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Transforming Water Management for Resilient Farming

DISCUSSION PAPER

Cover Crop Succession Modelling for Water-Resilient Agriculture:

A Process-Based and Data-Assimilative Framework for Quantifying Soil–Water–Nitrogen Legacy Effects within the GEORGIA Crop Digital Twin

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SYNELIXIS

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Abstract

Cover crops (CC) are increasingly promoted as a regenerative management practice to provide multiple soil, agricultural production, and environmental benefits, improving the resilience and adaptive capacity of cropping systems under increasing climate variability. However, their effects on succeeding cash crops are not uniformly beneficial and depend on species composition, biomass production, soil conditions, rainfall, termination timing and residue management. This paper proposes a Crop Digital Twin framework for evaluating these context-dependent legacy effects as part of the GEORGIA project. Rather than representing cover cropping as a binary management variable, the framework treats the cover crop as an active phase within a continuous crop succession. Soil-water content, mineral nitrogen, crop biomass, root residues, residue quality, surface cover and management events are transferred dynamically from the cover crop phase to the subsequent cash crop. APSIM (Agricultural Production Systems sIMulator) is identified as the principal succession-modelling engine because of its capacity to integrate crop development, soil-water balance, nitrogen cycling, residue turnover and management events across multiple seasons. The framework is contextualised through the GEORGIA Pilot 2 maize–cover crop–maize sequence, in which multi-species cover crop treatments are compared with bare fallow, and linked to soil sensors, laboratory analyses, crop observations and remote-sensing products. Intended decision-support outputs include termination-timing assessment, irrigation adjustment, nitrogen-release and immobilisation warnings, crop-establishment risk and uncertainty estimates. By representing both ecosystem services and potential agronomic trade-offs, the proposed framework supports an explainable and evidence-based integration of cover crops into smart irrigation and sustainable crop-management strategies.

Keywords: cover crops; crop succession; Crop Digital Twin; APSIM; soil-water dynamics; nitrogen cycling; residue decomposition; decision support; regenerative agriculture

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1. Introduction

Cover crops are increasingly incorporated into arable production systems to reduce the environmental consequences of bare fallow periods and to enhance the functional diversity of agricultural rotations. They are generally cultivated between successive cash crops, primarily to provide regulating and supporting ecosystem services rather than a directly harvested product. Depending on species selection, establishment success and management, cover crops may reduce soil erosion, retain residual nutrients, contribute biologically fixed nitrogen, suppress weeds, increase organic-matter inputs and modify soil physical, chemical and biological properties (Blanco-Canqui et al., 2015; Schipanski et al., 2014). Nevertheless, these potential benefits do not constitute intrinsic or spatially uniform properties of cover cropping. Their magnitude and agronomic relevance are governed by interactions among climate, soil, cover crop functional traits, biomass accumulation, termination timing, residue management and the requirements of the subsequent cash crop.

This context dependence is particularly pronounced in water-limited production environments. Replacing fallow with a living cover crop introduces an additional phase of transpiration and nutrient acquisition into the crop sequence. During growth, cover crops may reduce direct soil evaporation and runoff, but simultaneously deplete plant-available water through transpiration. They may capture mineral nitrogen that would otherwise be susceptible to leaching, yet temporarily reduce its availability to the succeeding crop. The resulting legacy cannot therefore be inferred from cover crop presence alone. It emerges from the balance between resources acquired during cover crop growth and the quantity, timing and form in which those resources are subsequently returned to the soil crop system.

Evidence from dryland modelling illustrates the importance of this balance. Garba et al. (2023) used APSIM to examine the effects of contrasting cover crop functional types across historical climatic variability in a subtropical dryland system. Their results indicated that cover crops reduced subsequent cash-crop yields in dry-to-normal years, largely because biomass production was associated with soil-water extraction, whereas yield benefits were possible in wetter years. Multi-species mixtures accumulated substantial biomass but also generated greater downside yield risk and instability than some monoculture treatments. These findings demonstrate that increasing functional diversity does not necessarily increase production-system resilience when water is the dominant limiting resource. Rather, cover crops may need to be deployed opportunistically and managed according to antecedent soil water, expected rainfall and the requirements of the subsequent crop.

The agronomic effects of cover crops also extend beyond the active crop phase. At termination, above-ground biomass is transformed into standing, surface-retained, incorporated or removed residue, while roots remain distributed within the soil profile. These pools influence subsequent water, carbon and nitrogen dynamics through decomposition, mineralisation, immobilisation and surface-cover effects. Surface residues can alter soil evaporation, temperature, infiltration, crop establishment and nutrient cycling, and their effects persist while residue mass and cover decline. Consequently, the representation of residue decomposition is a critical component of conservation-agriculture and crop-succession models. Tadiello et al. (2023) emphasised that residue decomposition is controlled not only by crop-specific properties but also by environmental conditions, particularly air temperature, soil-water content and initial residue mass. Their sensitivity analysis further showed that the relative importance of model parameters varies among residue types and simulation periods, highlighting the need for dynamic rather than fixed residue effects.

The temporal coupling of cover crop growth, termination and residue turnover creates a succession problem. The soil state at cash-crop sowing is determined partly by the conditions inherited from the preceding cash crop, modified during the cover crop phase, and further transformed between cover crop termination and subsequent establishment. Key inherited variables include plant-available water by soil layer, mineral nitrogen, surface and below-ground residue pools, residue carbon-to-nitrogen ratio, organic-matter fractions and soil-surface cover. These state variables determine whether cover cropping results in improved crop establishment and resource-use efficiency or, alternatively, in water limitation, nitrogen immobilisation or yield reduction.

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Despite this continuity, cover crops are frequently represented in agronomic assessment as a categorical treatment, such as cover crop versus fallow, or evaluated through discrete measurements of biomass, soil properties and subsequent yield. Such comparisons are necessary for empirical assessment but are insufficient for explaining the mechanisms underlying treatment responses or for extrapolating beyond the observed season. A neutral yield response, for example, may coexist with reduced nitrate leaching, greater carbon input or altered irrigation requirements. Conversely, an apparent soil-health benefit may be accompanied by lower soil-water availability at sowing. Evaluation based on a single response variable therefore risks obscuring agronomically important trade-offs.

