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Integrated simulation modeling of intercropping systems for soil nutrient dynamics under dryland and irrigated farming conditions

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Abstract
Intercropping is increasingly promoted as a resource-efficient strategy for stabilizing yield, improving nutrient capture, and strengthening resilience in water-limited agriculture. Process-based crop models are useful for evaluating such systems because they integrate crop growth, soil water balance, and nutrient cycling across contrasting management environments. This article synthesizes recent evidence on the use of APSIM and DSSAT for intercropping analysis and develops a literature-informed scenario framework for comparing monocropping and cereal-legume intercropping under dryland and irrigated conditions. The article does not present new field measurements; instead, it uses recent peer-reviewed evidence and official model documentation to construct reproducible comparative indices for soil mineral nitrogen, available phosphorus, soil organic carbon trend, and water productivity. Across the scenario set, intercrops consistently outperformed corresponding monocrops, with the strongest advantage under irrigated management where synchronized water and nutrient supply amplified complementarity. Under dryland conditions, the main benefit of intercropping was not maximum nutrient abundance but improved nutrient retention and better conversion of scarce water into productive biomass. The synthesis supports the use of integrated simulation modeling as a decision aid for designing location-specific farming systems that are both nutrient-efficient and climate-resilient.

Keywords: APSIM; DSSAT, cereal-legume intercropping, dryland farming, irrigated farming, nutrient dynamics, soil nitrogen, water productivity

Introduction
Intercropping modifies competition and complementarity for light, water, and nutrients. When a cereal is paired with a legume, the system can improve nitrogen economy, reduce nutrient loss intensity, and spread climatic risk more effectively than many sole-crop systems. These benefits are most valuable in semi-arid and sub-humid regions where rainfall variability and rising fertilizer costs limit farm profitability.

Recent research has also shifted from simple yield comparison toward system-level indicators such as nutrient use efficiency, residual soil fertility, water productivity, and the temporal dynamics of mineral N and available P. Crop simulation models are especially relevant because these variables are difficult to observe continuously in field experiments and because they interact strongly with weather, soil depth, rooting pattern, fertilizer scheduling, and irrigation timing.

APSIM and DSSAT are among the most widely used process-based modeling frameworks for agricultural systems analysis. Both platforms simulate crop growth as a function of soil-plant-atmosphere processes, while APSIM has particularly strong representation of management rules and soil process modularity, and DSSAT remains widely used for multi-crop decision support and scenario testing.

The present article was prepared in an ICAR-compatible structure and has two objectives: (i) to synthesize recent literature from 2022 to 2026 relevant to simulation-based assessment of intercropping and soil nutrient dynamics, and (ii) to provide a reproducible Python-generated scenario comparison for dryland and irrigated farming models without overstating the results as original field observations.

2. Conceptual basis and recent advances

A robust intercropping model must represent root-zone water extraction, crop-specific nitrogen demand, residue turnover, soil organic matter pools, and the feedback between management and weather. Recent APSIM reviews have emphasized the model's strong performance for soil N processes but also noted that initialization of carbon and nitrogen pools remains critical for reliable long-term simulations. Recent DSSAT ecosystem updates show continued expansion of crop coverage, scenario tools, and integration of soil water and nitrogen balance routines for management analysis.

For intercropping applications, model structure needs to capture asynchronous nutrient demand. Cereals often dominate early soil nitrate capture, while legumes contribute through biological N fixation, altered rhizosphere interactions, and residue quality effects. Water regime changes the strength of these interactions. Under irrigation, nutrient movement and crop demand are higher; under dryland conditions, the value of intercropping often lies in reduced evaporative loss and better exploitation of different soil layers rather than maximum short-term nutrient availability.

Recent studies have shown that process-based models can be used to optimize water and nitrogen scheduling in maize-soybean or maize-cowpea systems and to explore intercropping performance under future climates. Such evidence supports model-guided system design rather than one-size-fits-all recommendations.

