



Reading the Soil Through Weeds: From Folk Indicators to Evidence-Based Bioindication of Edaphic Conditions in Agroecosystems

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ABSTRACT

Weeds are conventionally viewed as competitors that reduce crop productivity, yet their presence, abundance, spatial distribution, and community composition may also provide information about underlying soil and environmental conditions. Popular agronomic narratives frequently associate *Cyperus rotundus* with compacted soil, *Rumex crispus* with acidic or poorly drained soil, *Portulaca oleracea* with fertile and loose soil, *Amaranthus* spp. with high nitrogen availability, and *Plantago major* with trampling and compaction. This qualitative literature review critically evaluates these claims using contemporary peer-reviewed evidence published predominantly between 2020 and 2026. The synthesis indicates that weed communities respond to soil physical, hydrological, and chemical gradients, including compaction, moisture, pH, salinity, organic matter, and nutrient availability. However, the relationships are strongly modified by tillage, irrigation, crop competition, fertilization, herbicide regimes, climate, propagule pressure, and historical seedbanks. Consequently, individual weed species generally have insufficient diagnostic specificity to function as stand-alone soil tests. Assemblage-level information, functional traits, ecological indicator values, repeated spatial observations, and targeted soil measurements provide more defensible inference

INTRODUCTION

Soil is not merely a medium that physically anchors crops. It is a multifunctional ecological system regulating water storage, nutrient cycling, organic matter transformation, biological activity, carbon sequestration, plant productivity, and resilience to climatic stress. The contemporary concept of soil health therefore integrates physical, chemical, and biological functions rather than reducing soil quality to a narrow set of fertilizer requirements. This broader interpretation has also stimulated demand for indicators that are biologically meaningful, inexpensive, repeatable, and understandable to farmers while remaining sufficiently robust for scientific interpretation (Lehmann et al., 2020; Yang et al., 2020; Nunes et al., 2020; Bhaduri et al., 2022). Recent work further stresses that soil-health science must remain interpretable and practical across heterogeneous management contexts rather than rely on isolated metrics (Wood and Blankinship, 2022).

A central challenge is that soil indicators are highly context dependent. Bulk density has different implications in sandy and clay-rich soils; organic matter concentrations must be interpreted against texture, climate, and land-use history; and even biological indicators respond differently according to cropping system and management. Research on orchard soils, long-term cropping systems, and soil-health benchmarking has consequently emphasized regional reference values and production-environment-specific interpretation instead of universal thresholds (DuPont et al., 2021; Sainju et al., 2021; Lazicki, 2021; Amsili et al., 2023). Recent methodological reviews similarly conclude that soil-health assessment is moving toward integrated, spatially explicit, and increasingly data-driven approaches but still requires strong regional calibration (Buthelezi-Dube and Kibirige, 2026). Recent benchmarking frameworks reinforce this point by showing that interpretation improves when climate, texture, peer-group context, and spatial monitoring units are incorporated explicitly (Nunes et al., 2024; Deel et al., 2024; Gutierrez et al., 2024). Gyawali et al. (2022) likewise demonstrated the value of multivariate interpretation when several soil-health parameters respond differently over short time scales.

Within this context, weeds deserve more attention as potential biological indicators. Agricultural weeds are usually defined operationally as plants growing where they are unwanted. Such a definition emphasizes competition and control but provides limited insight into why particular weed species occur in particular locations. Ecologically, weeds are plant populations filtered by soil conditions, climate, crop competition, disturbance, management, propagule availability, and species traits. Their distribution is therefore structured rather than random. A long-term precision-agriculture case study, for example, demonstrated that spatial weed patterns could be related to measurable soil properties, although substantial variation remained unexplained by soil alone (Pätzold et al., 2020). Weed ecology has increasingly shifted toward this broader systems perspective, arguing that weed communities should be understood as outcomes of agroecosystem processes rather than only as targets for elimination (MacLaren et al., 2020).

This perspective provides a scientific basis for a long-standing practical observation: spontaneous vegetation can sometimes reveal something about land condition. Farmers, gardeners, pastoralists, and traditional land managers often associate certain plants with wet soils, dry soils, fertile patches, compacted paths, saline ground, or particular nutrient conditions. The initial material motivating this review reflects precisely this type of interpretation. It proposes five readily understandable relationships: *Cyperus rotundus* as an indicator of dense or compacted soil; *Rumex crispus* as an indicator of low pH or poor drainage; *Portulaca oleracea* as a sign of fertile, loose soil; *Amaranthus* spp. as a sign of high nitrogen; and *Plantago major* as an indication of trampling or compaction. Such claims are attractive because the “sensor” is already present in the field and can be observed at virtually zero cost. They also appear intuitively plausible because plant species do have different ecological niches. Nevertheless, four distinct propositions are easily confused. First, a species may tolerate a condition. Second, it may occur disproportionately often under that condition, establishing an association. Third, the relationship may be sufficiently consistent for the plant to become an indicator. Fourth, the plant may possess enough specificity to support diagnosis. These four levels are not interchangeable. A species capable of tolerating waterlogging, for example, does not necessarily occur only in poorly drained soil.

The distinction has strong conceptual support in plant ecology. Ellenberg-type indicator values assign plant species relative ecological positions along environmental gradients including moisture, soil reaction, nutrients, temperature, light, and salinity. Modern harmonization efforts have extended this concept to thousands of European vascular plants. Tichý et al. (2023), for example, compiled indicator values for 8,908 European species and emphasized that such values represent species' ecological optima along environmental gradients rather than direct measurements of soil variables. Thus, vegetation can function as a biological proxy for environmental conditions, but an indicator score is not equivalent to a soil laboratory result.

This distinction is particularly important when indicator concepts are transferred geographically. A plant's realized niche is influenced by climate, biotic interactions, management, soil type, and the species pool available in the region. Indicator systems calibrated in Europe cannot therefore be assumed to apply unchanged in Indonesia or other tropical agroecosystems. Tropical systems differ in rainfall seasonality, weathering intensity, soil mineralogy, multiple-cropping schedules, irrigation practices, and year-round weed growth. An evidence-based weed indicator framework must therefore be explicitly regional rather than universal.

The present article is a qualitative literature review rather than a systematic literature review. Its objective is not to calculate a pooled effect size or exhaustively count publications but to integrate contemporary evidence concerning relationships among weeds, edaphic gradients, management, functional traits, and soil-health assessment. Five weed taxa from the initial popular infographic are used as illustrative cases, but the broader objective is

conceptual: to establish when weed observations are informative, when they become misleading, and how they can be integrated with direct measurements. Specifically, the review addresses seven questions. First, to what extent can spontaneous vegetation indicate physical, chemical, and hydrological soil conditions? Second, what scientific support exists for the five focal weed–soil relationships? Third, which soil gradients most consistently structure weed communities? Fourth, how do agricultural practices confound those relationships? Fifth, are multi-species assemblages and functional traits more useful than individual species? Sixth, what verification is required before weed observations guide soil management? Seventh, what research is necessary before weed-based indicator systems can be confidently applied in tropical agriculture?

