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Agroforestry Decision Support Through Local Ecological Indicators

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Abstract

Agroforestry decisions are highly context dependent because the performance of trees within agricultural landscapes changes with soil properties, rainfall, slope, crop requirements, tree architecture, management intensity, household objectives, and seasonal conditions. Conventional decision-support systems can provide scientifically derived recommendations, yet they may inadequately represent ecological variation perceived by farmers through repeated observation of fields and tree–crop interactions. Local ecological indicators—including soil color, indicator plants, litter decomposition, vegetation vigor, soil moisture behavior, tree phenology, erosion traces, canopy characteristics, and the presence of particular organisms—can provide rapid and inexpensive information about changing field conditions. Their usefulness, however, depends on reliability, local specificity, seasonal interpretation, and appropriate scientific validation. This study develops a methodological framework for integrating local ecological indicators into agroforestry decision support without treating local and scientific knowledge as competing systems. Because authenticated farm observations, ecological monitoring records, and soil analyses were not supplied, the quantitative component is explicitly simulation based. A synthetic sample of 160 agroforestry management profiles is evaluated across tree-species selection, shade and pruning management, soil-fertility intervention, and moisture or erosion management.

A Local Ecological Indicator Decision Support Index is developed from indicator reliability, site specificity, temporal sensitivity, farmer interpretability, correspondence with scientific measurements, and management relevance. Simulated analysis shows an increase in mean decision-support performance from 65.2 under technical-data-only assessment to 84.8 when scientifically screened local ecological indicators are incorporated. The study argues that local indicators are most valuable as rapid contextual signals that help determine where, when, and what additional management or measurement is required. Effective agroforestry decision support should therefore combine farmer-observed ecological evidence with targeted soil, climate, vegetation, and agronomic measurements while retaining transparent information concerning uncertainty and validation status.

Keywords: agroforestry, local ecological knowledge, ecological indicators, decision support, farmer knowledge, soil fertility indicators, tree selection, participatory agroecology

1. Introduction

Agroforestry differs from simplified annual cropping because farmers manage simultaneous interactions among trees, crops, livestock, soil, water, microclimate, and household livelihood objectives. The same tree species may provide shade, fodder, timber, fuelwood, soil protection, litter, or income while also competing with crops for water, nutrients, or light. This multifunctionality makes standardized recommendations difficult to apply uniformly across farms. Research on agroforestry decision support has consequently demonstrated that tree selection becomes more useful when recommendations account for both local biophysical conditions and services valued by individual farmers. A decision-support system developed for coffee and cocoa farms, for example, used farmer rankings of tree species and locally valued ecosystem services to generate context-sensitive shade-tree recommendations rather than assuming one universally optimal tree mixture.

Farmers have an additional information source that formal agricultural systems sometimes underuse: repeated ecological observation. Through long-term interaction with particular fields, farmers may associate soil color with fertility, specific weeds with soil conditions, rapid litter decomposition with nutrient cycling, crop appearance with moisture stress, tree phenology with seasonal transition, or surface crusting and runoff with erosion risk. Studies comparing farmer soil assessments with laboratory measurements have found substantial correspondence in several contexts. Farmers in Ghana, for example, differentiated soil fertility through characteristics including color, water-holding behavior, soil workability, weeds, crop growth, and macrofauna, and many of these qualitative classifications corresponded with measured differences in soil nutrients and organic matter. Research in Kenya has likewise shown that farmer-derived soil-quality assessments can correlate with scientifically calculated soil-quality indices.

The value of local ecological indicators is especially apparent where conventional measurement is costly, infrequent, or spatially sparse. A laboratory analysis provides detailed information concerning soil chemistry at the sampled location and time, but a farmer may observe the field throughout the season and recognize how surface moisture, plant vigor, litter, weeds, insects, and tree behavior change following rainfall or management. Local indicators therefore have a different informational strength: they can be inexpensive, continuous, geographically specific, and immediately interpretable within management practice. Barrios and colleagues demonstrated the methodological value of linking farmer-defined soil-quality indicators with technical measurements to create a common language between farmers, researchers, and extension personnel, particularly for early recognition of land-degradation processes.