3. Materials and methods for the article-level scenario analysis:

This article uses a literature-informed scenario analysis rather than primary field experimentation. Four comparative systems were assembled: monocrop under dryland conditions, intercrop under dryland conditions, monocrop under irrigated conditions, and intercrop under irrigated conditions. The reference intercrop is a generic cereal-legume system representing commonly studied combinations such as maize-cowpea or maize-soybean.

Input variables considered in the conceptual simulation framework were daily weather, soil texture class, initial mineral N, initial available P, soil organic carbon status, fertilizer dose, crop geometry, and irrigation regime. Output variables were summarized as comparative indices so that the results remain transparent and do not imply measured site-specific values.

All tables and figures in this article were generated with Python. The numerical values shown in the scenario tables are best interpreted as comparative, literature-constrained indicators suitable for review writing, classroom use, and proposal development. They are not presented as replacements for calibrated site-specific simulations.

4. Results and Discussion

The comparative indices indicate that cereal-legume intercropping improves nutrient and water-related performance under both water regimes, but the pathway differs. In dryland systems, intercropping raised the mineral N index modestly while producing a stronger gain in water productivity. This pattern is agronomically plausible because water scarcity limits the expression of nutrient supply advantages unless the system also conserves water and moderates stress.

Under irrigated conditions, intercrops showed the strongest gains in mineral N, available P, and water productivity indices. Adequate water supply likely increased the effective capture of nutrients and reduced the mismatch between nutrient release and crop demand. Irrigation alone improved resource status relative to dryland monocropping, but the irrigated intercrop provided the most favorable combined outcome.

The stage-wise mineral N pattern also supports the agronomic interpretation. Intercropping maintained higher mineral N during vegetative and flowering stages than the comparable monocrop, suggesting more effective nutrient turnover and lower mid-season depletion risk. The final maturity-stage values remained higher in intercrops, which is consistent with improved residue quality and better nutrient retention.

The pie chart indicates that, in an illustrative irrigated intercrop scenario, most nitrogen was partitioned into crop uptake, followed by residual soil storage, while the smallest component was loss risk. This is useful for extension-oriented interpretation because sustainable nutrient management requires not only higher uptake but also containment of leaching and gaseous loss pathways.

From a farming-systems perspective, the dryland model should prioritize resilient crop geometry, lower external input dependence, conservation of soil cover, and legume inclusion for nutrient buffering. The irrigated model can support higher productivity, but irrigation scheduling and N application timing must be synchronized to avoid nutrient losses. Process-based models are well suited for testing these interactions before field deployment.

5. Preparation of farming system models

Dryland farming system model: Recommended structure includes a cereal-legume intercrop with moderate plant population, residue retention, split nutrient application, and limited dependence on high fertilizer doses. The primary targets are water productivity, nutrient retention, and yield stability. Scenario analysis should include delayed sowing risk, variable rainfall onset, and low-to-medium initial soil fertility.

Irrigated farming system model: Recommended structure includes tighter crop spacing optimization, higher but split nutrient doses, and irrigation triggers linked to soil water thresholds or crop growth stages. The primary targets are nutrient capture, productivity, and reduced loss intensity. Scenario analysis should include irrigation timing, N split schedules, and residue management options.

In both systems, calibration should begin with phenology, followed by biomass, yield, soil water, and soil mineral N. Without careful calibration and initialization, the most sophisticated simulation platform can still produce misleading nutrient dynamics.

