inference from general operational data.

Resource-use reporting must also recognize that precision-farming effects vary across technologies, farming systems, regions, and management conditions. Research examining the relationship between precision farming, agricultural production, and environmental performance shows that technology effects are heterogeneous and dependent on adoption, farm context, behavioral responses, and the specific resource being assessed [16]. Operational and input-use data may support calculations concerning fuel, energy, fertilizer, water, pesticide, or other resource use, but comparisons

require harmonized units and consistent system boundaries. Evidence concerning precision-agriculture technologies and greenhouse-gas mitigation further indicates that emissions-related interpretation depends on technology-specific assumptions, management effects, and economic conditions [17]. Carbon or emissions reporting should therefore document activity data, emission factors, estimation methods, versions, exclusions, and uncertainty rather than presenting model-derived values as directly measured or independently verified outcomes.

Environmental accountability introduces additional governance concerns because data may be used not only for learning and reporting but also for monitoring, evaluation, or institutional scrutiny. Digitized agri-environmental governance can increase visibility and traceability while also creating new forms of oversight that affect farmer autonomy [18]. The proposed architecture therefore separates evidence organization from determinations of responsibility, compliance, or environmental causation. Metadata, provenance, auditability, and traceability should allow authorized reviewers to reconstruct how an indicator was produced, while farmer response and correction pathways should permit inaccurate records or contextual omissions to be challenged. Sustainability verifiers may be represented as conditional actors where supported, but their role must be limited to a defined evidence scope. The architecture does not guarantee sustainability accuracy, biodiversity benefit, emissions reduction, or reporting compliance, and it does not replace qualified scientific, reporting, or jurisdiction-specific review.

Finance, Insurance, and Risk Assessment Applications

Farm data may support finance, insurance, and agricultural risk analysis when reuse is tied to a clearly defined question and when the evidence is sufficiently accurate, current, representative, and authorized. Potential inputs include remotely sensed vegetation conditions, weather observations, crop models, yield records, operational histories, climate-risk variables, and farm-management information. Integrative research on agricultural risk management shows that remote sensing, crop modeling, and economic analysis can be combined to improve the characterization of production risks, although each component introduces assumptions and uncertainty [19]. In agricultural finance, remotely sensed vegetation-health indicators have been examined as supplementary variables for explaining credit risk in a specific microfinance context [20]. Such evidence demonstrates a possible reuse pathway but does not justify treating satellite indicators as universal measures of borrower quality, repayment capacity, or creditworthiness.

Insurance applications similarly depend on whether the selected data and index design correspond to the losses experienced by an individual farm. Weather, vegetation, phenology, and production indicators may support index construction, exposure assessment, or claims-related evidence. However, index insurance remains vulnerable to basis risk when the calculated payment trigger does not correspond to actual farm-level loss. Reviews of grassland index insurance show that performance depends on data availability, index structure, geographic scale, farm heterogeneity, and regional conditions [21]. Temporal context is also material: incorporating crop phenology into weather-index design may reduce temporal basis risk by aligning weather exposure more closely with sensitive crop-development periods [22]. Reused data must therefore retain crop stage, location, season, measurement method, and uncertainty rather than being converted into decontextualized risk variables.

A quality gate is especially important when remote-sensing products are reused in financial or insurance settings. Different satellite products may represent vegetation or production conditions differently because of sensor characteristics, spatial resolution, processing methods, temporal frequency, cloud contamination, and calibration choices. Research evaluating remote-sensing products for agricultural index insurance demonstrates that product quality must be assessed specifically for the intended insurance function rather than inferred from general technical reputation [23]. Provenance records should identify the source product, processing history, spatial and temporal coverage, transformation steps, validation data, and known limitations. When quality is inadequate or provenance is incomplete, the data should be excluded, flagged for human review, or restricted to exploratory analysis.

Consequential reuse also requires procedural safeguards beyond predictive accuracy. Risk scores may compress heterogeneous farm conditions into a single classification that conceals missing data, regional disadvantage, unusual

management practices, or the weaker digital records of smaller farms. Bias assessment should examine whether errors differ across crops, farm scales, regions, production systems, or levels of digital access. Fairness review should consider both model performance and the practical distribution of benefits, exclusions, and opportunities. Farmers should receive understandable information about what data were used, the purpose of the analysis, the limits of the result, and the responsible decision-maker. Correction, appeal, and dispute pathways should be available where outputs may affect access or treatment. The architecture therefore treats finance and insurance data reuse as bounded evidentiary support, not as proof of financial fairness, insurance fairness, creditworthiness, insurability, or underwriting readiness.