Process-based crop-system models provide a means of integrating these processes through time. By simulating crop development, soil-water balance, nitrogen cycling, residue decomposition and management events, they can represent the transfer of state variables between successive crop phases and evaluate interactions under climatic conditions not directly observed in a field experiment. This capability is especially relevant where field observations cover only a limited number of seasons and cannot encompass the full distribution of rainfall and temperature variability. However, the usefulness of such models depends on their ability to represent the dominant processes, their parameterisation for the target species and environment, and their calibration against intermediate state variables rather than yield alone.

A further challenge concerns the representation of multi-species cover crops. Mixtures are promoted because functionally contrasting species may provide complementary services, such as nitrogen fixation by legumes, nitrate capture by grasses and deeper nutrient acquisition by brassicas. However, the realised contribution of each species depends on emergence, competition, resource availability and environmental conditions.

Sown proportions may therefore differ substantially from biomass proportions at termination. Moreover, mixtures that generate greater biomass may also increase water extraction and subsequent production risk. Modelling cover crop mixtures thus requires either species-specific simulation of competition and resource acquisition or a defensible functional-group approximation supported by observations of realised composition.

Crop Digital Twins (CDTs) provide a framework for combining such process-based simulation with repeated field observations. Unlike a static scenario model, a CDT can be periodically updated using soil sensors, crop measurements, laboratory analyses, management records and remote-sensing products. This enables simulated soil water, mineral nitrogen, biomass and residue states to be corrected as the crop succession continues. The resulting virtual representation can then be used to evaluate alternative termination dates, residue-management strategies, irrigation schedules and fertilisation decisions under multiple weather scenarios.

Within the GEORGIA project, this approach is being developed to support a holistic optimisation of irrigation, fertilisation and soil-health management. The project integrates in-situ monitoring, drone and Earth Observation data, process-based crop models, machine learning and explainable decision-support services within a multi-engine Crop Digital Twin architecture. For cover crop succession, the principal scientific requirement is to preserve continuity across crop phases: the simulated and observed state at cover crop termination must be transferred through the residue-transition period and used to initialise the succeeding cash crop. The present paper therefore proposes a process-based and data-assimilative framework for cover crop succession modelling within the GEORGIA Crop Digital Twin. The framework is structured around the maize cover crop maize sequence of GEORGIA Pilot 2 in Bulgaria but is intended to be transferable to comparable arable systems. Specifically, the paper aims to: (i) identify the principal soil-water, nitrogen and residue processes governing cover crop legacy effects; (ii) define the state variables that must be transferred between successive crop phases; (iii) establish a modelling and monitoring framework suitable for species and multi-species treatments; and (iv) specify the explainable decision-support outputs required for cover crop termination, irrigation and nitrogen management.

The proposed approach does not assume that cover crops are inherently beneficial. Instead, it seeks to identify the environmental and management conditions under which cover crops deliver ecosystem services without imposing unacceptable resource costs or production risks.

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2. Cover crops as dynamic legacy-generating phases within crop successions

2.1 Soil-water dynamics and the role of termination timing

The influence of cover crops on soil-water availability is governed by the interaction of biological water use, soil-surface protection, rainfall distribution, soil hydraulic properties, and management timing. During active growth, cover crops transpire water and extract it from the soil profile according to their rooting depth, root-length density, phenological stage, and atmospheric demand. At the same time, canopy development may reduce direct soil evaporation, attenuate raindrop impact on soil surface, and limit runoff. Consequently, the net effect of a cover crop on soil-water storage cannot be inferred solely from its presence, biomass production, or canopy cover. It reflects the balance between additional transpiration and any reductions in evaporation or runoff achieved during the cover crop phase.

Following termination, transpiration ceases, but retained residues continue to influence water dynamics. Surface mulch can reduce soil exposure to radiation and wind, moderate temperature fluctuations and restrict evaporation. Residues may also slow overland flow and protect soil aggregates, although their effects on infiltration depend on residue cover, rainfall intensity, antecedent moisture and soil condition. These post-termination benefits may partly compensate for water consumed during cover crop growth, but the degree of compensation is governed principally by subsequent rainfall and the interval between termination and cash-crop sowing.

The resulting legacy is both temporally and vertically differentiated. Wang et al. (2021) found that cover crops reduced fallow precipitation-storage efficiency and whole-profile soil-water storage at succeeding-crop planting, while increasing water storage in the upper 0 30 cm layer and improving water-use efficiency under some conditions. The average succeeding-crop yield response was comparatively small, but the variability among studies was substantial, indicating that profile depth, climate, residue management and termination interval must be considered jointly rather than represented by a single soil-water value (Wang et al., 2021).

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Water-related risks are particularly pronounced where stored soil water is a major determinant of subsequent crop performance. In a dryland meta-analysis, Garba et al. (2022) showed that cover crop effects on soil water, mineral nitrogen and cash-crop yield varied strongly with precipitation and management context. APSIM simulations subsequently indicated that cover crops reduced cash-crop yields by approximately 12% relative to fallow in dry-to-normal years, whereas benefits were more likely in wet years. High-biomass mixtures were not uniformly advantageous because greater biomass production was accompanied by greater pre-sowing water use and yield risk (Garba et al., 2022, 2023).

Termination timing is therefore a central control variable. Delayed termination may increase biomass, nutrient uptake, surface cover and carbon input, but it also prolongs transpiration and shortens the period available for soil-water recharge. Earlier termination reduces this risk but may limit biomass-dependent services. The appropriate termination window must consequently be evaluated against measured soil-water content by depth, expected rainfall, planned sowing date, residue-management strategy and the establishment requirements of the succeeding crop. Within a Crop Digital Twin, termination should be evaluated through scenario analysis rather than prescribed as a fixed calendar date. The model should quantify how alternative termination dates affect biomass production, soil-water storage at cash-crop sowing and the probability of establishment stress under contrasting rainfall scenarios. This requires continuous observations at more than one soil depth because improved near-surface moisture retention beneath residues may coexist with depletion of deeper profile water.