Local indicators nevertheless require careful interpretation. An indicator can be highly reliable in one ecological setting while being weak or misleading elsewhere. The presence of a particular weed may be associated with fertile soil in one location because of moisture or nutrient relationships but may occur for completely different reasons under another farming system. Seasonal stage, rainfall, grazing, previous cultivation, seed dispersal, and management history can further alter indicator meaning. The most defensible approach is therefore not to elevate local knowledge above scientific measurement or to dismiss it as anecdotal. Research in northern Thailand provides a strong example of integration: farmer-identified tree species used to judge soil suitability were compared with measured soil properties, and many of the perceived relationships between indicator trees and soil characteristics were empirically supported.

The present study develops this integrative principle into a structured framework for Agroforestry Decision Support Through Local Ecological Indicators. The framework treats local observations as potentially valuable ecological evidence whose relevance should be documented, tested, and linked with management decisions. It proposes a Local Ecological Indicator Decision Support Index that considers reliability, site specificity, temporal behavior, interpretability, scientific correspondence, and practical management value. Because no authenticated ecological dataset was provided, all quantitative results are explicitly simulated. The objective is methodological: to establish how farmer-observed indicators and conventional measurements can be combined transparently to improve tree selection, canopy management, soil-fertility intervention, and soil-water conservation decisions.

2. Objectives of the Study

2.1 To Develop a Structured Local Ecological Indicator Framework for Agroforestry

The first objective is to develop a framework through which farmer-observed ecological signals can be recorded systematically rather than remaining as undocumented oral knowledge. The model recognizes indicators associated with soils, plants, trees, water movement, microclimate, and biological activity while requiring each indicator to be associated with an explicit ecological interpretation.

An observation such as "dark soil is better" is therefore insufficient by itself. A structured record should indicate what farmers mean by "better," under which crops and field conditions the relationship is observed, during which season it is most informative, and what management action normally follows. This process converts local knowledge into decision-relevant evidence without removing its ecological context.

2.2 To Evaluate Complementarity Between Local and Scientific Indicators

The second objective is to determine how local ecological indicators can complement scientific measurements. The proposed framework does not assume that agreement is always necessary. Agreement strengthens confidence, but disagreement can also be informative because it may reveal an unmeasured ecological process, an indicator whose meaning has changed, or a farmer interpretation requiring further investigation.

The approach therefore assigns indicators different validation states ranging from locally consistent but scientifically untested to empirically supported or contextually uncertain. This prevents decision-support systems from treating all locally reported relationships as equally reliable while avoiding the opposite error of excluding knowledge simply because laboratory validation has not yet occurred.

2.3 To Assess the Contribution of Integrated Indicators to Agroforestry Decisions

The third objective is to evaluate whether combining locally observed and scientifically measured indicators improves decision support across four practical agroforestry domains: tree-species selection, shade and pruning management, soil-fertility intervention, and moisture or erosion management.

These decisions were selected because each depends strongly on local ecological interactions. The suitability of a tree is influenced by soil, rainfall, crop compatibility, crown architecture, and farmer needs; pruning depends on changing shade and moisture conditions; fertility intervention depends on both soil status and vegetation response; and erosion management requires understanding where water actually concentrates across the farm.

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3. Review of Literature

3.1 Local Ecological Knowledge as an Agroforestry Information System

The formal treatment of farmer ecological knowledge has developed substantially through methodologies designed to record complex qualitative understandings of agroecosystems. Sinclair and Walker developed systematic approaches for representing local knowledge concerning complex agroecosystems through explicit statements and relationships, allowing farmer and scientific knowledge to be analyzed rather than treated as fundamentally incomparable forms of information. Their work was developed particularly with agroforestry in mind, where multiple interactions among trees, soils, crops, and management make exclusively quantitative representation difficult.