Table 1 summarises responsible farm data reuse pathways across production analytics, sustainability reporting, finance, insurance, and risk assessment.

Table 1. Responsible Farm Data Reuse Pathways in a Circular Data Economy for Precision Agriculture: Production Analytics, Decision Support, Sustainability Reporting, Environmental Accountability, Resource-Use Reporting, Finance Applications, Insurance Applications, Risk Assessment, Bias Review, Fairness Boundaries, and Farmer Protection

Reuse pathway	Core reuse question	Required data or condition	Reuse function	Potential output	Failure or fairness risk	Governance or validation need	
Production analytics	What farm condition or pattern is relevant to a defined production question?	Validated sensor, machine, crop, soil, weather, imagery, operational, and management data	Descriptive, diagnostic, predictive, or prescriptive analysis	Monitoring indicator, forecast, classification, or decision-support option	Overfitting, model drift, missing context, automation bias	External validation, uncertainty reporting, agronomic review, human oversight	re
Decision support	How should analytical evidence be presented without displacing accountable judgment?	Interpretable outputs, alternatives, uncertainty, farmer objectives, and local context	Translate analysis into bounded options	Alert, scenario, ranked option, or explanation	Inappropriate reliance, information overload, false precision	Usability assessment, override mechanism, responsibility assignment	H
Sustainability reporting	What resource-use or sustainability evidence can be documented within a defined scope?	Validated environmental, operational, input-use, and contextual data	Calculate bounded indicators using documented methods	Sustainability evidence package or qualified indicator	Incomplete scope, false comparability, greenwashing	Metadata, method disclosure, auditability, uncertainty statement	S re
Environmental accountability	What environmental	Environmental observations,	Organize traceable	Environmental-accountability	Unfair attribution,	Provenance, farmer	A re

	action, pressure, or condition is represented by the evidence?	management records, baselines, and attribution limits	evidence for review	record	surveillance, proxy misuse	response, causal caution, proportional review	
Resource-use reporting	How were water, nutrients, pesticides, energy, or other resources used?	Consistent units, boundaries, timing, source records, and allocation rules	Convert operational records into resource-use measures	Water-, nutrient-, pesticide-, fuel-, or energy-use indicator	Measurement error, inconsistent boundaries, unsupported comparison	Reconciliation, calculation audit, domain interpretation	s
Finance application	What authorized farm information is relevant to a defined financial analysis?	Current, purpose-specific, representative, and validated data	Assemble supplementary evidence for human analysis	Bounded financial evidence package	Exclusion of data-poor farms, proxy discrimination, opaque inference	Data minimization, bias review, explanation, human decision authority	f
Credit assessment where supported	Can selected indicators supplement a broader credit assessment?	Appropriate outcome definition, historical evidence, validation, and authorization	Generate a bounded supplementary indicator	Contextual credit-risk input	Misclassification, feedback loops, unsupported borrower ranking	External validation, fairness assessment, correction and appeal	
Insurance application	Can farm and environmental data support a defined insurance function?	Validated exposure, hazard, crop, weather, imagery, and production data	Support index design, monitoring, or evidence review	Candidate insurance index input or claims evidence	Basis risk, unequal coverage quality, inaccessible processes	Product-specific validation, farmer explanation, dispute pathway	re
Risk assessment	Which hazards, exposures, and uncertainties are represented?	Explicit risk definition, time horizon, model assumptions, and contextual evidence	Construct a scenario-specific risk profile	Qualified risk indicator or scenario	Hidden assumptions, omitted vulnerability, deterministic interpretation	Sensitivity testing, uncertainty disclosure, accountable human review	C
Risk scoring boundary	Is compression into a score	Representative data, justified outcome,	Produce a bounded score only	Interpretable indicator with	Ranking bias, structural exclusion,	Independent validation, monitoring,	C