2.2. Nitrogen capture, biological fixation and post-termination availability

Cover crops affect nitrogen cycling through residual nitrogen uptake, biological fixation and the subsequent decomposition of shoots and roots.
Non-leguminous species retain mineral nitrogen that might otherwise remain unused during the fallow period and become vulnerable to leaching. Grasses and cereals are often effective scavengers because of their rapid establishment, fibrous rooting and high biomass production, while sufficiently

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deep-rooted species may acquire nitrate from below the principal rooting zone of the preceding crop. The magnitude of this service is well supported by meta-analytic evidence. Thapa et al. (2018) reported that non-leguminous cover crops reduced nitrate leaching by an average of 56% relative to uncovered controls. Earlier planting and greater shoot biomass were associated with stronger reductions. Nouri et al. (2022) subsequently estimated a global mean reduction of 69%, with Brassicaceae and Poaceae among the most effective functional groups. The latter analysis found no corresponding mean reduction in water drainage, indicating that biological nitrogen acquisition, rather than reduced drainage alone, was a primary mechanism (Thapa et al., 2018; Nouri et al., 2022).

Leguminous cover crops provide a distinct pathway through symbiotic nitrogen fixation. However, their potential contribution to the succeeding crop depends on successful establishment, nodulation, biomass production, soil-water availability and background mineral nitrogen. The nitrogen contained in legume biomass should therefore not be interpreted automatically as a fertiliser equivalent, because only part of it will become mineralised within the period of demand of the following crop.

After termination, residue quality and placement determine whether nitrogen is released or temporarily immobilised. Residues with relatively low C:N ratios and higher concentrations of labile nitrogen generally decompose rapidly, whereas mature cereal residues with high C:N ratios can increase microbial demand for soil mineral nitrogen. Leaves, stems and roots may also mineralise at different rates. Consequently, a single estimate of total cover crop nitrogen is insufficient for predicting the availability of nitrogen to the succeeding crop. The key agronomic variable is temporal synchronisation between nitrogen supply and crop demand. Rapid mineralisation before substantial root development, can create a period of elevated nitrate-loss risk. Conversely, delayed mineralisation or early immobilisation may constrain establishment and initial vegetative growth. Under the latter condition, a targeted starter-nitrogen application may be justified even where total nitrogen retained in residues is high. Termination timing further modifies these dynamics by influencing biomass maturity, residue C:N ratio and the duration of post-termination decomposition before sowing.

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Cover crop succession modelling should therefore generate a time-dependent nitrogen balance. At minimum, it should represent soil mineral nitrogen at cover crop establishment and termination, nitrogen accumulated in above- and below-ground biomass, biological fixation where applicable, residue quality, post-termination mineralisation or immobilisation and mineral nitrogen available during the early development of the succeeding crop. This provides a more defensible basis for nitrogen crediting, starter-N recommendations and nitrate-loss assessment than a fixed treatment-level coefficient.

2.3. Biomass, residue dynamics and soil legacy effects

Cover crop biomass integrates several of the principal benefits and trade-offs associated with the practice. Greater biomass commonly increases soil cover, nutrient capture, weed competition and organic inputs, but it also reflects water and nutrient consumption during active growth. Biomass should therefore be assessed together with its functional composition, rooting distribution, tissue quality and environmental cost in terms of stored soil water. This is particularly important in water-limited systems, where high biomass production may strengthen residue-mediated services while simultaneously increasing the risk of reduced soil-water availability for the succeeding crop (Blanco-Canqui et al., 2015; Garba et al., 2022, 2023).

Termination converts living biomass into functionally distinct residue pools. Plant material may be removed, incorporated, retained on the surface or left standing, while roots remain distributed within the soil profile. These fractions differ in their rates of decomposition and their influence on evaporation, nutrient turnover and surface protection. Surface-retained residues generally persist longer because soil contact is limited, whereas incorporated material is exposed more directly to microbial decomposition (Greub et al., 2023; Tadiello et al., 2023). Residue placement must consequently be represented as an explicit management variable. Residue quality governs carbon and nitrogen turnover after termination. C:N ratio, lignin and cellulose content, tissue maturity and the relative proportions of leaves, stems and roots influence decomposition and nutrient mineralisation (Quemada & Cabrera, 1995; Thapa et al., 2023). Thus for mixtures, the aggregate residue may contain components with markedly different biochemical characteristics. A model based only on total biomass may therefore reproduce residue quantity while misrepresenting both the persistence of surface cover and the timing of nitrogen availability.

Cover crops also contribute carbon through shoots, roots, rhizodeposition and microbial products. Long-term meta-analyses generally report positive average effects on soil organic carbon, although the magnitude varies with biomass production, climate, soil properties, baseline SOC and the duration of cover cropping (Jian et al., 2020; Joshi et al., 2023; Poeplau & Don, 2015). Consequently, short-duration pilots can quantify residue carbon inputs and selected changes in labile or total carbon pools, but they cannot demonstrate a stable long-term sequestration rate. Long-term SOC estimates generated by the CDT should thus be reported as conditional projections rather than verified pilot outcomes.

Potential physical effects include increased aggregate stability, reduced surface sealing, improved infiltration and changes in pore continuity. These responses are not immediate or universal. Surface protection may develop within a single season, whereas persistent changes in bulk density, hydraulic conductivity or plant-available water capacity generally require repeated cover crop cycles and robust field measurements (Blanco-Canqui and Ruis, 2020; Yan et al., 2025). Such properties should not be modified in the process model solely because a treatment is classified as regenerative.