The Agroecological Knowledge Toolkit extended this approach by providing a structured environment for eliciting and representing knowledge from farmers, researchers, and written sources. It was designed to convert semi-structured interviews into formal knowledge bases containing explicit ecological statements and relationships, thereby supporting systematic analysis by research and extension personnel. The methodological significance lies in making local ecological knowledge inspectable. Different farmers may agree, disagree, or qualify particular relationships, and this variation can be documented rather than being compressed into a general claim concerning "traditional knowledge."

Agroforestry studies demonstrate that farmers' ecological understanding is often highly operational. Research in Ethiopia documented farmer knowledge concerning tree–crop relationships, litter decomposition, soil-fertility improvement, crop effects, fodder value, shade, and other tree characteristics. Farmers used these attributes to distinguish useful from problematic trees and to guide farm-level management. Such evidence supports the interpretation of farmers as ecological observers whose knowledge is directly connected with management rather than being purely descriptive.

3.2 Local Indicators of Soil, Vegetation, and Ecosystem Function

Soil indicators have received particular attention because laboratory analysis is often unavailable at the spatial and temporal frequency required by smallholders. Barrios and colleagues developed a participatory methodology linking local soil-quality indicators with technical soil measurements across farming contexts. The approach was intended to create a common language among farmers, extension personnel, and researchers while supporting practical monitoring of degradation and soil-management responses.

Empirical comparisons provide evidence that farmer classifications can correspond meaningfully with measured soil conditions. Dawoe and colleagues found that observable features including soil color, crop vigor, water retention, soil workability, weeds, plant symptoms, and macrofauna informed farmers' fertility classifications, and many classifications agreed with laboratory evidence. In Kenya, Wawire and colleagues found that farmer soil-quality assessments constituted a consistent classification system and showed significant relationships with scientifically constructed soil-quality indices.

The relevance to agroforestry extends beyond soils. Trees themselves may act as ecological indicators. Research in northern Thailand found that farmers used the abundance of particular tree species to assess whether fallow land was suitable for renewed cropping, and measured soil properties supported several of these tree–soil associations. This is particularly important for agroforestry because trees integrate environmental processes over time. Their vigor, leafing pattern, litter behavior, crown architecture, root effects, and associated vegetation can provide information that short-term measurements may not fully represent.

3.3 From Local Knowledge Documentation to Decision Support

The central challenge is converting ecological knowledge into decisions without oversimplifying it. Van der Wolf and colleagues developed a tree-selection decision-support tool using farmer rankings of shade-tree species according to locally perceived ecosystem services. The resulting system could provide context-specific recommendations based on farmer objectives rather than delivering one generalized species list. This represents an important progression from documenting local knowledge toward making it operational within advisory systems.

Bukomeko and colleagues similarly combined farmer assessments of tree suitability with ecological information concerning tree diversity in coffee agroforestry systems. Farmers' priorities and the suitability of different trees varied with local conditions, and the authors proposed matching farm tree diversity more explicitly with farmer-defined ecosystem-service needs. Wagner and colleagues further showed that small-scale coffee farmers distinguish the ecosystem services supplied by different tree species, supporting locally differentiated approaches to tree management rather than generic tree-presence targets.

Research on indigenous agroforestry management also demonstrates that farmers can formulate multiple criteria and indicators covering agricultural management, livestock, forest sustainability, and social benefits. Such work reinforces the proposition that agroforestry sustainability cannot be inferred from tree density alone; farmers evaluate trees and management practices through several linked ecological and livelihood criteria. The remaining methodological opportunity is to create decision-support architectures in which local indicators possess an explicit validation status and can be combined with targeted scientific measurements rather than being used as unweighted qualitative additions.

4. Research Methodology

4.1 Research Design and Synthetic Agroforestry Environment

The study adopts a quantitative simulation-based methodological design. No authenticated farm surveys, soil laboratory results, tree inventories, local ecological knowledge interviews, climate records, or management histories were supplied. Consequently, the numerical findings do not represent an actual farming population.

A synthetic portfolio of 160 agroforestry management profiles is constructed. Each profile represents a farm-level decision environment containing trees, annual or perennial crops, varying soil conditions, differences in rainfall or moisture exposure, and different farmer management objectives.