	necessary, valid, and proportionate?	calibration, and explainability	where warranted	confidence or uncertainty	concealment of uncertainty	explanation, right to contest	
Bias review	Do errors or outcomes differ across farm types or contexts?	Subgroup data, representative evaluation, and appropriate metrics	Detect systematic performance disparities	Bias and subgroup-performance report	Aggregate accuracy conceals unequal error	Independent technical and contextual assessment	
Fairness review	Are the process and consequences substantively and procedurally fair?	Technical findings, stakeholder input, impact evidence, and decision context	Examine distributive and procedural effects	Approval conditions, redesign, restriction, or rejection	Metric-only fairness, exclusion of vulnerable farmers	Multidisciplinary and farmer-inclusive oversight	C
Farmer transparency	Can the farmer understand the purpose, data, output, and responsible actor?	Accessible notice, data summary, explanation, and contact pathway	Communicate the reuse process and its limits	Individualized explanation and access record	Opaque scoring and inability to correct errors	Explanation standard, accessible records, response timelines	
Appeal or dispute pathway	Can incorrect data or an adverse use be challenged?	Evidence access, responsible reviewer, timelines, and remediation authority	Correct records and reconsider contested use	Correction, review, or documented resolution	Nominal appeal without authority or transparency	Independent escalation and auditable outcome	
No productivity-guarantee boundary	What cannot be concluded from production analysis?	Explicit limitations and uncertainty	Prevent overstatement of benefit	Qualified decision-support result	Productivity claims unsupported by field outcomes	Outcome evaluation and cautious communication	
No sustainability-accuracy guarantee boundary	What uncertainty remains in sustainability evidence?	Scope and uncertainty statement	Prevent automatic equation of data availability with accuracy	Qualified sustainability output	Unsupported or incomplete claims	Verification and correction process	
No financial-fairness	What cannot be inferred from governed	Distributional and procedural review	Prevent inherent-	Qualified finance application	Digitized exclusion	Continuing fairness	F

guarantee boundary	financial reuse?		fairness claims		presented as objective	monitoring and appeal	
No insurance- fairness guarantee boundary	What cannot be inferred from improved insurance data?	Basis-risk and distributional evidence	Prevent automatic fairness claims	Qualified insurance application	Improved average fit harms individual farms	Product-level evaluation and redress	
Farmer protection	What harms to autonomy, privacy, livelihood, or bargaining position may arise?	Impact assessment, farmer participation, safeguards, and exit conditions	Identify and reduce farmer- facing harm	Protection conditions or reuse rejection	Surveillance, dependency, value extraction, service exclusion	Independent representation and grievance process	

Responsible Data Reuse and Governance Requirements

Responsible reuse begins with recognition that “ownership” does not provide a universally settled answer to every question concerning farm data. Agricultural data may involve overlapping interests associated with farmers, workers, equipment manufacturers, service providers, platforms, contractors, advisers, and public bodies. Contractual access may differ from practical control, and possession of a copy may not establish an unrestricted right to reuse it. Research examining farmer reluctance to share smart-farming data shows that uncertainty regarding rights, access, downstream use, and legal protection can inhibit participation [24]. The architecture therefore begins with a rights-and-interests assessment that documents relevant claims without asserting that all farm data are governed by a single ownership rule. Access permissions should be role-based and purpose-specific, while farmer control should include usable options concerning collection, transfer, correction, retention, and withdrawal where feasible.

Consent and participation must be connected to purpose limitation. A farmer who authorizes use of machinery records for maintenance should not be presumed to have authorized their use for credit analysis, insurance classification, environmental monitoring, or unrelated commercial profiling. Each reuse should have a clear purpose, compatible data scope, identified recipient, retention period, and statement of prohibited use. Ethical analysis of smart farming emphasizes privacy, autonomy, justice, responsibility, and power as core considerations for responsible innovation [25]. Consent should therefore be understandable, revisitable, and sufficiently granular to distinguish lower-consequence operational uses from potentially consequential reporting, financial, insurance, or scoring uses. Where consent is not the appropriate or only governance basis, the responsible basis and limits should still be made transparent and subject to oversight.

Data stewardship provides the organizational function needed to preserve quality, meaning, access discipline, and lifecycle accountability. A named steward should coordinate metadata, provenance, quality checks, corrections, retention, interoperability, portability, and incident handling. Privacy controls should limit unnecessary exposure of location, production, household, worker, or commercially sensitive information. Cybersecurity measures should protect confidentiality, integrity, and availability through authentication, encryption where appropriate, backups, access monitoring, vulnerability management, and response planning. Interoperability should allow authorized data exchange without semantic loss, while portability should permit farmers to obtain usable copies of relevant information and reduce dependence on a single proprietary provider. Political-economy research on digital agriculture warns that infrastructures and platforms may reinforce existing asymmetries of knowledge, access, and value capture [26]. Governance must consequently examine not only whether exchange is technically possible but also who controls standards, interfaces, permissions, and exit conditions.

A responsible circular data economy must also prevent the language of reuse from masking extraction. Precision-agriculture infrastructures can allow farm observations to become accumulated assets controlled by actors outside the farm, potentially increasing surveillance, dependency, and unequal appropriation [27]. Auditability and traceability should reveal who accessed data, how they were transformed, what model or rule was applied, and who was accountable for the resulting use. Bias assessment is mandatory where data contribute to ranking, scoring, eligibility, or differential treatment. Fair value review should identify who provides the data, who bears collection and decision risks, who receives economic or institutional benefits, and whether farmers retain meaningful alternatives. These controls can structure responsible practice, but they do not independently establish legal compliance, eliminate privacy or cybersecurity risk, guarantee fair value distribution, or ensure farmer benefit.