Microbial biomass, respiration and enzyme activities can provide complementary evidence of biological responses to living roots and residue inputs. Meta-analyses indicate that cover cropping generally increases microbial abundance and activity relative to bare fallow, although effect sizes depend on climate, tillage, termination method, soil texture and cover crop management (Kim et al., 2020; Muhammad et al., 2021). However, most operational crop-system models do not simulate microbial community composition or enzyme activity explicitly. These indicators are therefore most appropriately used for interpretation, validation or statistical correction rather than as direct mechanistic engine inputs. The CDT should represent the principal measurable carbon, nitrogen transformations and water processes while retaining clear boundaries around biological mechanisms that are not directly modelled.

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3. A Crop Digital Twin framework for cover crop succession

3.1. State continuity across successive crop phases

The principal modelling requirement for cover crop succession is continuity of soil, crop, and residue states across time. A cover crop should not be simulated as an isolated crop followed by an independently initialised cash crop. Rather, the soil-water, nitrogen, carbon, and residue conditions generated during cover crop growth and post-termination decomposition must be transferred directly to the succeeding crop. This continuity may be expressed conceptually as:

$$S_{cash,0} = T\,(S_{cover,t}, M_{term}, R_{quality}, W_{post})$$

where $S_{cover,t}$ represents the cover crop and soil state at termination, M_{term} represents termination and residue-management operations, $R_{quality}$ represents the quantity and biochemical characteristics of the resulting residues, and W_{post} represents environmental conditions between termination and establishment of the succeeding crop. The resulting $S_{cash,0}$ defines the initial condition of the subsequent cash crop.

The state variables transferred between crop phases should include soil-water content by layer, mineral nitrate and ammonium by layer, soil temperature, surface and below-ground residue pools, residue carbon and nitrogen, surface-cover fraction, organic-matter pools, and relevant management history. Depending on data availability and model structure, the transferred state may also include changes in bulk density, hydraulic conductivity, rooting depth, or other soil properties. These additional variables should be incorporated only where repeated observations support their modification. The importance of state continuity extends beyond technical model configuration. It defines the causal interpretation of cover crop effects. A subsequent yield response should be traceable to inherited changes in soil water, mineral nitrogen, residue cover, and related processes. If the soil profile is reinitialised at cash-crop sowing, the model cannot reproduce the principal mechanisms through which the cover crop influences the next crop.

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3.2. Operational modelling workflow

The proposed modelling framework consists of six connected phases.

3.2.1. Initial post-harvest state

The simulation begins after harvest of the preceding cash crop. Soil texture, layer thickness/depths, hydraulic properties, bulk density, soil-water content, mineral nitrogen, soil temperature, organic-matter pools, residual crop roots, and surface residues of the field are initialised. Irrigation, fertilisation, tillage, and harvest operations undertaken during the preceding crop should also be retained in the management record. The reliability of this initialisation is critical because errors present at the beginning of the cover crop phase propagate through the subsequent succession. Soil-water and mineral-nitrogen measurements obtained after harvest provide particularly valuable constraints.

3.2.2. Cover crop establishment and growth

The model, at cover crop establishment represents sowing date, species or mixture, seeding density, emergence, and plant population. During growth, it simulates phenological development, canopy expansion, above- and below-ground biomass production, rooting depth, soil-water extraction (water use), transpiration, nitrogen uptake, biological nitrogen fixation where relevant, stress responses, and senescence. Establishment should not be treated as automatically successful. Delayed emergence, low plant density, frost, drought, waterlogging, or poor seed soil contact may substantially reduce biomass and alter the expected legacy. The CDT therefore, should not assume successful establishment simply because a sowing event was recorded. Observed plant population and canopy cover should therefore be used to update the simulated crop state early in the season.

3.2.3. Termination and biomass partitioning

Termination is represented as an explicit management event. The model record should include date, crop developmental stage, method of termination (chemical, rolling, mowing, tillage, winter-kill, grazing), fraction of biomass removed, fraction retained on the surface, fraction incorporated, incorporation depth, and associated soil disturbance, where applicable. Biomass partitioning is particularly important because surface residues, incorporated residues, standing dead material, and roots follow different decomposition pathways.

A termination event that removes most above-ground biomass cannot be modelled in the same manner as one that leaves a complete mulch layer.

3.2.4. Post-termination soil and residue processes

The period between termination and cash-crop sowing is a distinct and agronomically important phase. The model simulates residue decomposition, carbon transfer among organic pools, nitrogen mineralisation / immobilisation, soil evaporation, infiltration, drainage, soil water recharge, soil temperature, and nitrate movement. Residue cover declines according to residue quality and environmental conditions. This phase determines whether water and nitrogen conditions improve or deteriorate before the succeeding crop is established. It is therefore not sufficient to terminate the cover crop and immediately initialise the cash crop without simulating this intervening period.

3.2.5. Succeeding cash crop

The subsequent crop is established using the updated soil-water, mineral-nitrogen, residue states, and soil-surface states. The model then predicts emergence, canopy development, water and nitrogen stress, biomass production, irrigation requirement, nitrogen requirement, and yield. The success of the succession model should be evaluated not only against final yield but also against intermediate states, including soil-water content at sowing, mineral nitrogen, early crop establishment, and crop stress.

3.2.6. Decision support and explanation

The final phase translates model outputs into management-relevant recommendations. These may include alternative termination dates, irrigation adjustments, starter-nitrogen requirements, residue-management options, and estimates of establishment, nitrogen immobilization or availability asynchronicity risk, or yield risk. The explainability component should identify the dominant mechanism underlying each recommendation. For example, a recommendation for earlier termination should be linked explicitly to a predicted risk of insufficient soil-water recharge rather than presented as an unexplained model output.