LITERATURE RIVIEW

1. Weeds as Ecological Responders

A weed community represents the outcome of multiple ecological filters acting simultaneously. At the broadest level, climate determines the potential regional species pool. Within an agricultural field, soil texture, water availability, nutrient status, pH, salinity, aeration, disturbance, crop canopy, herbicides, tillage, and timing of farm operations further determine which species emerge, survive, reproduce, and replenish the soil seedbank. Individual species differ in germination requirements, growth rates, rooting depth, life cycle, nutrient acquisition, stress tolerance, reproductive strategy, and seed persistence. Consequently, weed communities can retain information about the environmental conditions under which they were assembled (MacLaren *et al.*, 2020; Derrouch *et al.*, 2021; Guerra *et al.*, 2022; Bensch *et al.*, 2023).

The influence of management can be dramatic. Derrouch *et al.* (2021) studied fields that had practiced conservation agriculture for different periods and found changes in species richness, weed abundance, functional diversity, and between-field community composition after adoption. A related functional analysis showed that reduced disturbance acted as a filter favoring certain trait combinations (Derrouch *et al.*, 2022). In a German survey involving hundreds of maize fields, Bensch *et al.* (2023) found that crop rotation and tillage systems were associated not only with weed species composition but also with functional characteristics such as growth form, germination season, seed weight, and flowering behavior.

This evidence immediately creates a limitation for simplistic bioindication. If the same management practice modifies both the soil and the vegetation, a weed may appear associated with a soil property even though the actual causal pathway includes several interdependent processes. Repeated machinery traffic, for instance, can compact soil, redistribute residues, reduce infiltration, modify crop growth, and disturb the seedbank at the same location. Weed patches developing in wheel tracks can therefore reflect an integrated disturbance environment rather than bulk density alone.

2. Ecological Indicator Values and Realized Niches

Ecological indicator-value systems provide perhaps the clearest theoretical precedent for interpreting plants as environmental sensors. Ellenberg-type values characterize species along ordinal ecological gradients. Contemporary harmonization has extended these values to moisture, reaction, nutrients, salinity, temperature, and light across much of Europe (Tichý *et al.*, 2023). A complementary European indicator initiative has similarly sought to standardize environmental values across vegetation databases (Dengler *et al.*, 2023), while Tyler *et al.* (2021) developed ecological indicator and trait values for Swedish vascular plants.

The crucial point is that such indices describe relative ecological optima, not absolute measurements. A high nutrient indicator value means that the species tends to occur under relatively nutrient-rich conditions compared with other species in the calibrated flora; it does not mean that observing the species proves a specific concentration of mineral N. Tichý *et al.* (2023) explicitly derived community-level approaches in which values can be averaged across the species present, illustrating why multiple-species information is generally more informative than reliance on an isolated plant.

This logic provides a valuable model for agricultural bioindication. Instead of saying “weed X means soil condition Y,” the scientifically stronger formulation is: “the observed assemblage shifts the probability that condition Y is present.” The magnitude of that probability shift depends on ecological specificity, local calibration, abundance, co-occurring species, spatial pattern, and competing environmental explanations.

3. Physical Soil Properties

Physical soil properties influence plants through several mechanisms. Compaction raises mechanical resistance, can reduce macroporosity and infiltration, alters oxygen diffusion, and may constrain rooting. Texture influences water retention, nutrient storage, aeration, and the mechanical environment for germinating seedlings. Aggregate stability and surface crusting further affect emergence.

Management strongly modifies these conditions. Meta-analysis has shown that tillage intensity influences biological soil-health indicators and soil organic carbon, while field experiments show that the soil-health consequences of reduced tillage vary between conventional and organic production systems (Nunes *et al.*, 2020; Pearsons *et al.*, 2023). Pearsons *et al.* (2023), for example, reported that reducing tillage had contrasting effects between production systems, including differences in surface compaction. Similar field evidence from residue and tillage management confirms that physical, chemical, and biological soil-health responses must be interpreted jointly rather than as isolated effects (Keshavarz Afshar *et al.*, 2022).

Reduced tillage also modifies weed communities because seeds remain closer to the surface, perennial organs experience less disturbance, residue affects light availability, and germination conditions change. Steponavičienė *et al.* (2021), Derrouch *et al.* (2021), Adamič Zamljen *et al.* (2024), and Radicetti *et al.* (2025) collectively show that tillage systems can change weed composition, functional

structure, and seedbank behavior. The consequence is that compaction-associated plants must be interpreted together with the disturbance regime.

4. Hydrological Conditions

Water regime is another major plant-community filter. Moisture affects seed imbibition and germination, root respiration, nutrient mobility, microbial activity, crop competition, and survival. Excess water can produce oxygen limitation, whereas insufficient water filters species according to drought tolerance and rooting strategy.

Research on irrigated and rainfed cropping systems demonstrates that changing water availability can alter weed composition and competitive relationships. Souza *et al.* (2020) showed that soil-water availability affected weed communities and their interference with onion crops. Organic rice systems evaluated by Gao *et al.* (2022) similarly demonstrated that production mode and associated water and nutrient management influenced weed seedbank composition.

Hydrological indicators can nevertheless be confounded by topography and management. A weed concentrated in field depressions may reflect longer saturation, but the same depression may contain finer sediment, additional nutrients, or different herbicide exposure. Therefore, moisture-indicating vegetation becomes more convincing when its spatial pattern corresponds with visible drainage processes and when several moisture-associated species occur together.

5. Soil Ph and Chemical Environment

Soil reaction influences nutrient availability, metal solubility, microbial activity, root physiology, and community assembly. Plant species consequently differ in their preferred reaction ranges, which is why “reaction” is a standard variable in ecological indicator systems. Yet inference from a single weed to precise pH remains difficult because many successful agricultural weeds tolerate wide pH ranges.

The same principle applies to salinity. Species vary substantially in salt tolerance, and some apparently “fertile-soil weeds” can also survive high electrical conductivity. Salinity therefore provides a useful example of why ecological breadth reduces diagnostic specificity: a plant that grows well across both nutrient-rich and saline environments cannot uniquely identify either condition.

6. Nutrient Availability and Weed Communities

Fertility has one of the strongest documented relationships with weed ecology. Nutrient addition may directly stimulate weed growth, enhance crop competitiveness and indirectly suppress weeds, change nutrient ratios, alter soil microbial processes, or select species with particular resource-acquisition strategies. Consequently, the direction of the response depends on nutrient form, rate, timing, crop, weed species, and management history.

A review by Little *et al.* (2021) demonstrated that fertility amendments influence both weed growth and weed-crop competition and that responses depend strongly on relative crop and weed responsiveness, timing of emergence, fertilizer source, and nutrient-release patterns.