Table 2 maps responsible data reuse and governance requirements for circular farm data economies.

Table 2. Responsible Data Reuse and Governance Requirements for Circular Farm Data Economies: Ownership, Access, Control, Consent, Purpose Limitation, Data Stewardship, Privacy, Cybersecurity, Interoperability, Portability, Provenance, Auditability, Accountability, Fair Value Distribution, Bias Assessment, and Claim Boundaries

Governance requirement	Core responsible-reuse question	Required practice or condition	Governance function	Potential output	Failure risk	Oversight need	Area of impact
Data ownership	What legal, contractual, technical, or practical interests exist in the data?	Document relevant rights and unresolved interests without assuming universal ownership	Clarify claims and constraints	Rights-and-interests record	False assertion of exclusive ownership	Qualified review where required	Entire data lifecycle
Data access	Who may obtain which data for what purpose?	Least-privilege, role-based and time-bounded authorization	Limit availability	Access-control decision and log	Unauthorized or excessive use	Periodic access review	Cross-system data flow
Data control	What meaningful choices can farmers exercise?	Usable collection, transfer, correction, retention and withdrawal controls	Preserve farmer agency	Control settings and decision history	Nominal control with no practical effect	Farmer representation and complaint review	Individual farmer data
Consent and participation	Is participation informed, understandable and revisitable?	Specific notices, accessible choices, records and	Authorize defined uses	Consent or participation record	Bundled or uninformed agreement	Consent audit and feedback	Auditable data use

		non-coercive participation					
Purpose limitation	Is the reuse compatible with the communicated purpose?	Defined purpose, prohibited uses, expiry and compatibility assessment	Prevent function creep	Approved, conditional, or rejected reuse	Uncontrolled secondary use	Reuse review and accountable steward	M go
Data stewardship	Who maintains quality, context, access and lifecycle controls?	Named steward, duties, resources and escalation procedures	Coordinate responsible handling	Stewardship plan and issue register	Diffused responsibility	Periodic stewardship review	On go
Data governance	How are roles, rights, standards and accountability integrated?	Formal charter, decision authority, documentation and representation	Coordinate the data lifecycle	Governance charter and decisions	Fragmented controls	Multi-stakeholder oversight	Are fr
Privacy	What sensitive information may be exposed or inferred?	Necessity review, minimization, restricted access and suitable de-identification	Reduce unjustified exposure	Privacy assessment and controls	Re-identification, surveillance, commercial harm	Privacy review and breach response	Cro s
Cybersecurity	Can data or systems be accessed, manipulated or disrupted?	Authentication, encryption where appropriate, backups, monitoring and incident planning	Protect confidentiality, integrity and availability	Security plan and incident record	Theft, manipulation, ransomware, outage	Security testing and incident oversight	T s
Data interoperability	Can authorized systems exchange data without losing meaning?	Common formats, identifiers, vocabularies, APIs and semantic mappings	Enable controlled exchange	Interoperable data package	Semantic mismatch despite technical transfer	Conformance testing	er
Data portability	Can farmers obtain and	Documented export formats, metadata and	Reduce lock-in and	Portable data package	Unusable export or contractual obstruction	Portability testing and	s

	transfer usable data copies?	reasonable delivery	support choice			complaint route	
Data quality assurance	Are data fit for the proposed reuse?	Quality criteria, thresholds, exception handling and correction	Prevent unsuitable use	Quality status and acceptance decision	Error propagation	Independent quality review	M
Data provenance	Can origin and transformation history be reconstructed?	Source identifiers, lineage metadata, versions and processing logs	Establish evidentiary lineage	Provenance record	Disputed or unverifiable origin	Lineage audit	Evi
Metadata documentation	Is meaning and context preserved?	Definitions, units, methods, dates, spatial scope and limitations	Prevent semantic drift	Data dictionary and metadata package	Misinterpretation after transfer	Steward review and version control	Co
Auditability	Can an authorized reviewer reproduce data handling and calculations?	Accessible source records, logic, versions and permissions	Enable verification	Audit package and findings	Opaque or irreproducible use	Independent or separate audit	A
Traceability	Can transfers and transformations be followed across actors?	Access, transaction, transformation and custody logs	Allocate responsibility	End-to-end trace record	Accountability gaps	Cross-organizational review	Acc
Accountability	Who must explain, correct and remedy failure?	Named owners, escalation, remediation and consequences	Connect authority with responsibility	Accountability map and remedy record	Responsibility shifted to systems or farmers	Senior oversight and independent challenge	D
Farmer protection	What harms to autonomy, privacy, livelihood or access may arise?	Impact assessment, safeguards, redress and farmer participation	Identify and reduce harm	Protection conditions or rejection	Surveillance, exclusion, dependency	Independent representation and grievance route	P
Fair value distribution	How are benefits, costs	Transparent value logic,	Assess value creation and	Value-distribution	Farmers bear risk while others	Farmer-inclusive	gc