Four decision domains are represented:

- tree-species selection for new planting or regeneration management;
- shade-density and pruning decisions;
- soil-fertility intervention;
- and moisture-conservation or erosion-control intervention.

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Local ecological indicators are simulated as observations that farmers could reasonably record during normal farming activities. Scientific indicators represent information that could be obtained through soil testing, vegetation measurement, rainfall information, slope assessment, or agronomic monitoring.

Table 1: Structure of the Local Ecological Indicator Decision-Support Framework

Indicator Domain	Illustrative Local Ecological Indicator	Complementary Scientific Evidence	Potential Agroforestry Decision
Soil condition	Color, friability, moisture retention, ease of cultivation	Organic carbon, pH, nutrient analysis, bulk density	Fertility amendment, tree placement, mulch strategy
Vegetation response	Crop vigor, indicator weeds, leaf color, spontaneous regeneration	Biomass, nutrient status, botanical survey	Soil-management intervention or field differentiation
Tree performance	Crown density, leaf fall, litter decomposition, phenology	Canopy measurements, litter chemistry, tree-growth records	Species selection, pruning frequency, density management
Water behavior	Persistent wet patches, runoff paths, rapid drying, erosion traces	Soil moisture, slope, infiltration, runoff monitoring	Contour planting, barriers, tree positioning
Biological activity	Earthworms, termites, macrofauna, decomposition activity	Soil-biological assessment, organic-matter measurements	Organic-matter management and disturbance decisions
Crop–tree interaction	Suppression or vigor near particular trees	Yield-distance measurements, light and root-zone assessment	Retention, removal, spacing, or pruning of trees

Source: Author-developed methodological framework synthesized from local soil knowledge, agroforestry knowledge representation, and farmer tree-selection research.

4.2 Construction of the Local Ecological Indicator Decision Support Index

The proposed Local Ecological Indicator Decision Support Index (LEIDSI) evaluates the quality of an indicator before it is incorporated into management recommendations.

For local indicator (i):

$$LEIDSI_i = w_r R_i + w_s S_i + w_t T_i + w_f F_i + w_v V_i + w_m M_i$$

where:

- (R_i) = repeatability or reliability of the indicator;
- (S_i) = site specificity and ecological contextualization;

- (T_i) = temporal and seasonal interpretability;
- (F_i) = farmer interpretability and ease of observation;
- (V_i) = validation or correspondence with independent scientific evidence;
- (M_i) = management relevance.

For the baseline simulation:

$$w_r=w_s=w_t=w_f=w_v=w_m=\frac{1}{6}$$

and:

$$\sum_{j=1}^{6}w_j=1$$

The resulting index ranges from 0 to 1.

An indicator is not excluded simply because scientific validation has not yet occurred.

Instead, each observation receives a validation category:

- **Locally established:** repeatedly recognized by experienced farmers but not yet independently tested.
- **Convergent:** local observations and scientific evidence indicate a consistent relationship.
- **Conditional:** useful only under particular seasons, soils, crops, or management conditions.
- **Uncertain:** reported relationship remains inconsistent or insufficiently documented.
- **Contradicted:** available evidence does not support the proposed ecological interpretation.

This classification enables the decision-support system to preserve knowledge without treating uncertainty as fact.

4.3 Integrated Decision-Support Procedure

The proposed decision-support process combines local ecological observations with targeted scientific evidence rather than requiring comprehensive scientific measurement for every decision.

For management alternative (j), an integrated decision score is expressed as:

$$ADS_j= \alpha L_j+ \beta S_j+ \gamma C_j$$

where:

- (ADS_j) = Agroforestry Decision-Support Score;
- (L_j) = weighted local ecological indicator evidence;
- (S_j) = scientific or technical evidence;
- (C_j) = farmer management-context fit.

For methodological demonstration:

$$\alpha=0.30,\qquad \beta=0.40,\qquad \gamma=0.30$$

The model therefore gives the largest individual weight to independently measured scientific evidence but assigns sixty percent of the total decision value to local ecological information and contextual fit combined.