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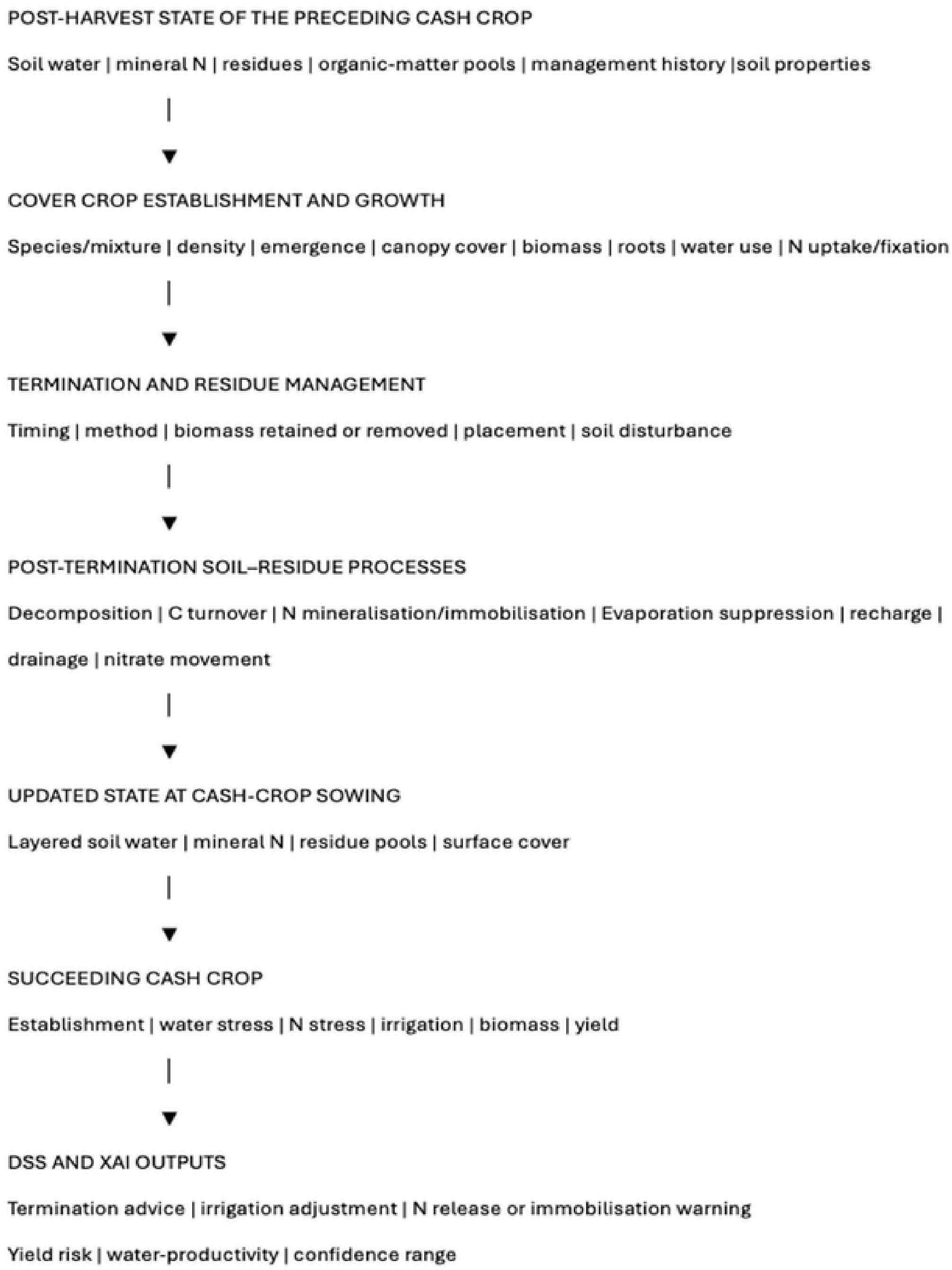

Figure 1. Operational logic for cover crop succession modelling in the GEORGIA CDT

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3.3. Representation of species and multi-species mixtures

Species-specific modelling is preferable where validated crop parameters are available. Cover crop species differ in phenological development, thermal-time requirements, canopy structure, rooting depth, water use, nutrient acquisition, biological nitrogen fixation, frost response, and residue quality. These differences can strongly influence both the active cover crop phase and the subsequent legacy. However, insufficiently calibrated species-level parameterisation may create an appearance of precision without corresponding predictive reliability. Where adequately calibrated species-specific parameters are unavailable, a trait-informed functional-group representation provides a pragmatic approximation. This is supported by studies showing that functional traits can classify cover crop strategies and help predict growth, nitrogen acquisition and ecosystem-service provision across multiple species (Damour et al., 2015; Tribouillois et al., 2015). Trait-based frameworks are also used to generalise plant responses and effects when complete species-level information is unavailable (Damour et al., 2018). A practical classification may include legumes, grasses or cereals, brassicas, and other broadleaf species. Legumes are distinguished by their potential for biological nitrogen fixation and comparatively nitrogen-rich residues. Grasses and cereals commonly produce fibrous root systems, substantial biomass, and residues that decompose more slowly and may induce temporary nitrogen immobilisation. Brassicas may combine rapid growth with deeper rooting and substantial nitrogen uptake, although their specific effects depend on species and environment. However, the approximation must remain cautious. Tribouillois et al. (2015) found that combined leaf traits explained only about half of the variation in cover crop growth and nitrogen acquisition, which may be insufficient for precise species ranking. More recent evidence showed that species identity explained more variation in nitrogen uptake and nitrogen loss than broad functional groups, partly because of substantial within-group trait variation (Fernandez Pulido et al., 2025).

Mixtures should not be characterised solely by seed proportions. Competition, temperature, water availability, nutrient status, and emergence success may cause realised biomass composition to differ markedly from the sown mixture. Consequently, species-separated biomass or functional-group biomass at termination provides a more relevant calibration variable than seed ratio alone. Where the modelling platform permits, mixture components should be simulated separately so that they compete for radiation, water, and nitrogen. Where this is not technically or parametrically feasible, weighted functional-group approximations may be used, provided that weights are based on observed biomass composition.

Lastly, the assumption that more diverse mixtures are inherently more effective should be avoided. Functional diversity may increase multifunctionality where species traits are complementary, but mixture performance depends on realised composition and environmental conditions (Finney & Kaye, 2017). Under water-limited or dry conditions, a high-biomass mixture may impose greater water use than a less complex treatment. Species richness should therefore be evaluated in relation to functional performance and production risk.