	and risks distributed?	negotiated terms, alternatives and review	capture	statement	capture value	governance	
Bias assessment	Do scoring errors differ across farm contexts or groups?	Representative evaluation, subgroup testing and monitoring	Detect systematic disparities	Bias report and mitigation plan	Hidden exclusion	Independent model review	Con
No legal-compliance claim boundary	What legal conclusion is outside the architecture?	Explicit separation of conceptual controls from jurisdiction-specific legal review	Prevent false assurance	Qualified governance statement	Architecture presented as legally sufficient	External qualified assessment	M leg
No farmer-benefit guarantee boundary	What benefits remain uncertain or unevenly distributed?	Distributional evidence, farmer-defined outcomes and exit mechanisms	Prevent automatic benefit claims	Qualified value proposition	Participation without meaningful value	Continuing farmer-centred evaluation	M b

Proposed Circular Data Economy Architecture

The proposed architecture organizes circular reuse as a sequence of controlled stages rather than a continuous flow in which any available data may be repurposed automatically. Its first stage is farm data generation, covering sensor, machine, remote-sensing, weather, soil, crop, livestock, operational, management, input-use, water-use, nutrient-use, pesticide-use, energy-use, yield, environmental, sustainability, and climate-risk data where appropriate. Collection and ingestion then authenticate transfers, register sources, preserve timestamps, and detect missing, duplicated, corrupted, or unauthorized records. The architecture is embedded within a multi-actor agricultural innovation system involving farmers, advisers, technology providers, platforms, intermediaries, public institutions, cooperatives where relevant, supply-chain actors, sustainability reviewers, finance actors, and insurance actors. Research on the digitalization of agricultural innovation systems supports treating these relationships as multi-level institutional arrangements rather than as isolated farm-to-platform transactions [28].

The second architectural stage is a combined quality, provenance, metadata, and curation layer. Each proposed reuse is assessed against application-specific requirements rather than a single generic quality score. Curation may harmonize units, resolve identifiers, document transformations, assign quality flags, and create versioned data objects, but it cannot replace absent observations or make unsuitable evidence reliable. Interoperability and portability functions operate only after meaning, permissions, and lineage have been preserved. The architecture assigns distinct responsibilities to technology suppliers, platform providers, service organizations, public actors, and other intermediaries because supply-side structures and incentives materially influence how agricultural digital systems develop and who controls their infrastructures [29]. These responsibilities include documentation, interface maintenance, error correction, security, portability, and support for independent review.

The third stage is a consent, purpose-limitation, stewardship, and governance core. Every proposed reuse is routed through a purpose gate identifying the requested data, intended application, recipient, duration, downstream-transfer

limits, potential consequences, and responsible decision-maker. The core may approve, condition, restrict, or reject reuse. Production analytics, sustainability reporting, environmental accountability, finance, and insurance therefore operate as separate branches rather than as interchangeable uses of the same data asset. The architecture also includes a fair-value and farmer-protection review that examines dependency, bargaining power, benefit distribution, exit options, and the possibility that farmers bear data or decision risks while other actors capture value. Privacy, cybersecurity, accountability, and claim boundaries are applied across all branches rather than delegated to one final compliance check.

The fourth stage consists of application-specific reuse pathways. Production analytics generate bounded monitoring, prediction, or decision-support outputs. Sustainability and environmental branches organize traceable evidence under explicit calculation and attribution limits. Finance and insurance branches require additional bias, fairness, explanation, and dispute controls because their outputs may contribute to differential treatment. Auditability and traceability span all pathways, linking raw data, transformations, models, recipients, decisions, and corrections. A layered technical pattern involving continuous data integration, modeling, and feedback is consistent with the logic of digital twins in smart farming, although the present architecture extends that pattern by making governance and reuse boundaries explicit [30]. It does not imply a continuously autonomous system.