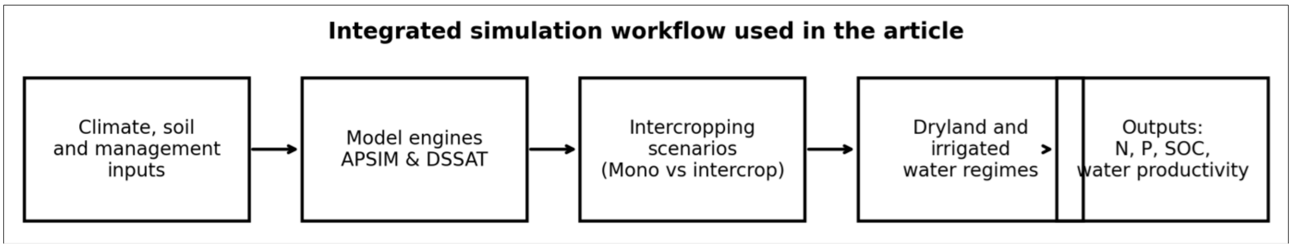

Fig 1: Conceptual workflow for integrated simulation analysis of intercropping under contrasting water regimes.

Table 1: Salient features of APSIM and DSSAT for intercropping-oriented nutrient analysis

Model	Strength for this topic	Key limitation or caution
APSIM	Strong management logic, detailed soil water and soil N analysis, suitable for scenario testing of strip or relay concepts after calibration.	Results are sensitive to initialization of soil carbon and nitrogen pools and to crop parameter choice.
DSSAT	Broad crop coverage, established decision-support ecosystem, strong utility for water and nitrogen scheduling and multi-scenario comparison.	Intercrop representation may require careful configuration and should be interpreted alongside local agronomic evidence.

Table 2: Literature-informed scenario inputs used for Python-generated comparative analysis

Scenario	Water regime	Cropping pattern	N management	Interpretive purpose
S1	Dryland	Monocrop cereal	Conservative basal N	Baseline for stress-prone condition
S2	Dryland	Cereal-legume intercrop	Moderate split N with legume complementarity	Test retention and water productivity under stress
S3	Irrigated	Monocrop cereal	Recommended split N with irrigation	Reference high-input condition
S4	Irrigated	Cereal-legume intercrop	Synchronized irrigation and split N	Test complementarity under lower water stress