Long-term evidence reinforces this complexity. Cordeau et al. (2021) found that 14 years of nutrient management influenced taxonomic and functional weed-community composition even when total seedbank density did not necessarily differ among treatments. Kordbacheh et al. (2023) found that repeated use of different nutrient sources modified crop biomass and weed communities; treatments increasing soil N availability tended to produce greater crop biomass and lower weed diversity.

Esposito et al. (2023) showed that soil nutrition management differentiated weed communities in rainfed winter wheat and that surplus fertilization could reduce community differentiation and richness. Wang et al. (2023) similarly demonstrated that six years of different fertilization regimes shifted weed-community composition and crop-weed competition in winter oilseed rape.

These studies strongly support nutrient sensitivity at the community level while simultaneously undermining simple “one weed = one nutrient concentration” rules. Nutrient-responsive vegetation is therefore most informative when interpreted together with crop competitiveness, fertilizer history, and measured soil nutrient status.

7. Seedbanks as Ecological Memory

Visible weeds represent only a fraction of the weed population. Agricultural soils contain dormant and persistent seeds accumulated across previous seasons. The seedbank therefore functions as an ecological memory of past crop rotations, weed-control failures, disturbance regimes, dispersal, and environmental conditions.

Gao et al. (2020) demonstrated long-term changes in weed seedbanks under chemical control in rice-wheat systems. Otto et al. (2023) examined two decades of crop rotation and fertilization and found that herbicide management could obscure some expected rotational effects. Adamič Zamljen et al. (2024) found that changing from conventional to conservation or no-tillage rapidly altered the germinable seedbank and affected persistent seed distribution.

For bioindication, this means that current vegetation can partly reflect past rather than present soil conditions. A flush of weeds after cultivation may emerge because seeds were moved into favorable germination positions even though the present soil environment is not the ecological optimum associated with that species. Repeated seasonal observation is therefore much more defensible than a single field visit.

METHODOLOGY

1. Review Approach

This study uses a qualitative literature-review design. It is intentionally not presented as a systematic literature review, bibliometric analysis, or meta-analysis. The purpose is to integrate heterogeneous empirical, ecological, agronomic, and methodological evidence around a conceptual question: under what conditions can weeds serve as credible indicators of soil properties?

A qualitative approach is suitable because the evidence spans multiple research designs. Some studies manipulate fertilizer rates; others compare tillage systems, survey weed communities over large areas, quantify seedbanks, model plant ecological niches, analyze functional traits, investigate focal species experimentally, or examine soil-health indicators independently of weeds. These bodies of literature cannot be pooled meaningfully into a single effect size without substantially narrowing the research question.

2. Literature Identification

The literature-search architecture included combinations of the terms weed, weed community, arable flora, spontaneous vegetation, bioindicator, indicator species, ecological indicator value, Ellenberg, soil properties, edaphic, soil health, compaction, bulk density, soil moisture, drainage, waterlogging, pH, soil reaction, nitrogen, phosphorus, fertility, salinity, seedbank, and the scientific names of the focal species. Search combinations were refined iteratively as recurring concepts and competing explanations emerged from the literature, and backward and forward citation tracing was used selectively to identify additional relevant studies.

The principal publication period was January 2020 to September 2026. Emphasis was placed on peer-reviewed journal articles from established international publishers and journals covering weed science, soil science, agronomy, plant ecology, precision agriculture, and environmental science. Older conceptual sources were unnecessary because the article was explicitly designed around contemporary evidence.

3. Evidence-Selection Principles

Studies were prioritized when they fulfilled at least one of the following criteria: they measured soil properties together with weed distributions; experimentally manipulated edaphic conditions; investigated nutrient-weed relationships; evaluated tillage or irrigation effects on weed communities; developed ecological indicator values; examined environmental tolerance of one of the focal taxa; or contributed a methodological framework relevant to soil-health interpretation. Priority was given to studies that allowed the ecological signal of weeds to be separated, at least conceptually, from confounding effects of management, climate, crop competition, or seedbank history.

Medicinal, pharmacological, or purely phytochemical studies of the focal weeds were not used unless they contained directly relevant ecological information. Retracted publications were excluded. This is important because the article aims to assess common claims critically rather than accumulate literature supporting a predetermined conclusion.

4. Analytical Categories

Evidence was synthesized using four interpretive levels. Tolerance indicates that a species can persist under a condition, whereas association indicates that its presence or abundance repeatedly covaries with that condition. Indicator value requires a reproducible relationship that provides meaningful ecological information, while diagnostic value requires sufficient specificity and validation to permit confident inference of the soil condition.

The final category carries the strongest evidential requirement. Many popular weed claims achieve the first or second level but have not demonstrated the specificity required for diagnosis.

5. Thematic Coding

Studies were organized into six themes: soil physical conditions; hydrology; soil chemistry and fertility; weed-community and functional-trait responses; management and seedbank confounding; and focal-species evidence. The synthesis then asked whether multiple independent bodies of evidence converged on the same interpretation.

The review also distinguished between direct and indirect evidence. A study measuring *P. major* abundance and bulk density directly would constitute stronger evidence for a plantain-compaction relationship than a general study showing that disturbed grasslands contain Plantago species. This distinction is essential when translating ecological associations into practical recommendations.

RESULT

1. Weed Patterns Contain Genuine Edaphic Information

The literature consistently demonstrates that agricultural weed communities are structured by environmental conditions rather than randomly distributed. Long-term spatial analysis has linked weed occurrence with soil properties such as texture, water availability, and soil organic carbon (Pätzold et al., 2020). Large ecological-indicator datasets similarly demonstrate that plant assemblages can meaningfully track gradients of moisture, soil reaction, fertility, and salinity (Tyler et al., 2021; Tichý et al., 2023; Dengler et al., 2023).

However, this finding should not be overstated. The same literature demonstrates that management and environmental interactions account for substantial variation. Nguyen and Liebman (2022) found differences in weed communities between simple and diversified cropping systems. Guerra *et al.* (2022) showed that weed-management practices shape plant functional diversity. Bensch *et al.* (2023) found clear associations among cropping system, tillage, weed species, and functional traits. Westbrook *et al.* (2024) identified substantial remaining uncertainty in weed-diversity research, particularly regarding interactions among multiple drivers.

Thus, weed communities can contain edaphic information, but extracting that information requires separation of soil effects from management filters. This distinction underpins the interpretation of all focal species considered below. The relationships identified across the literature are summarized conceptually in **Figure 1**. The figure emphasizes that weeds do not respond directly and exclusively to soil. Physical, hydrological, and chemical soil states interact with

management, climate, crop competition, seedbank history, and plant functional traits before generating the vegetation visible in the field.



Figure 1. Conceptual architecture of weed-based soil bioindication.

The figure illustrates the pathways from soil gradients to weed-based field indicators, the generation of probabilistic soil hypotheses, and the importance of ground-truthing with soil measurements before making management decisions. Arrows indicate the direction of inference, and the feedback loop highlights the dynamic interaction between management and soil-weed systems.