The final stage is feedback and architecture updating. Farmer corrections, model errors, audit findings, sustainability-review comments, dispute outcomes, security incidents, interoperability failures, and observed application limitations are returned to the relevant data, model, stewardship, or governance layer. Updates must be versioned, authorized, tested, and monitored so that corrective changes do not create new incompatibilities, biases, or unauthorized purposes. The architecture includes five explicit boundaries: no farmer-benefit guarantee, no legal-compliance claim, no financial-fairness guarantee, no insurance-fairness guarantee, and no implementation-readiness claim. These boundaries do not prevent research or carefully governed experimentation; they prevent conceptual completeness from being mistaken for empirical validation, institutional approval, or operational readiness.

Table 3 presents the proposed circular data economy architecture for precision agriculture.

Table 3. Proposed Circular Data Economy Architecture for Precision Agriculture: Farm Data Generation, Data Collection, Quality and Provenance Review, Metadata and Curation, Consent and Purpose Limitation, Data Stewardship, Interoperability, Production Analytics, Sustainability Reporting, Finance, Insurance, Fair Value Review, Auditability, Feedback, and Claim Boundaries

Architecture stage	Core purpose	Required input	Architectural function	Potential output	Validation or assessment need	Failure risk
Farm data generation	Create observations at the farm or production-system source	Sensor, machine, imagery, weather, soil, crop, livestock, operational and management observations	Capture data with source, time, place, method and responsible actor	Raw data object with source metadata	Calibration, necessity, representativeness and authorization	Excess collection, faulty observations, surveillance
Data collection and ingestion	Transfer authorized data into	Raw data, transfer authorization,	Authenticate, ingest, time-stamp and register	Ingested data package	Integrity, completeness, duplication and security checks	Corruption, unauthorized transfer, context loss

	controlled infrastructure	protocol and schema				
Data quality and provenance review	Determine fitness and reconstruct origin	Ingested data, quality criteria, lineage and intended use	Assess quality, verify source and flag errors	Quality and provenance report	Application-specific thresholds and independent checks	Error propagation and disputed origin
Metadata and curation layer	Preserve meaning and prepare controlled reuse	Accepted data, units, definitions, context and processing rules	Clean, harmonize, annotate and version	Curated data asset	Semantic consistency and transformation review	Semantic drift and undocumented changes
Consent and purpose-limitation layer	Determine whether reuse is authorized and compatible	Purpose, permission basis, restrictions and notice	Match proposed use to permitted scope	Approval, conditions, restriction or rejection	Comprehension, voluntariness and compatibility review	Function creep and coercive participation
Data stewardship and governance layer	Coordinate lifecycle decisions and responsibility	Governance charter, roles, policies and risk assessments	Oversee access, quality, retention, disputes and change	Governance decision and accountable owner	Independence, resources, representation and documentation	Diffused responsibility and dominant intermediaries
Interoperability and portability layer	Enable controlled exchange without semantic loss or lock-in	Curated data, standards, mappings, APIs and export rules	Transform and package authorized data	Interoperable or portable package	Conformance, semantic accuracy, security and usability	Broken mapping, lock-in, unauthorized replication
Production analytics reuse	Support defined monitoring or decision questions	Validated farm data, model, assumptions and user needs	Run bounded analytics with uncertainty	Insight, forecast, classification or support option	Model, agronomic, usability and drift validation	Overfitting, automation bias, unsuitable recommendation
Sustainability reporting reuse	Organize evidence for defined indicators	Validated environmental, input, operational and contextual data	Calculate indicators within explicit scope	Evidence package or qualified statement	Calculation audit, comparability, scope and uncertainty	Greenwashing and false precision
Environmental accountability reuse	Support review of environmental evidence	Observations, management records, baselines and responsibilities	Link evidence to bounded accountability questions	Traceable accountability record	Attribution, causal caution, proportionality and auditability	Unfair attribution and surveillance