The weighting is not proposed as universal. Tree-failure risk around buildings, for example, would require stronger professional and engineering assessment, whereas routine pruning timing or preliminary soil-health screening may appropriately rely more heavily on repeated farmer observation.

5. Analysis

5.1 Performance of Local Ecological Indicators

The synthetic analysis indicates that indicators differ substantially in decision value. Observable indicators with repeated seasonal expression perform most consistently. Soil color combined with crop vigor, for example, receives a stronger reliability rating than soil color used independently. Similarly, recurring runoff channels observed after several rainfall events provide stronger moisture-management evidence than a single observation following an unusually intense storm.

Tree indicators display high management relevance because farmers can connect visible tree characteristics directly with practical decisions. Crown density informs shade management, leaf-fall timing affects crop light availability, and perceived litter decomposition contributes to judgments concerning nutrient cycling. Nevertheless, tree-species effects require contextualization because the same species can interact differently with crops across rainfall regimes, soils, and management systems.

5.2 Comparison of Technical-Only and Integrated Decision Support

Four representative decision domains were evaluated under two synthetic conditions: technical data alone and technical data combined with screened local ecological indicators.

Table 2: Simulated Agroforestry Decision-Support Performance

Decision Domain	Technical Data Only	Local + Scientific Indicators	Simulated Improvement	Principal Local Contribution
Tree-species selection	66	86	+20	Farmer knowledge of ecosystem services, compatibility, and local performance
Shade and pruning management	63	81	+18	Seasonal canopy behavior, crop response, and moisture observations
Soil-fertility intervention	68	88	+20	Soil, vegetation, litter, and biological indicators contextualize laboratory values
Moisture and erosion management	64	84	+20	Recurrent runoff, drying, infiltration, and erosion observations identify micro-sites
Mean	65.2	84.8	+19.5	Integrated context improves interpretation

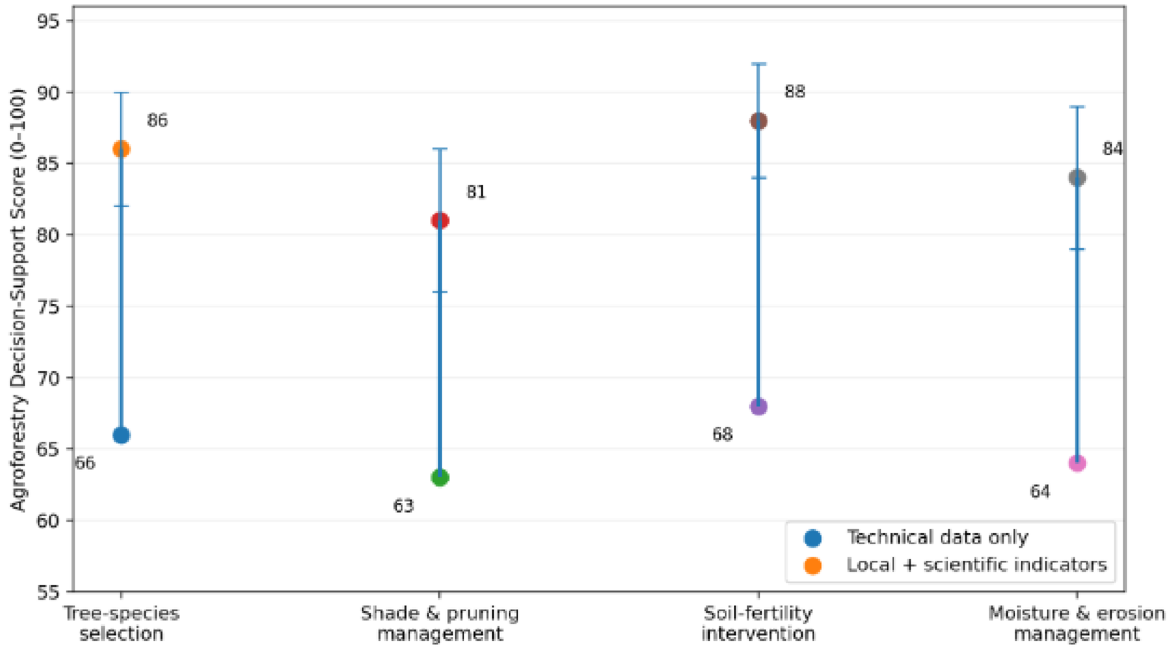
Note: All scores are simulated methodological values. They do not represent observed performance from an identifiable agroforestry project.