Figure 1. Conceptual Architecture of Weed-Based Soil Bioindication

Figure 1 should be read from left to right as a chain of inference rather than causation from a single variable. Soil properties contribute to the ecological environment in which weeds are filtered, but the observable vegetation carries signatures from several processes simultaneously. Consequently, the valid scientific output of weed observation is initially a **hypothesis**, not a final diagnosis. Direct soil measurements represent the ground-truthing stage that converts an ecological signal into management-relevant evidence.

2. *Cyperus Rotundus*: A Persistent Generalist Rather Than a Specific Compaction Meter

Cyperus rotundus is among the world's most persistent agricultural weeds because its underground tubers support vegetative regeneration and allow rapid recolonization after disturbance. The popular interpretation that its presence directly indicates compacted soil is therefore problematic: persistence can itself be generated by propagule biology and cultivation history.

Mijani et al. (2021) demonstrated strong temperature effects on tuber sprouting, confirming that thermal environment is important to its emergence biology. Du et al. (2022) studied 24 Chinese populations and found substantial genetic diversity and ecotypic differences in tolerance to environmental conditions. The authors concluded that such diversity contributes to the species' strong environmental adaptability.

This broad ecological amplitude weakens diagnostic specificity. If a species survives across multiple pH, temperature, moisture, and disturbance environments, its presence alone cannot identify one physical soil condition. Compaction may coexist with *C. rotundus*, particularly in repeatedly trafficked agricultural fields, but the available contemporary literature does not justify using the species as a stand-alone compaction diagnosis.

A more scientifically defensible field interpretation would therefore be: persistent *C. rotundus* should trigger investigation of soil physical condition, but also of cultivation history, tuber density, moisture regime, temperature, crop competition, and repeated soil disturbance. Penetration resistance or bulk density must be measured before concluding that compaction is the main causal constraint.

3. *Plantago Major*: A Plausible Disturbance Signal Requiring Verification

The case for *Plantago major* as an indicator of trampling or compaction is ecologically more plausible but remains context dependent. The species frequently occupies disturbed sites and can tolerate repeated physical disturbance. Evidence from productive grassland systems is informative: Klötzli et al. (2024), while primarily examining *Rumex obtusifolius*, identified soil bulk density as an important factor associated with problematic parcels, with *P. major* occurring among indicator vegetation associated with those disturbed conditions.

This constitutes useful but indirect support. It does not establish a universal bulk-density threshold above which *P. major* appears. Furthermore, the genomic analysis of Lyu et al. (2023) illustrates the broad environmental adaptability of *P. major*, including capacity to occupy stressful substrates. Aioub et al. (2021) similarly demonstrated physiological and molecular responsiveness to contaminated environments.

Accordingly, *P. major* is best used as a spatial clue. Its diagnostic usefulness increases when plants repeatedly dominate wheel tracks, pathways, animal routes, gateways, headlands, or other visibly trafficked areas. If abundance falls sharply outside those zones, the spatial correspondence strengthens a compaction hypothesis. Verification through penetration resistance, bulk density, infiltration, and root examination remains necessary.

4. *Rumex Crispus*: Separating Moisture from Acidity

The popular claim concerning *Rumex crispus* combines two soil properties that should be evaluated separately: water regime and soil reaction. Association with wet or disturbed habitats is ecologically credible, but a categorical relationship with low pH is much less defensible from contemporary literature.

Tillage studies illustrate why the interpretation is complicated. Steponavičienė et al. (2021) found weed communities responding simultaneously to tillage, moisture, soil reaction, and nitrogen-related gradients. Individual species therefore occurred within a broader community structure shaped by several environmental filters. Studies of related *Rumex* problems in grassland further demonstrate that high soil bulk density and fertility can be important, challenging overly simple ideas that dock species necessarily diagnose acidity (Klötzli et al., 2024).

For practical purposes, *R. crispus* concentrated in field depressions or chronically saturated microsites can reasonably trigger a hypothesis of impaired drainage. That hypothesis becomes stronger if other hydrophilic species co-occur and the area exhibits slow infiltration, standing water, mottling, or poor crop rooting. Soil acidity, however, should be evaluated through a pH test rather than inferred directly from *R. crispus*.

This distinction illustrates one of the principal themes of the review: the same plant can be informative without being uniquely diagnostic. Diagnostic confidence should therefore depend on spatial context, co-occurring species, and direct measurements rather than taxonomic identity alone.

5. *Portulaca Oleracea*: Fertility Response Does Not Equal Fertility Diagnosis

Purslane presents perhaps the clearest example of why popular indicators require critical revision. It is frequently associated with warm, open, disturbed, and productive soils, and experimental studies confirm that its growth can respond strongly to nutrient supply. Hosseinzadeh *et al.* (2021) demonstrated responses of purslane to organic amendments, nitrogen, biological fertilizer, and drought conditions. Chrysargyris *et al.* (2023) also showed that different ammonium-to-total-nitrogen ratios substantially affected plant growth and nutritional characteristics.

Yet nutrient responsiveness alone does not make purslane a fertility-specific indicator. Recent research demonstrates exceptional tolerance to salinity. Yazdani-Bioui *et al.* (2023) experimentally characterized *P. oleracea* as strongly salt tolerant, while Silva *et al.* (2022) identified physiological and molecular responses enabling plants to cope with high NaCl exposure. He *et al.* (2023) likewise examined purslane under artificial seawater treatments.

A species that can perform under both productive and saline conditions has low specificity as a universal fertility indicator. In agricultural fields, purslane may signal warm open microsites, recent disturbance, irrigation, resource availability, salinity tolerance, drought adaptation, or combinations of these factors.

Consequently, seeing purslane should not lead automatically to the conclusion that “the soil is fertile and loose.” A more appropriate response is to examine nutrient status, EC, water regime, disturbance, surface structure, and crop canopy.

6. *Amaranthus* Spp.: Comparatively Strong Association With High-Resource Environments

Among the five focal examples, the association between *Amaranthus* species and high-resource conditions is one of the more defensible propositions. Members of the genus include rapidly growing, competitive weeds capable of exploiting favorable nutrient conditions, and fertilizer experiments frequently demonstrate strong interactions between nutrient availability and amaranth competitiveness.

The broader evidence on fertilizer–weed interactions supports this interpretation. Little *et al.* (2021) showed that weed responses to nutrient additions are influenced by relative crop and weed responsiveness. Cordeau *et al.* (2021) found long-term nutrient regimes altered weed-community structure and functional composition. Kordbacheh *et al.* (2023), Esposito *et al.* (2023), and

Wang et al. (2023) all demonstrated significant community-level responses to repeated nutrient management.

Baraibar and Knudsen (2024) provide particularly relevant evidence because *Amaranthus palmeri* was used in crop-weed competition experiments. They found that soil characteristics, management system, and fertilizer affected competition between maize and Palmer amaranth, with fertilizer capable of shifting competitive outcomes.

Nevertheless, the genus cannot be treated as a nitrogen meter. Khan et al. (2022) showed that *A. retroflexus* and *A. viridis* differ in germination and persistence under environmental stresses, illustrating species-level ecological variation. Seedbank history and herbicide selection can also produce high abundance independently of current nitrogen status.