Finance application reuse	Provide supplementary evidence for defined financial analysis	Authorized, validated and relevant data	Assemble contextual indicators	Bounded finance evidence package	Bias, relevance, explainability and human review	Proxy discrimination and exclusion of data-poor farms
Insurance and risk assessment reuse	Support defined insurance or risk functions	Hazard, exposure, weather, imagery, crop and operational data	Construct and evaluate bounded risk indicators	Candidate risk profile or insurance input	Basis risk, subgroup performance, uncertainty and product fit	Coverage gaps, false certainty and unfair treatment
Fair value and farmer protection review	Assess distribution, autonomy and dependency	Proposed reuse, stakeholder roles, value flows and impact evidence	Evaluate benefit sharing, bargaining power, exit and harm	Conditions, redesign, restriction or rejection	Farmer participation and distributional assessment	Extractive reuse and uncompensated value capture
Auditability and traceability layer	Make handling and decisions reconstructable	Provenance, access, transfer, model and decision logs	Create end-to-end evidence trails	Reproducible audit package	Completeness, integrity and reviewer independence	Audit gaps and responsibility shifting
Bias and fairness review	Detect systematic error and unfair impact where scoring occurs	Model, data, outcome, subgroup and impact context	Test disparities and practical consequences	Conditional approval, mitigation or rejection	Representative evaluation and multi-criteria review	Discriminatory proxies and hidden exclusion
Stakeholder feedback	Incorporate user knowledge, corrections and complaints	Explanations, errors, experience and impact observations	Record, assess and respond	Documented change or reasoned non-change	Accessibility, representation and responsiveness	Token participation and uncorrected harm
Architecture updating	Revise data, models, standards or governance controls	Monitoring, incidents, audits and stakeholder feedback	Version, test, approve and monitor changes	Updated component and change record	Regression testing, impact review and rollback	Uncontrolled change and reintroduced bias
No farmer-benefit guarantee boundary	Prevent circulation from being equated with farmer benefit	Distributional evidence and farmer-defined outcomes	Require qualified value claims	Benefit limitation statement	Benefits captured outside the farm	Farmer-centred evaluation and exit options

No legal-compliance claim boundary	Separate conceptual safeguards from legal determination	Jurisdiction-specific review outside the architecture	Label assumptions and unresolved questions	Legal-boundary statement	False assurance	Qualified external review
No financial-fairness guarantee boundary	Prevent governed reuse from being equated with fair finance	Procedural, distributional, bias and impact evidence	Require qualified financial claims	Fairness limitation statement	Digitized exclusion appears objective	Independent monitoring and appeal
No insurance-fairness guarantee boundary	Prevent better data from being equated with fair insurance	Basis-risk, access, pricing, claims and impact evidence	Require qualified insurance claims	Insurance-fairness limitation	Unequal coverage and ineffective disputes	Product-level evaluation and redress
No implementation-readiness boundary	Separate conceptual design from operational approval	Technical, organizational, legal, security and impact validation	Define a research and assessment agenda	Validation roadmap	Premature deployment	Staged evaluation and redesign

Figure 1 presents the proposed circular data economy architecture for precision agriculture, linking farm data generation, governed reuse, production analytics, sustainability reporting, finance, insurance, farmer protection, accountability, and feedback updating.