The largest integrated score occurs for soil-fertility intervention. This reflects the strong conceptual and empirical basis for combining locally visible soil and vegetation characteristics with laboratory evidence. Research across different smallholder environments has demonstrated that farmer soil classifications can capture meaningful variation in fertility and that traditional soil knowledge can be associated with measurable soil-management ability.

Tree-species selection also performs strongly because local knowledge contains information that standardized databases may not easily represent, including perceived fodder quality, decomposition behavior, crop compatibility, product value, pest interactions, shade characteristics, and household preference. Agroforestry decision-support research has already shown that these farmer-defined services can be incorporated systematically into species-selection tools.

5.3 Decision-Support Improvement Through Indicator Integration

Graph 1: Simulated Decision Support From Integrating Local Ecological Indicators



The graph illustrates the difference between technical-only assessment and integrated decision support. Mean performance increases from 65.2 to 84.8, producing an average simulated improvement of 19.5 points.The vertical intervals around the integrated results represent modeled uncertainty. Their inclusion is important because locally informed decision support should not imply false certainty. Even well-established ecological indicators can become less reliable when climatic conditions, cropping practices, species composition, or land management change.

The improvement does not arise because local indicators are assumed to be intrinsically superior to technical measurements. Instead, technical measurements and farmer observations contribute different types of information. A soil test may identify nutrient status precisely at a sampling point, while repeated farmer observations reveal whether the corresponding field behaves differently across rainfall events, crop stages, or interactions with particular trees.

Key Finding: The simulation suggests that agroforestry decisions become more context responsive when scientific measurements establish ecological constraints while locally validated indicators explain how those constraints are expressed through time and across individual farm locations.

6. Discussion

6.1 Local Indicators as Early-Warning and Contextualization Tools

The principal implication of the study is that local ecological indicators are particularly valuable for screening, early warning, and contextual interpretation. Their greatest strength does not necessarily lie in replacing precise quantitative measurements.

Barrios and colleagues explicitly emphasized the potential of farmer-observed soil indicators to support early identification of degradation and to establish a common working language between farmers and technical specialists. This function is highly relevant to agroforestry because tree-based systems change gradually. Soil-organic-matter improvement, crown competition, erosion protection, root interactions, and microclimate effects may develop across several seasons.

A farmer noticing slower litter decomposition, declining crop vigor below a previously beneficial tree, or persistent drying near a particular tree arrangement may therefore detect a change before formal monitoring is scheduled. The observation should trigger investigation rather than immediate causal attribution.

This distinction protects both local and scientific integrity. Farmer knowledge is not dismissed simply because it is qualitative, while causal claims remain open to testing. A decision-support system can therefore use local observations to decide where measurement is most necessary, reducing the need to measure every variable across every part of a heterogeneous farm.

6.2 Integrating Knowledge Without Erasing Its Source

The second implication concerns knowledge governance. Integrating local and scientific evidence should not mean stripping farmer observations of their source and context until they appear to be generic scientific rules.

The methodologies developed by Sinclair, Walker, and subsequent agroecological knowledge systems are important precisely because they retain explicit knowledge statements and their relationships rather than collapsing local knowledge into undifferentiated descriptions. A farmer may know, for example, that a particular tree improves the crop "when the rain is good but not on the upper dry field." The conditional phrase is scientifically valuable because it identifies an interaction between tree effect, topography, and moisture.

Decision-support tools should preserve such conditions. An indicator database should therefore record location, farmer group, season, crop, tree species, soil context, management history, confidence level, and validation evidence where available.This requirement becomes more important when digital tools are developed. A software system can easily produce a clean recommendation such as "retain Species A," even though the underlying local knowledge may have contained several qualifications.