Thus, dense amaranth populations can legitimately increase suspicion of a resource-rich environment, especially where several nitrophilic species occur together, but mineral N and fertilizer history should be evaluated before making a nutrient-management decision. The signal becomes more credible when abundance patterns coincide with known fertilizer placement or other independent evidence of elevated nutrient availability.

7. Tillage Reshapes the Signal

The evidence consistently shows that tillage is one of the dominant confounders in weed bioindication. Tillage changes both the physical environment and the weed propagule system. Inversion moves seeds vertically; reduced tillage accumulates seeds nearer the surface; no-tillage can favor perennial or surface-germinating species; residue changes light and moisture; and machinery alters soil strength.

Derrouch et al. (2021) found increasing species richness and abundance after adoption of conservation agriculture, together with longer-term convergence in weed communities. Bensch et al. (2023) found tillage and cropping sequence among the most important management dimensions structuring maize weeds and their traits. Adamič Zamljen et al. (2024) observed rapid seedbank responses during transition toward conservation and no-tillage systems.

Pearsons et al. (2023) further demonstrate why this matters for inference: reduced tillage can itself alter soil-health indicators and compaction differently depending on the wider production system. A weed associated with reduced tillage may therefore appear correlated with bulk density even when tillage regime is an important common cause.

8. Fertility Modifies Communities in Multiple Directions

The influence of nutrients is equally complex. Fertilizer can directly stimulate weeds, indirectly suppress them by strengthening crops, or change competitive hierarchies among weed species.

Kordbacheh et al. (2023) found increased crop biomass but reduced weed diversity under nutrient sources that generated high available N. Esposito et al. (2023) observed that surplus fertilization could simplify winter-wheat weed communities. Wang et al. (2023) reported that balanced fertilization increased oilseed rape growth and reduced weed density, whereas prolonged fertilizer regimes shifted community composition.

Kousta *et al.* (2023) similarly showed interactions between fertilizer treatments, weed management, and crop performance in hemp. Simard and Ziadi (2024), however, found that decades of mineral fertilization did not always produce strong differences in all weed-community metrics, emphasizing that fertilizer effects can be constrained by herbicides, crop competition, and other management filters.

The implication is critical: a plant's abundance can increase because nutrients directly benefit the weed, but it can also decrease because nutrients allow the crop to suppress that same species more effectively. Bioindication must therefore interpret vegetation as the outcome of competition, not merely nutrient availability.

9. Crop Rotation and Temporal Dynamics

Crop identity and rotation create recurring patterns of sowing date, harvest date, canopy development, disturbance, herbicide timing, and resource competition. Nguyen and Liebman (2022) demonstrated that more diverse rotations can substantially alter weed-community composition. Duchene *et al.* (2023) found shifts in weed communities as perennial intermediate wheatgrass stands aged, including changes in grass versus broadleaf components.

Otto *et al.* (2023) found that the effects of crop rotation and fertilization on long-term weed seedbanks can become difficult to separate from the strong filtering imposed by herbicide management. This finding is especially relevant to weed indicators: a plant may be absent from apparently ideal soil simply because effective herbicide selection has eliminated it from the local propagule pool.

Thus, **absence is generally weaker evidence than presence**. Failure to observe an indicator weed does not establish that the relevant soil condition is absent.

10. Community-Level Indicators Are More Defensible

The most important synthesis from the results is that multi-species approaches are intrinsically more robust than single-species rules. Several species responding independently to the same environmental gradient provide ecological replication.

Ellenberg-type systems operationalize this through community means. Tichý *et al.* (2023) harmonized values for thousands of vascular plant species and demonstrated their use for community-level estimation of environmental conditions. Such approaches reduce dependence on unusual behavior by any one species.

Functional-trait analyses offer a complementary approach. Guerra *et al.* (2022) showed that weed management can select combinations of traits through processes of convergence and divergence. Bensch *et al.* (2023) similarly demonstrated management-associated functional differences in maize weeds. A community dominated by acquisitive, rapid-growing, nutrient-demanding species provides stronger evidence of a high-resource environment than the isolated presence of one such species.

The different levels of support for the five focal weeds are summarized in Figure 2, which should be interpreted as an evidence matrix rather than as a deterministic identification guide. The figure contrasts common field claims with

the narrower conclusions supported by recent ecological and agronomic evidence.

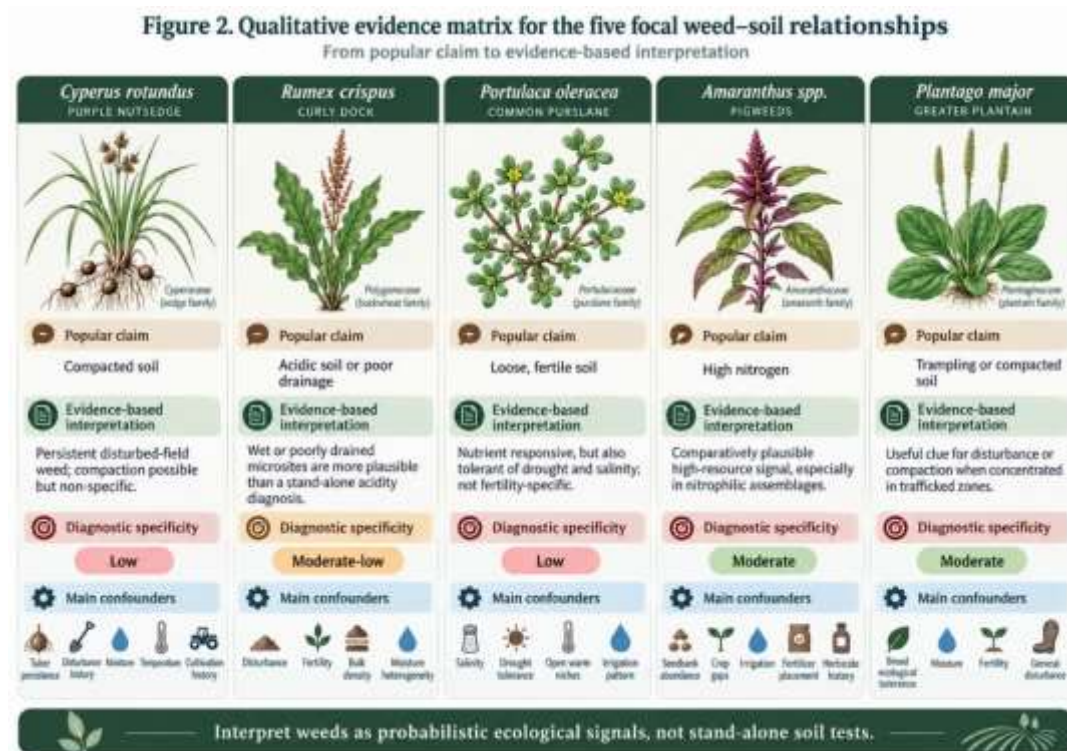


Figure 2. Proposed Evidence Matrix for the Five Focal Weeds and Edaphic Conditions

Figure 2 highlights why “indicator” should not be treated as a binary category. A plant may have high ecological relevance but low diagnostic specificity. The figure therefore intentionally distinguishes between a popular interpretation and the narrower conclusion justified by recent research.