3.4. Data assimilation and uncertainty representation

A CDT differs from a conventional static simulation because its state can be updated as new observations become available. This capability is particularly relevant for cover crops, where establishment, biomass accumulation, species dominance, and water use may diverge substantially from pre-season assumptions. High-value assimilation points include early establishment, peak vegetative growth, immediately before termination, shortly after termination, and cash-crop sowing. Observations of soil moisture, biomass, canopy cover, mineral nitrogen, tissue nitrogen, and realised mixture composition can be used to correct simulated states.

The method of updating should be proportional to the maturity of the system and the density of available observations. Direct state replacement may be appropriate where a variable is measured reliably and corresponds closely to a model state. More advanced methods, including Bayesian updating or ensemble-based filtering, may be justified where multiple uncertain variables and measurement errors must be reconciled.

Uncertainty should be represented explicitly rather than concealed within deterministic outputs. Important uncertainty sources include weather forecasts, spatial soil variability, hydraulic parameters, cover crop establishment, rooting depth, mixture competition, residue quality, decomposition rates, termination effectiveness, and cash-crop response. Scenario ensembles provide a practical mechanism for propagating these uncertainties. Alternative rainfall sequences, termination dates, biomass levels, and nitrogen-release parameters can be simulated to generate probability distributions for soil water, nitrogen availability, irrigation demand, and yield. Decision support should then communicate risk and confidence rather than a single apparently exact value. For example, a termination recommendation may be expressed as the probability of maintaining soil water above a defined establishment threshold under alternative rainfall scenarios.

4. Model and data implementation within GEORGIA

4.1. Selection and complementary use of simulation engines

APSIM is the most appropriate principal engine for the GEORGIA cover crop succession use case. It was designed to simulate interactions among crops, soil, climate, and management across multi-season agricultural systems. It has modular structure that includes components for soil-water, nitrogen, residues, organic-matter, and crop sequencing (Holzworth et al., 2014; Keating et al., 2003). Within the GEORGIA framework, APSIM should represent the preceding maize crop, cover crop establishment and growth, soil-water extraction, nitrogen uptake or fixation, termination, residue allocation, decomposition, post-termination recharge, and the subsequent maize crop. The model should preserve state continuity across the complete sequence. Where a particular cover crop species lacks sufficiently validated parameters, the preferred approach is to calibrate an existing generic or functional-group representation using field observations. Assigning unverified species parameters merely to retain botanical detail would reduce rather than strengthen model credibility.

AquaCrop may provide an independent benchmark for the succeeding maize crop, particularly for water productivity, evapotranspiration, biomass, and irrigation response. Its role, though, is complementary rather than substitutive. It is less suitable as the primary engine where residue decomposition and detailed nitrogen succession are central. HYDRUS-1D may be used selectively where the research question requires detailed vertical water or solute transport, such as nitrate movement below the root zone or irrigation-induced redistribution. Its use should be restricted to cases in which the necessary hydraulic parameters and calibration observations are available. Additional model complexity is not beneficial where it cannot be adequately constrained.

4.2 Model-ready data requirements

The field monitoring framework should prioritise variables that directly support model initialisation, state updating, calibration, and validation. The objective is not to measure the maximum possible number of indicators, but to obtain the observations required to constrain the dominant processes.

Table 1. Priority observational data for initialisation, state updating, calibration, and validation of the cover crop succession CDT

Data category	Priority variables	Role within the CDT	Principal source
Environmental forcing	Rainfall, temperature, solar radiation, humidity and wind or reference evapotranspiration	Daily simulation forcing	SynField and meteorological services
Soil profile	Texture, layer depth, bulk density, field capacity, wilting point, saturation and hydraulic conductivity	Soil-Water balance and root-zone configuration	Laboratory and field characterisation
Dynamic soil state	Volumetric water content, soil temperature, EC, nitrate and ammonium by depth	Initialisation, state correction/updating, and validation	Sensors and laboratory analyses

Cover crop state	Emergence, plant density, canopy cover, phenology, above-ground biomass, realised mixture composition, tissue N and rooting depth	Crop-growth and nutrient calibration	Field sampling and drone observations
Termination and residues	Date, method, retained and removed biomass, C:N ratio, residue placement and surface-cover fraction	Residue decomposition, N turnover, and post-termination simulation	Management records, laboratory analyses, and drone imagery
Succeeding crop	Emergence, phenology, canopy, biomass, tissue N, irrigation, fertilisation, and yield	Validation of transferred legacy effects	Field records and crop measurements

Weather observations are essential because cover crop water use and residue decomposition respond strongly to temperature, rainfall, radiation, and atmospheric demand. Soil hydraulic properties are required to simulate infiltration, storage, drainage, and root extraction. Dynamic soil-water measurements provide the principal means of evaluating the water balance.

Mineral nitrogen should be measured by depth at critical stages, particularly after the preceding crop, during cover crop growth where feasible, at termination, and before sowing of the succeeding crop. Biomass and tissue nitrogen measurements are required to constrain nitrogen uptake and residue pools.

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For mixtures, realised composition should be measured directly in a representative subset of quadrats. Remote-sensing products may support canopy cover and biomass estimation but require calibration against ground observations. Mixed-species canopies and index saturation can weaken direct relationships between vegetation indices and biomass.
Termination and residue data are especially important because omission of residue mass, C:N ratio, or placement introduces substantial uncertainty into decomposition and nitrogen-release simulations. Management records should therefore capture the actual field operation rather than only the intended treatment.

4.3. Calibration and Validation Strategy

Calibration should follow the causal structure of the succession rather than adjusting all parameters simultaneously.
The first stage should address the soil-water balance. Soil hydraulic parameters, evaporation, runoff, drainage, and root-water extraction should be constrained using rainfall, irrigation, and soil-moisture observations. Crop growth should not be calibrated before the water balance is shown to be plausible because simulated biomass and nitrogen uptake depend on water availability.
The second stage should calibrate cover crop establishment, phenology, canopy development, biomass accumulation, and rooting depth. Observed plant density, canopy cover, biomass, and phenological stages provide the principal constraints.