Digital decision support should expose those qualifications rather than hiding uncertainty behind a ranking score.

The local-knowledge-based shade-tree tool developed for smallholder coffee and cocoa systems illustrates the feasibility of formalizing farmer rankings without eliminating farmer priorities. The broader lesson is that digitalization should improve the organization and accessibility of ecological knowledge while retaining traceability to its ecological and social context.

6.3 Toward Adaptive Agroforestry Advisory Systems

The third implication is that agroforestry decision support should become more adaptive. Static recommendations are particularly problematic in tree-based systems because environmental conditions and household objectives can change substantially during the lifespan of planted trees.

Farmers may initially select a tree for shade and soil improvement, but changing rainfall or crop prices may later alter the desired canopy structure or product mix. Research in Uganda demonstrates that farmer priorities for ecosystem services and the suitability of tree species vary across ecological conditions, supporting approaches in which tree composition is aligned with locally defined needs rather than standardized diversity targets. Work on coffee agroforestry at Mt. Kilimanjaro likewise confirms that farmers differentiate common trees according to the ecosystem services they provide.

An adaptive decision-support system could therefore operate as a recurring cycle:

Farmer Observation → Indicator Recording → Validation Status → Technical Measurement Where Needed → Management Recommendation → Field Response → Updated Indicator Knowledge

This process converts the advisory system from a one-time recommendation tool into a learning system. Extension personnel would play a particularly important role in this architecture. Rather than functioning only as transmitters of externally developed recommendations, they could document locally observed indicators, identify conflicting interpretations, coordinate field validation, and return verified findings to farming communities.

The approach also creates opportunities for participatory monitoring at scale. If multiple farmers independently report that a specific tree is associated with reduced crop vigor under dry conditions, the system can identify the pattern for targeted research. Conversely, if laboratory data repeatedly contradict a local indicator, extension services can investigate why the belief persists and whether a different ecological mechanism has been overlooked.

7. Conclusion

Agroforestry management requires decisions within ecological environments that are too heterogeneous and dynamic to be represented completely by generalized recommendations. Farmers continuously observe soils, trees, crops, water, vegetation, and biological activity, and these observations can contain decision-relevant ecological information. The central argument of this study is therefore not that local ecological indicators should replace scientific analysis, but that agroforestry advisory systems lose potentially valuable contextual evidence when farmer observations are excluded from formal decision support.

The Local Ecological Indicator Decision Support Index developed in this study provides a structured method for evaluating indicators through reliability, site specificity, temporal interpretation, farmer usability, scientific correspondence, and management relevance. Within the synthetic analysis, integrated local and scientific evidence increases the mean Agroforestry Decision-Support Score from 65.2 to 84.8. The largest simulated benefits occur in soil-fertility assessment and tree-species selection, areas in which empirical literature already demonstrates substantial potential for combining farmer observations with technical measurement. The numerical values remain illustrative and should not be interpreted as observed field effects.

A major methodological requirement is preservation of uncertainty. Local ecological knowledge should not be romanticized as universally correct, just as scientific datasets should not be treated as complete representations of local conditions. Indicator meaning can change across soils, seasons, species, elevations, rainfall regimes, and management histories. The most defensible system therefore records where knowledge came from, under which conditions it applies, how consistently it has been observed, and whether independent evidence supports the proposed relationship.

Future empirical research should validate the proposed framework through paired farmer interviews and ecological measurements across contrasting agroforestry systems. Longitudinal studies could examine whether local indicators predict changes in soil fertility, crop performance, tree competition, infiltration, erosion, pest pressure, and microclimate before those changes become visible in conventional monitoring. Research should also investigate how indicator knowledge differs by gender, age, farm experience, livelihood strategy, and agroecological zone. Agroforestry decision support will be strongest when farmers and scientists are not treated as competing authorities but as observers working at different scales, each contributing evidence to an adaptive understanding of complex tree-based farming systems.

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