DISCUSSION

1 What Can Weeds Legitimately Tell Us?

The strongest defensible conclusion is that weeds can identify **patterns that deserve investigation**. They are more useful for generating hypotheses than for replacing direct soil analyses.

This difference matters because vegetation integrates conditions over time. A laboratory sample measures soil at particular locations and times; weed communities reflect repeated environmental filtering throughout emergence, growth, survival, and reproduction. This temporal integration is potentially advantageous. A persistent weed patch may reveal a stable environmental difference that sparse soil sampling misses.

However, integration also creates ambiguity. The plant signal incorporates current soil conditions, previous weather, seedbank history, crop competition, management, and propagule availability. Biological integration therefore trades analytical specificity for ecological information.

This is similar to broader soil-health assessment, in which no single indicator reliably captures all soil functions. DuPont et al. (2021) emphasized regional and management-goal-specific soil-health indicator sets. Amsili et al. (2023) developed production-environment benchmarks rather than universal values. The 2026 review by Buthelezi-Dube and Kibirige similarly emphasizes regionally calibrated and process-informed approaches.

The appropriate conceptual transition is therefore from weed occurrence to an ecological clue, then to competing hypotheses, targeted testing, and finally diagnosis. In other words, weed occurrence should initiate an evidence-gathering process rather than be treated as the diagnosis itself.

2. Sensitivity and Specificity

A useful indicator needs both sensitivity and specificity. A highly sensitive species may frequently appear when a condition is present, but if it also appears under many alternative conditions, its diagnostic value remains low.

Portulaca oleracea illustrates this distinction. Nutrient responsiveness may make it sensitive to high-resource conditions, yet its demonstrated tolerance of salinity means that observing purslane does not specifically distinguish high fertility from saline or drought-prone environments.

Cyperus rotundus creates the same problem through broad adaptive capacity. Environmental and genetic variation in tuber sprouting permits persistence across diverse conditions, weakening any unique connection with compaction.

By contrast, diagnostic confidence increases when a species appears in a spatial pattern strongly aligned with the hypothesized process. *Plantago major* occurring throughout a field is weak evidence of compaction. The same species repeatedly concentrated in machinery wheel tracks while being scarce in adjacent soil provides a stronger signal because the spatial pattern introduces an independent line of evidence.

3. A Multi-Species Evidence Model

The logical next step is to shift from single weeds toward **indicator assemblages**. Suppose one field contains several species independently associated with high nutrient availability, whereas a second field contains one

nutrient-responsive weed together with several species characteristic of low-resource environments. The first field supplies stronger evidence of high fertility.

Community-weighted indicator values formalize precisely this principle. They can incorporate both species identities and their relative abundance. Tichý et al. (2023) demonstrated the scalability of this framework for moisture, soil reaction, nutrients, and salinity across European vegetation.

In tropical agriculture, equivalent systems could be developed empirically. Common agricultural weeds could be assigned provisional local indicator values using paired vegetation and soil observations. Values could then be validated independently against measured soil properties. The output would be far more scientifically defensible than transplanting European values uncritically or repeating traditional weed-soil associations without calibration.

4. The Weed-Soil Inference Framework

Based on the literature synthesis, this paper proposes the Weed-Soil Inference Framework (WSIF). The framework is designed to convert an observed weed pattern into a testable soil hypothesis before any management intervention is selected.

Step 1: Observe Vegetation Systematically

Observation should document more than presence. Useful information includes abundance, percentage cover, phenological stage, spatial pattern, patch size, crop position, elevation within the field, relationship to drainage lines, and association with vehicle or livestock traffic; photographs and GPS coordinates can further improve repeatability.

Step 2: Identify Multiple Species

A conclusion should not be based on one conspicuous weed if several other species are present. Co-occurring vegetation provides independent ecological information and can reveal whether the focal plant is representative or incidental.

Step 3: Generate Competing Hypotheses

Every observation should initially produce more than one explanation. For example, a *Plantago major* patch may reflect compaction, disturbance, moisture, fertility, or seedbank legacy; a *Portulaca oleracea* patch may reflect nutrient-rich soil, salinity, a warm exposed surface, drought tolerance, or irrigation pattern; and *Amaranthus* dominance may reflect high nutrient availability, crop gaps, seedbank abundance, fertilizer placement, or herbicide selection. Framing several alternatives makes the subsequent field test falsifiable rather than confirmatory.

Step 4: Examine Management History

Management variables should include previous crops, fertilizer types and rates, manure, tillage, irrigation, herbicides, machinery traffic, grazing, and recent earth movement. This step is indispensable because management can generate both the soil condition and the weed community, creating an apparent association that may otherwise be misinterpreted as a direct soil effect.

Step 5: Conduct Targeted Soil Verification

Only parameters implicated by the hypothesis need to be measured initially. Suspected compaction can be tested with penetration resistance, bulk density, infiltration, and rooting depth; poor drainage with soil moisture profiles,

infiltration, saturation duration, and redox or mottling observations; acidity with pH; salinity with electrical conductivity; and fertility with mineral N, available P, exchangeable K, organic matter, and fertilizer history.

Step 6: Assign Inference Confidence

A practical three-level confidence system can be used. Low confidence applies when only one species is present and neither spatial correspondence nor supporting measurements are available; moderate confidence applies when several consistent species or a strong spatial pattern aligns with management history; and high confidence requires agreement among assemblage evidence, spatial pattern, management history, and direct soil measurements.

Step 7: Separate Diagnosis From Intervention

Even when soil diagnosis is confirmed, the weed-control decision remains separate. If high bulk density is confirmed, modifying traffic or improving soil structure may address the underlying condition, but established weeds may still require direct control. Likewise, if high N favors particular weeds, adjusting fertilizer timing or placement may alter competitive relationships while persistent seedbanks continue producing weeds for years. Ecological diagnosis should therefore complement rather than replace integrated weed management.

The seven steps above are summarized in **Figure 3**. The key conceptual innovation is the explicit insertion of competing hypotheses and independent soil verification between vegetation observation and management intervention.