The third stage should evaluate nitrogen uptake, biological fixation, tissue nitrogen, and soil mineral nitrogen. Nitrogen parameters should not be inferred solely from final biomass because similar biomass can occur under different nitrogen dynamics.

The fourth stage should address residue decomposition, surface-cover persistence, and nitrogen mineralisation or immobilisation. Measurements of residue mass, residue C:N ratio, surface-cover decline, and mineral nitrogen after termination are particularly valuable.

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The final stage will validate the complete succession against the succeeding maize cash crop. Validation variables should include soil-water content and mineral nitrogen at sowing, emergence, early biomass, water and nitrogen stress, irrigation requirement, total biomass, and yield. Validation against intermediate states is necessary because final yield alone may conceal compensating errors. A model can reproduce yield while simulating soil-water or nitrogen dynamics incorrectly. Scientific confidence requires that the principal causal pathway is reproduced, not merely the final output.

Biological indicators and remote-sensing indices should be treated as explanatory and validation variables, and calibrated proxies. They may support interpretation of model residuals or indicate processes not represented explicitly, but they should not be used as direct model drivers without established relationships. For example, NDVI, NDRE and related indicators may support canopy cover, biomass or nitrogen estimation, but mixed canopies, exposed soil and index saturation can weaken direct relationships. Ground measurements remain necessary for calibration.

5. Application to the GEORGIA pilot 2 maize-cover crop-maize sequence

Pilot 2 is implemented by Agrovar in northern Bulgaria under a continental climatic regime characterised by cold winters, warm to hot summers, and recurrent periods of seasonal water limitation. These conditions provide a relevant context for evaluating the trade-offs between cover crop biomass production, water use, nutrient retention, and subsequent maize performance. The operational succession considered is: maize → winter cover crop treatment → maize. The experimental design comprises three multi-species cover crop mixtures and a bare-soil (fallow) control. The exact sowing date, realised species composition, biomass production, and termination timing should remain explicit model inputs because these variables may vary with harvest timing, field traffic, weather, and establishment success. The principal analytical objective is not limited to detecting differences in maize yield among treatments. The more scientifically relevant objective is to determine whether treatment effects can be explained through the measurable succession pathway that has been described throughout the paper.

5.1 Soil monitoring

The soil sensor configuration comprises eight TEROS-12 sensors, with two depths monitored in each treatment: a) 15 cm, representing the surface soil and early maize rooting zone; b) 40-45 cm, representing deeper root-zone storage and cover crop water extraction. The sensors provide continuous measurements of volumetric water content, soil temperature, and bulk electrical conductivity. The exact installed depth and georeferenced position will be recorded in the data platform. The two-depth configuration is necessary because treatment effects may differ among soil layers. Surface residues may increase moisture retention near the surface, while active cover crop growth may reduce water storage at greater depth. A single sensor could therefore provide an incomplete or misleading interpretation of the treatment effect. Sensor locations should be representative of each treatment and should avoid plot boundaries, wheel tracks, local depressions, and atypical irrigation patterns. Where possible, they should remain fixed throughout the full maize cover crop maize sequence.

Repeated laboratory sampling is recommended at **0-10 cm** and **10-30 cm**. An additional **30-60 cm baseline characterisation** is valuable for soil texture, mineral nitrogen, and hydraulic interpretation, but need not be repeated at every sampling date if resources are limited. Sensor and soil sampling depths do not need to coincide exactly. Sensors provide continuous point measurements, whereas laboratory samples integrate material across a defined soil interval. Their functions are complementary rather than interchangeable.

5.2. Crop and residue measurements

Cover crop observations should include emergence, plant density, canopy cover, phenology, above-ground biomass, realised mixture composition, tissue nitrogen, rooting depth or root score, and termination date.
At termination, biomass should be separated where feasible into species or functional groups. The quantities retained, removed, incorporated, or left standing should be documented. Residue C:N ratio and surface-cover fraction should be measured because they are central to decomposition and evaporation processes.

Post-termination monitoring should include residue-cover decline, soil moisture, mineral nitrogen, and relevant management operations. These observations allow the model to distinguish between water consumed during growth and water conserved after termination.

Measurements for the succeeding maize should include emergence, phenology, canopy development, biomass, tissue nitrogen, irrigation volume, fertiliser application, grain yield, and harvest moisture. These variables provide the basis for validating whether the simulated legacy effects are transferred correctly to the cash crop.

Supporting soil indicators may include SOC, bulk density, aggregate stability, infiltration, field capacity, and permanent wilting point. Short-term changes in these variables should be interpreted cautiously and should not automatically be attributed to persistent structural improvement.

5.3. Scenario Analysis

Once calibrated, the CDT will simulate each observed cover crop mixture under actual management and compare it with the bare-soil control. It will also evaluate plausible alternative scenarios, including: earlier and later termination, different starter-nitrogen rates, alternative rainfall sequences between termination and maize sowing, and conventional versus CDT-informed maize irrigation. Where operationally realistic, residue retention and/or incorporation scenarios may also be compared. However, only management alternatives that could be implemented in practice should be included in decision-support outputs.

The principal model outputs should include: soil-water content by layer at termination and maize sowing, cover crop nitrogen uptake or fixation, residue nitrogen-release trajectory, duration and magnitude of predicted immobilisation, maize establishment stress, irrigation requirement, nitrogen requirement, biomass, grain yield, water-use efficiency, nitrogen-use efficiency, drainage, and nitrate-loss risk.

Observed treatment results and simulated scenarios should remain clearly distinguished. Scenario outputs represent conditional projections and should not be reported as measured pilot outcomes.