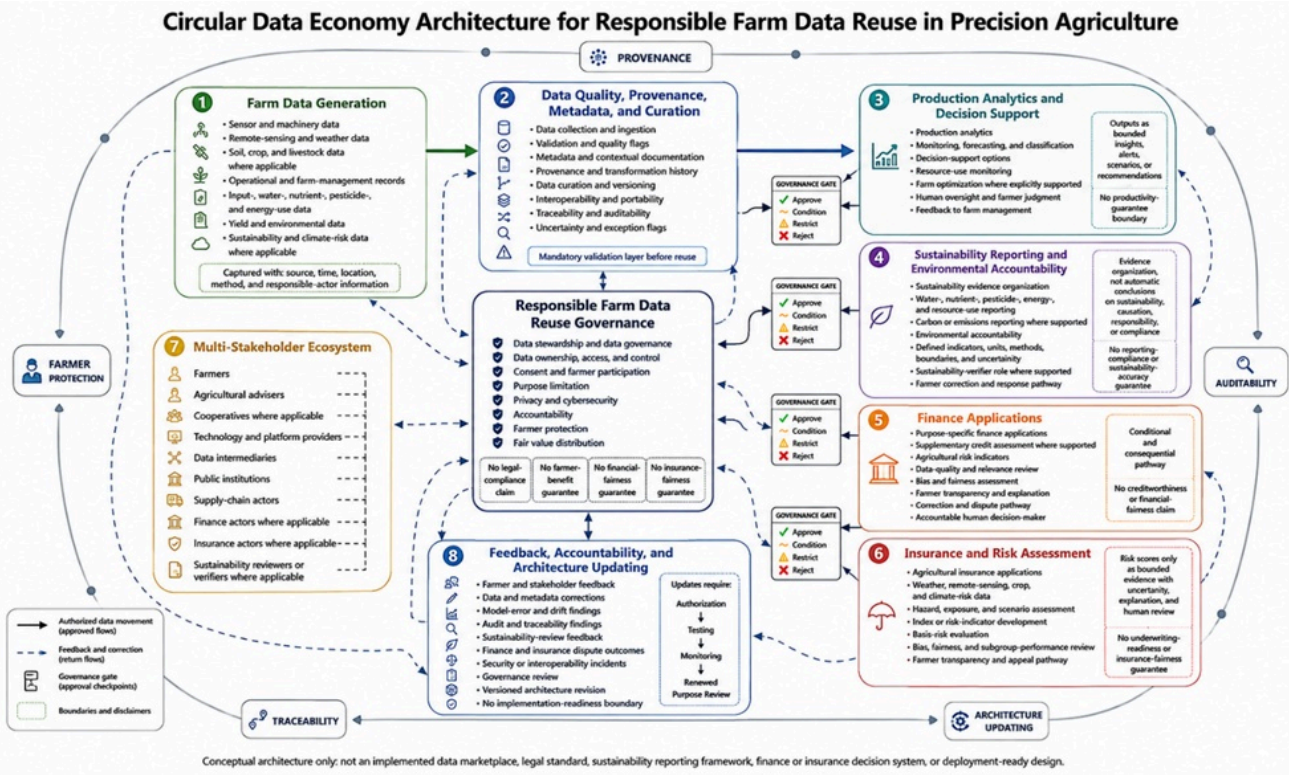


Figure 1. Circular Data Economy Architecture for Responsible Farm Data Reuse in Precision Agriculture

Alt-text description: A conceptual circular architecture showing farm data generated in precision agriculture moving through quality review, provenance, curation, consent, governance, interoperability, production analytics, sustainability reporting, finance, insurance, farmer protection, auditability, accountability, and feedback loops.

Practical Implications and Future Research

For farmers, advisers, cooperatives, technology providers, platform operators, and data intermediaries, the architecture clarifies that reuse readiness depends on more than technical access. Organizations would need to identify data stewards, document purposes, maintain metadata and provenance, support portability, communicate downstream uses, and establish mechanisms for correction and withdrawal where feasible. Advisers could serve as interpreters between analytical outputs and farm context, but their role should not be used to legitimize opaque systems or transfer responsibility away from data controllers and decision-makers. Cooperatives and farmer organizations may warrant study as possible governance and bargaining structures because they could aggregate technical capacity while representing farmer interests. These implications remain conceptual and require empirical investigation across different farming systems, infrastructure conditions, legal settings, and distributions of digital capability.

For sustainability verifiers, finance actors, insurers, supply-chain organizations, and public institutions, the architecture highlights the need to separate evidence collection from consequential judgment. Research should test whether purpose-specific quality thresholds, traceability records, uncertainty statements, bias reviews, explanations, and dispute pathways improve the legitimacy and reliability of reuse. Finance and insurance studies should examine error distribution across farm scales, regions, crops, production systems, and levels of digitalization rather than relying only on aggregate predictive performance. Sustainability research should evaluate whether data-based indicators remain comparable, auditable, and contextually meaningful and whether environmental accountability systems preserve farmer response and correction rights. Longitudinal assessment is needed because governance arrangements that appear acceptable at adoption may produce dependency, surveillance, or unequal value capture over time.

Future research should operationalize and test individual architectural stages without presuming that the whole design is validated. Priority areas include interoperable agricultural metadata, application-specific data-quality protocols, provenance and audit methods, consent interfaces, privacy-preserving analytics, cybersecurity testing, farmer-centred value assessment, bias and fairness evaluation, and governance of model and architecture updating. Comparative studies could investigate alternative stewardship arrangements, including platform-based, cooperative, public-interest, and distributed models. Participatory research should involve farmers in defining acceptable reuse purposes, benefit expectations, explanation needs, and dispute procedures. These are research directions and conceptual implications rather than legal, financial, insurance, investment, policy, procurement, agronomic, or operational advice.

Conclusion

This article proposes a circular data economy architecture for precision agriculture that connects farm data generation and curation with responsible reuse across production analytics, decision support, sustainability reporting, environmental accountability, finance, insurance, and risk assessment. Its central contribution is to place data quality, provenance, metadata, consent, purpose limitation, stewardship, interoperability, portability, privacy, accountability, fair value review, farmer protection, auditability, bias assessment, and feedback updating within one integrated conceptual structure. The architecture treats circularity as governed and revisable reuse rather than unrestricted data extraction or monetization. It also separates technical possibility from justified use by maintaining explicit boundaries concerning productivity, sustainability accuracy, legal compliance, creditworthiness, underwriting readiness, financial fairness, insurance fairness, farmer benefit, and implementation readiness. Responsible agricultural data reuse should therefore be assessed through

farmer agency, contextual integrity, transparency, accountability, proportionality, and purpose-specific evidence rather than through data availability or analytical capability alone.

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