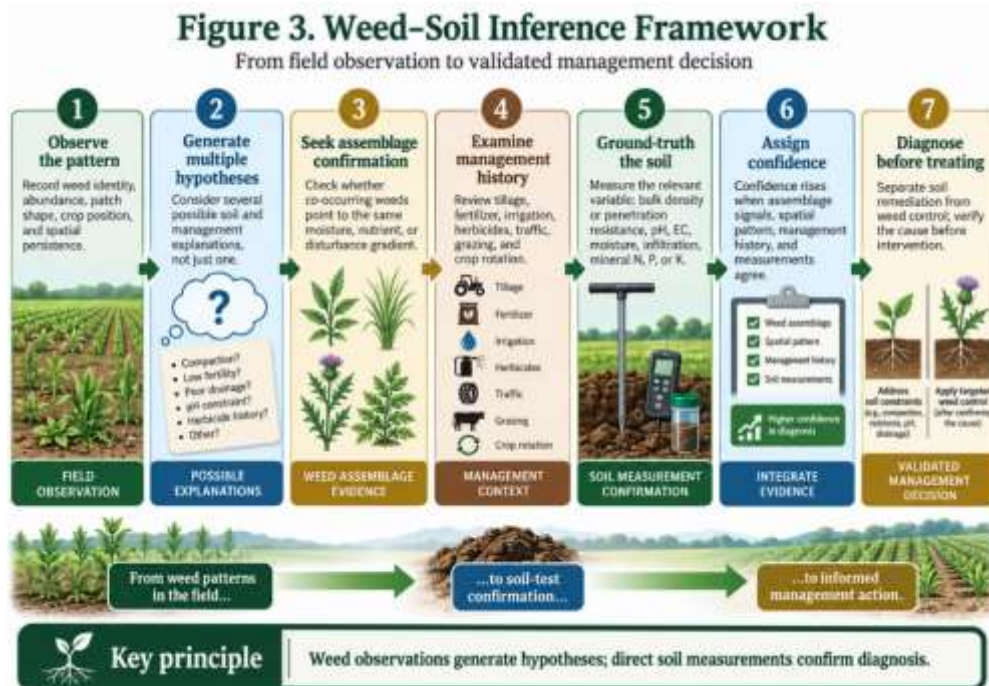


Figure 3. Weed-Soil Inference Framework for Evidence-Based Field Diagnosis

Figure 3 illustrates that the framework minimizes confirmation bias. A farmer who expects *Cyperus rotundus* to mean compaction might otherwise interpret every occurrence as confirmation. By requiring alternative explanations and measurement of penetration resistance or bulk density, WSIF converts folk knowledge into a falsifiable ecological hypothesis.

5. Implications For Sustainable Weed Management

Treating weeds as ecological information changes the question from “How can this weed be killed?” to “Why is this weed successful here, and what does that tell us about the agroecosystem?” This additional diagnostic question does not diminish the need for control but helps distinguish symptom management from correction of underlying field constraints.

MacLaren et al. (2020) argue that sustainable weed science must move beyond repeated reliance on herbicides and tillage toward agroecological regulation of weed populations. Their systems perspective is consistent with using weed occurrence as ecological information while retaining integrated management as the operational response.

Nutrient-management studies reinforce this idea. Fertilizer source and rate can change weed competition and community structure (Little *et al.*, 2021; Cordeau *et al.*, 2021; Kordbacheh *et al.*, 2023). In some cases, modifying nutrient timing or resource availability could strengthen crop competitiveness rather than directly stimulating weeds. Gannett *et al.* (2024), for example, explored manipulation of soil resource availability and microbial communities as a mechanism for weed management.

However, ecological management should not be romanticized. Some weeds remain serious agricultural problems because biological persistence can overwhelm attempts to manage the underlying soil condition. Improving soil structure will not automatically eliminate a large *C. rotundus* tuber bank. Similarly, improving fertility management will not immediately eliminate persistent *Amaranthus* seeds.

The framework should therefore be regarded as an additional layer of information within integrated weed management, not an alternative to effective control. Its main value is to improve diagnosis, monitoring, and targeting while conventional and agroecological control tools remain available according to the weed problem.

6. Soil-Health Surveillance

The most practical near-term application may be in spatial soil-health surveillance. Conventional soil sampling is necessarily sparse because laboratory testing costs money and labor. Vegetation, by contrast, occurs continuously across the field.

If recurring weed patches identify zones with potentially different soil conditions, they can be used to stratify sampling. Candidate zones include *Plantago*-dominated machinery paths, persistent wet-site vegetation in depressions, high-density *Amaranthus* patches near fertilizer application zones, and saline-tolerant vegetation near irrigation margins; each zone can then be compared with an adjacent reference area using the relevant soil measurements. This approach does not reduce the value of soil testing. It potentially improves **where** soil tests are placed.

Such targeted sampling is consistent with precision agriculture's principle of managing within-field variability rather than assuming homogeneous soil conditions. Repeated vegetation observations can therefore help define management zones and improve the placement of confirmatory soil samples.

7. Precision Agriculture and Artificial Intelligence

Technological development creates a pathway for scaling weed-based bioindication. Computer vision can increasingly recognize and map weeds automatically. Hasan et al. (2021) reviewed deep-learning approaches for weed identification from field imagery. Rai et al. (2023) found rapid growth in deep-learning methods for site-specific weed management, including ground and aerial imaging, transfer learning, object detection, and semantic segmentation. Murad et al. (2023) similarly reviewed dozens of image-based weed-detection applications. More recent syntheses confirm rapid advances in crop-weed classification and recognition while emphasizing persistent limitations associated with dataset bias, crop coverage, field variability, and model generalization (Adhinata et al., 2024; Darbyshire et al., 2024; Saini and Nagesh, 2025).

Most existing systems are designed to answer a control question – **where is the weed so that it can be removed?** The present framework proposes an additional analytical question – **what environmental information does the weed's spatial distribution contain?**

A future workflow could overlay several georeferenced data layers rather than rely on imagery alone. These layers may include UAV- or robot-derived weed-species maps, digital elevation and drainage information, soil electrical conductivity, yield maps, machinery-traffic maps, fertilizer application records, and soil-test observations.

Machine-learning algorithms could then estimate conditional relationships among weed assemblages, management history, and soil properties. Importantly, models would require independent farm-level validation because high predictive accuracy within one dataset does not guarantee transferability to different regions. Recent reviews of weed-detection technology explicitly identify generalization across field conditions and datasets as a continuing technical challenge (Rai et al., 2023; Murad et al., 2023).

Figure 4 expands the framework toward digital agriculture by showing how weed observations could become one layer of a multi-source soil-monitoring platform. It also makes explicit that model-based prioritization must be followed by targeted ground-truth measurements before a prescription map is finalized.



Figure 4. Proposed Digital Architecture For Weed-Assisted Soil Surveillance

Figure 4 illustrates that the purpose of the digital model is not to allow artificial intelligence to infer soil conditions without measurement. Instead, machine learning would identify spatial relationships and prioritize ground-truth sampling. This hybrid architecture preserves the efficiency of automated vegetation mapping while retaining laboratory and field measurements as the final validation layer.

8. Why Tropical Calibration is Indispensable

The largest scientific gap relevant to Indonesia is the lack of region-specific calibration. Many well-developed ecological indicator systems originate in temperate Europe. Their direct transfer into tropical agroecosystems would violate a fundamental principle of indicator ecology: species' realized niches depend on regional environmental and biotic context.