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6. Decision-Support Value, Limitations, and Research Priorities

6.1. Termination Decision Support

Termination timing represents a multi-objective decision. Later termination may increase biomass, nitrogen capture, surface cover, and carbon inputs, but may also increase water depletion and reduce the period available for recharge. Earlier termination may protect soil-water reserves while reducing biomass-related services. The CDT should therefore compare alternative termination dates under multiple weather scenarios. The recommendation should identify the expected gain in biomass or nutrient capture and the associated probability of inadequate soil-water content at maize sowing. A scientifically appropriate output would not simply identify one optimal date. It would state the conditions under which a date becomes preferable and the uncertainty surrounding the recommendation.

6.2. Irrigation Adjustment

The model can evaluate whether the cover crop has created a soil-water deficit relative to the fallow control, whether rainfall has replenished that deficit, and whether residue cover has reduced evaporation after termination. Irrigation recommendations should be based on the layered soil profile rather than a single sensor depth. A dry 15cm upper layer with adequate deeper storage at 40-45cm has different implications from uniform depletion throughout the root zone. Nevertheless, during early crop establishment, deeper water may not yet be accessible, so root development must also be considered. The CDT may therefore recommend maintaining, advancing, reducing, or delaying irrigation according to the inherited soil-water profile and forecast conditions. The recommendation should explain whether the dominant mechanism is soil water depletion caused by the cover crop uptake and transpiration (water use), insufficient post-termination soil-water recharge, or residue-mediated water conservation.

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6.3. Nitrogen Management

The nitrogen recommendation should distinguish among soil-derived nitrogen taken up by the cover crop (nitrogen captured), biologically fixed nitrogen, nitrogen retained in residues, nitrogen expected to mineralise during crop demand, and nitrogen temporarily immobilised. A legume-rich residue may contribute nitrogen relatively rapidly, whereas a cereal-dominated residue may generate an early immobilisation period. In the latter case, a limited starter-nitrogen application may be justified even though total system nitrogen retention is high. The decision-support system should avoid presenting a fixed nitrogen credit unless it is supported by residue quality, environmental conditions, and local calibration. A temporal nitrogen-release estimate is more informative than a single season-long value.

6.4. Scientific and Operational Limitations

Cover crop responses are strongly context dependent. Global meta-analyses provide useful priors but cannot replace local measurements and calibration. Species performance, biomass production, water use, and nitrogen release vary across soils, climates, and management systems. Mixture composition presents an additional uncertainty. Sown proportions may differ substantially from realised biomass proportions because of competition and differential establishment. Model parameterisation should therefore use observed composition wherever possible.

The duration of the GEORGIA pilot limits conclusions regarding long-term SOC sequestration, persistent bulk-density changes, hydraulic improvement, or microbial-community restructuring. The project can credibly report biomass inputs, residue decomposition, soil-water and nitrogen responses, and short-term soil indicators. Longer-term effects should be presented as modelled scenarios rather than validated outcomes.

In addition, process-based models also simplify biological complexity. APSIM can represent the principal soil-water, nitrogen, residue, and crop-growth processes, but it does not mechanistically simulate all microbial interactions, enzyme activities, or rhizosphere pathways. Biological measurements should therefore support interpretation without being overstated as directly simulated processes.

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The quality of management records is another important limitation. Missing or inaccurate information on irrigation, fertilisation, sowing, termination, or residue handling can introduce errors that cannot be corrected by model complexity. **Reliable field records** are therefore **essential** components of the CDT. Finally, cover crops should not be assumed to produce positive outcomes in every season. Meta-analyses report modest average yield benefits but also substantial variation, including neutral and negative responses. The purpose of the CDT, therefore, is not to confirm a predefined benefit but to identify the conditions under which a given cover crop strategy is likely to be beneficial, neutral, or risky.

6.5. Research Priorities

Further research should prioritise repeated crop cycles to distinguish short-term residue effects from cumulative soil change. One cover crop phase is insufficient to characterise long-term trajectories in SOC, hydraulic properties, or soil biological functioning. Local calibration of cover crop species and functional groups is also required, particularly for species that are poorly represented in existing crop models. Phenology, biomass partitioning, rooting depth, tissue nitrogen, and residue quality should be evaluated under Bulgarian conditions.

The practical communication of uncertainty should be tested with farmers and agronomists. Different users may prefer probability ranges, qualitative risk classes, or scenario comparisons. The XAI layer should be designed according to decision relevance rather than model convenience.
Finally, the added value of the full process-based CDT should be compared with simpler sensor-based or empirical decision rules. Model complexity is justified only where it improves prediction, explanation, scenario analysis, or management performance beyond what can be achieved through direct monitoring and transparent agronomic thresholds.

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7. Conclusions

Cover crop succession modelling requires continuous representation of the soil crop system across the preceding crop, cover crop, post-termination, and succeeding crop phases. Soil water, mineral nitrogen, residues, organic-matter pools, and management history should be transferred between phases rather than reinitialised independently. The most influential variables are cover crop biomass, rooting depth, water use, nitrogen uptake or fixation, termination timing, residue quantity, residue quality, and residue placement. Their effects are temporally dynamic and may be antagonistic. Active cover crop growth can reduce soil-water storage, while retained residues may subsequently reduce evaporation. Cover crops may retain or introduce nitrogen, but its agronomic value depends on mineralisation, immobilisation, and synchronisation with succeeding-crop demand.

For the GEORGIA Pilot 2 maize cover crop maize sequence, APSIM provides the most appropriate principal modelling engine because it can integrate crop development, soil-water balance, nitrogen cycling, residue decomposition, and management events across successive seasons. Sensor observations, laboratory analyses, crop measurements, management records, and calibrated remote-sensing products are required to constrain the model and validate intermediate processes rather than yield alone.

The proposed framework does not assume that cover crops are intrinsically beneficial. Its purpose is to determine which species or mixture, under which soil and weather conditions, terminated at what time and managed through which residue strategy, provides the most favourable balance among soil protection, water availability, nitrogen retention, irrigation demand, crop productivity, and yield risk. This conditional and process-based evaluation is necessary if cover cropping is to become an operational, scientifically transparent, and explainable component of regenerative and smart-irrigation management.

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