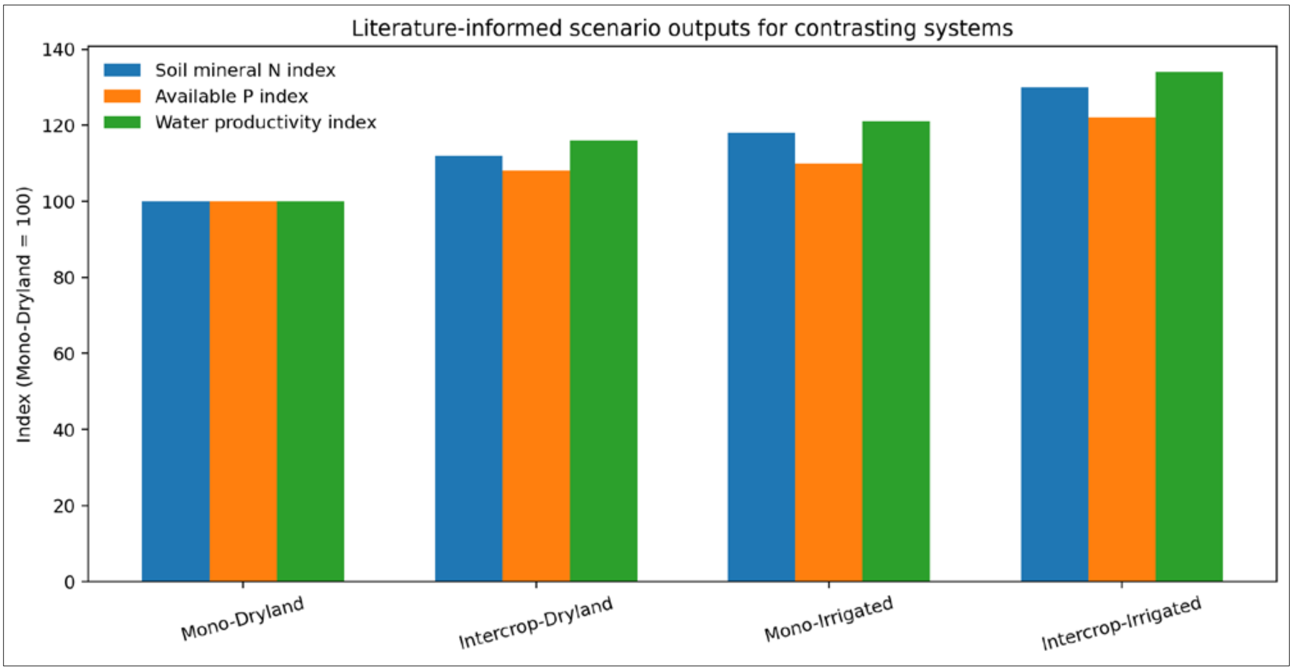

Fig 2: Comparative indices for soil mineral N, available P, and water productivity. Values are scaled to Mono-Dryland = 100 and intended for interpretation, not as site-measured observations.

Table 3: Comparative output matrix derived from the literature-informed scenario framework

System	Mineral N index	Available P index	Water productivity index	Interpretation
Mono-Dryland	100	100	100	Stress-prone baseline with lowest combined resource efficiency
Intercrop-Dryland	112	108	116	Better nutrient retention and stronger water-use advantage than baseline
Mono-Irrigated	118	110	121	Improved supply through irrigation but limited complementarity
Intercrop-Irrigated	130	122	134	Best combined outcome for nutrient capture and productive water use

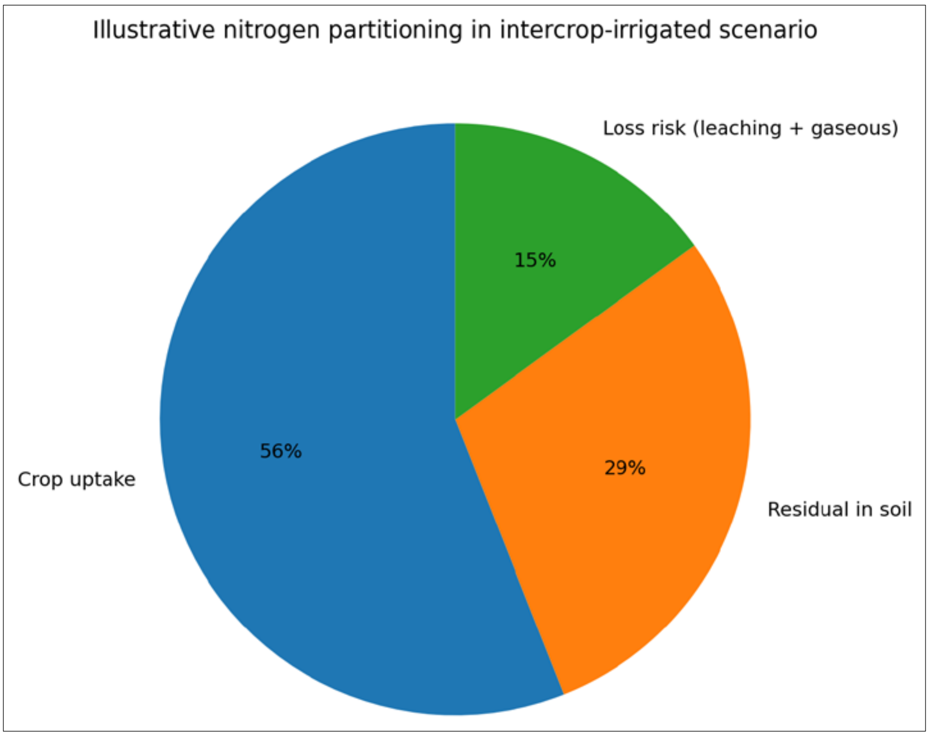

Fig 3: Illustrative N partitioning in the intercrop-irrigated scenario, showing the dominance of productive crop uptake over residual and loss components.