Indonesia contains highly diverse production environments: intensively irrigated rice, rainfed uplands, volcanic soils, highly weathered acidic mineral soils, plantation systems, peatlands, horticultural production, and peri-urban agriculture. The same weed may interact differently with soil moisture and fertility in these environments.

Tropical evidence already demonstrates context dependency. Gao et al. (2022) found different weed seedbanks among rice production systems influenced by management. Ripoché et al. (2024) showed that rotation and fertilization shaped weed communities in low-input rainfed agroecosystems in Madagascar, but responses were strongly context dependent. At a wider ecological scale, Qi et al. (2025) found that climate and soil variables, including precipitation and pH, influenced weed distribution and diversity in grasslands. A tropical indicator framework should therefore be developed empirically rather than translated literally from temperate guides. Local calibration is necessary to

account for differences in weed floras, soils, rainfall regimes, cropping calendars, and management histories.

9. Proposed Indonesian Calibration Program

A scientifically robust Indonesian research program could involve several phases. First, representative agroecosystems would be selected across major cropping systems and soil types, and georeferenced vegetation quadrats would quantify species identity, cover, density, and phenology. Second, paired soil measurements would quantify pH, EC, organic carbon, mineral N, available P, exchangeable K, bulk density, penetration resistance, texture, moisture, and infiltration.

Third, management information would be collected, including fertilizer history, irrigation, tillage, pesticide use, rotation, traffic, and crop density. Fourth, multivariate models would identify weed species and assemblages consistently associated with environmental variables after management effects had been accounted for.

Fifth, candidate relationships would be tested on independent farms rather than evaluated only on the calibration dataset. Sixth, indicator values would be transformed into extension tools only after external validation; together, these steps could ultimately support a Tropical Agricultural Weed Indicator Database that combines botanical knowledge with smartphone recognition and soil-health recommendations.

10. Revisiting the Five Popular Messages

The evidence allows the original infographic to be reformulated more accurately. Each popular statement can be retained as an observation prompt, but its wording should be narrowed to reflect uncertainty and the need for direct verification.

The popular statement “Teki means compacted soil” is too categorical. A scientifically stronger formulation is that persistent *Cyperus rotundus* can occur in heavily disturbed fields, but its wide environmental adaptability means that compaction should be tested rather than assumed.

The statement “*Rumex crispus* means acidic soil or poor drainage” combines two different mechanisms. Concentrated *R. crispus* in wet field positions may justify investigating drainage, whereas soil acidity should be confirmed with pH measurement rather than inferred from the species alone.

The statement “Purslane means fertile, loose soil” also overstates diagnostic specificity. *Portulaca oleracea* can respond to nutrient-rich conditions but is highly tolerant of drought and salinity, so its presence alone does not diagnose fertility.

The statement “Amaranth means high nitrogen” is better treated as a resource-availability hypothesis. Abundant *Amaranthus* spp., particularly together with other nitrophilic weeds, may indicate a high-resource environment, but soil N should be measured before fertilizer decisions are changed.

The statement “*Plantago major* means compacted soil” is most defensible when spatial context supports it. *Plantago major* concentrated in repeatedly trafficked areas is a useful clue for compaction or disturbance, but physical soil measurements are still required for diagnosis.

This reformulation preserves the practical value of field observation while eliminating deterministic claims that exceed the scientific evidence. It also provides language that extension materials can use without presenting ecological associations as laboratory-equivalent diagnoses.

11. Limitations of the Evidence Base

1The present literature contains several important limitations. First, direct recent experiments designed specifically to validate traditional weed-indicator claims are surprisingly scarce, and much of the available evidence is indirect, emerging from community ecology, management experiments, seedbank studies, and environmental-tolerance research.

Second, causal direction is difficult to establish. Fertility may change weed communities, but weed abundance can also influence nutrient cycling. Tillage modifies the physical soil environment while directly filtering seeds and vegetative propagules.

Third, geographic representation is uneven, with European and North American systems disproportionately represented in weed-community and indicator-value datasets. This imbalance limits confidence when transferring indicator relationships to tropical or underrepresented production environments.

Fourth, published studies frequently use different response variables: density, biomass, cover, species richness, seedbank density, functional traits, or ordination scores. This heterogeneity limits direct comparison.

Fifth, individual taxa can contain substantial ecotypic variation. The environmental adaptability documented for *C. rotundus* illustrates why species-level indicator values may conceal meaningful population differences (Du et al., 2022).

Finally, climate change may alter historic plant-environment relationships. Changes in rainfall, temperature, irrigation requirements, crop calendars, and disturbance regimes can shift species' realized niches. Weed-indicator frameworks must therefore be periodically recalibrated rather than treated as permanent botanical rules.

CONCLUSIONS AND RECOMMENDATIONS

Weeds can provide meaningful information about soil and field conditions, but they should be interpreted as **living ecological sensors rather than deterministic soil tests**. Contemporary literature demonstrates that weed communities respond to compaction, soil-water regime, pH, salinity, fertility, disturbance, and other environmental gradients. At the same time, those responses are strongly conditioned by crop competition, tillage, fertilization, irrigation, herbicide use, seedbank history, climate, and species-specific ecological plasticity.

The five focal examples demonstrate different degrees of evidential strength. *Amaranthus* spp. provide a comparatively plausible signal of high-resource conditions, but their presence cannot quantify soil N. *Plantago major* can contribute useful information about disturbance or compaction, especially when concentrated in trafficked zones. *Rumex crispus* may support a drainage hypothesis when spatial context indicates persistent wetness, whereas inferring acidity without direct pH measurement is unwarranted. The ecological breadth of *Cyperus rotundus* substantially limits its usefulness as a specific compaction indicator. *Portulaca oleracea* is nutrient responsive but also sufficiently tolerant of salinity and drought that it cannot be treated as a universal marker of fertile, loose soil.

The evidence therefore supports an **assemblage-based model**. Multiple weeds, abundance, functional traits, spatial distribution, repeated observations, and management history should be interpreted together. The resulting ecological hypothesis should then be ground-truthed through targeted soil measurements. For farmers and extension personnel, weed observations can provide a low-cost first-pass surveillance system. They can identify where compaction testing, drainage assessment, pH measurement, EC testing, or nutrient analysis should be concentrated. For researchers, weed communities provide a promising biological layer for integrated soil-health assessment. For precision agriculture, automated weed mapping creates opportunities to integrate vegetation, soil, topographic, crop, and management data.

The greatest priority is regional calibration. Tropical agroecosystems should not simply import temperate indicator values. Indonesia and comparable agricultural regions need paired weed–soil databases developed across crops, soil types, climates, and management systems.

The central conclusion can therefore be expressed succinctly: a weed should not be read as a laboratory result. It should be read as an ecological question asked by the field, with the answer established through contextual interpretation and direct measurement.

FURTHER STUDY

This research still has limitations, so further studies on the topic of Reading the Soil Through Weeds: From Folk Indicators to Evidence-Based Bioindication of Edaphic Conditions in Agroecosystems are needed to improve this research and expand the knowledge for both the writer and the readers.

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