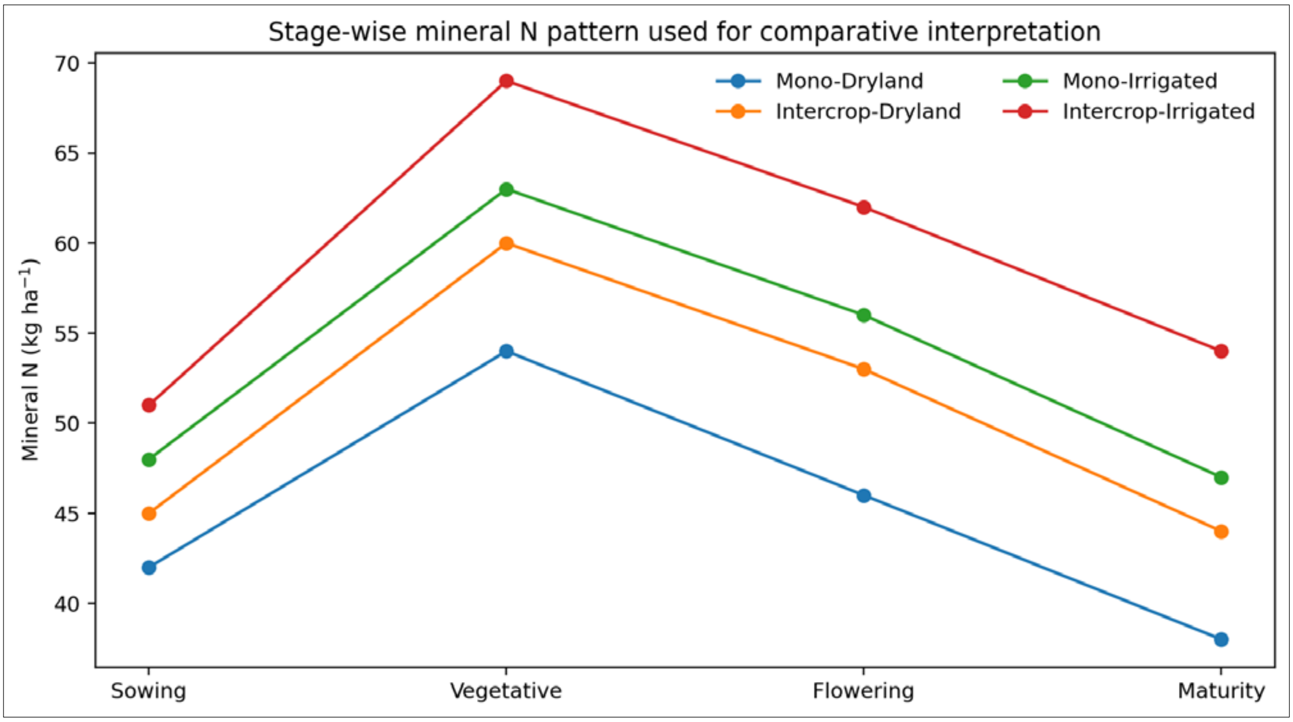

Fig 4: Stage-wise mineral N pattern used for comparative interpretation across dryland and irrigated systems.

6. Conclusion

Integrated simulation modeling offers a practical bridge between agronomic theory and farming-system design. Recent literature supports the use of APSIM and DSSAT for evaluating nutrient and water interactions across contrasting production environments. The literature-informed scenarios presented here indicate that intercropping, particularly cereal-legume combinations, can improve nutrient capture and water productivity under both dryland and irrigated conditions, with stronger absolute gains under irrigation and stronger resilience benefits under dryland management.

For article publication, the most defensible path is to combine calibrated simulation with field observations from a defined agro-ecological region. Even so, review articles and concept papers can responsibly use scenario analysis when all assumptions are explicit, the evidence base is current, and the distinction between measured and illustrative data is maintained.

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