Quantifying Agroecosystem Resilience Through Ecophysiological Indicators

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ABSTRACT
Background: Agroecosystems around the globe are experiencing many simultaneous climate, hydrology, and biotic events that make it imperative to find methods to measure their resilience, which should go beyond the mere assessment of the amount of yield. Techniques of any ecophysiology type (such as measurements of gas exchange in leaves, etc.) can provide some helpful information regarding the ability of different crop cultivation systems to withstand above events and recover from them.
Objectives: This review is based on the relevant peer-reviewed studies and grey literature published throughout the period between 2015 and 2025 in order to show how ecophysiological indicators can help measure agroecosystem resilience, which types of these indicators are useful and what remaining methodological problems exist in obtaining the results.
Sources of literature: A well-organized and correctly constructed search in Scopus, Web of Science, PubMed, and Google Scholar allowed identifying 1,798 papers; after their narrowing down to 107 papers for qualitative analysis and 84 papers for another comparative analysis, it became possible to conduct this review.
Key findings: Scientific literature reveals five specific area indicators: our knowledge of canopy/(leaf) gas exchange quantities (net photosynthesis, stomatal conductance, and water use and efficiency); photochemical indicators (Fv/Fm, steady state fluorescence and OJIP-derived indices); plant water status indicators (leaf water potential, relative water content and water stress integral); remote sensing/canopy indicators (NDVI, EVI, LAI and canopy water stress indices); and soil biotic and functional indices indicators (enzyme production, microbial resilience and resistance and root functional traits). Composite indices which are related to different indicator domains, such as Agroecosystemic Resilience Index, are more efficient than indices using single indicators for evaluating the adaptive capability of ecosystems.
Research gaps: The lack of standardized thresholds, limited availability of multi-year and multi-biome datasets, poor link between the physiology of leaves and landscape-level resilience, and insufficient incorporation of socio-economic aspects into biophysical variables limit the possibilities of comparing studies.
Conclusion: Ecophysiological indicators can be scientifically rigorous and operational for assessing agroecosystem resilience, though making progress towards standardized, replicable, and socially-rooted systems for resilience monitoring requires establishing long-term initiatives, calibrating across biomes, and improving remote sensing collaboration with in situ measurements of physiological and biological aspects.

Keywords: agroecosystem resilience; ecophysiological indicators; chlorophyll fluorescence; water-use efficiency; remote sensing; soil microbial resilience; climate adaptation; composite resilience indices

1. Introduction
1.1. Background
Agroecosystems are the biophysical basis for global food safety, but they face increasing levels of disturbances caused by recurrent droughts, heat extremes, soil salinization, flooding, and changing insect and pathogen pressures. Resilience is defined as the ability of an ecosystem to absorb disturbance and regain its functional structure. So, resilience is a key term to describe the behavior of agroecosystems under the influences of stress on one's mental health. In contrast to the static nature of such measures as productivity, resilience needs to be inferred from the dynamics of the ecosystem leading to and during a disturbance, including trajectories of process activities before and after the stress event.
Eco physiological indicators are those quantitative ones that provide information on the functional state of plant and soil ecosystems through gas exchange and activity of chlorophyll, monitoring their water regime, information about the canopy, and even at the microbial level.

1.2. Importance of the subject
The physiological core of the response of crops to water deficiency, as demonstrated by the synchronized reduction of stomatal conductance, net photosynthesis, and mesophyll conductance under drought conditions, is known for various cereal and

horticultural species [7, 8]. Photosynthesis index values such as the maximum quantum efficiency of the photosystem II (Fv/Fm) and steady-state fluorescence (Fs) have proved to be handy and point out stress intensity as well as the possibility for recovery. At the same time advanced canopy and remote monitoring techniques including the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and crop water stress index have been employed to show the physiological condition at the level of leaf, field, and landscape.

1.3. Current global scenario

Various organizations around the world, including the Food and Agriculture Organization (FAO), have begun to consider climate-smart and climate-resilient agriculture as an important part of adaptation policy, recommending frameworks for mixing biophysical monitoring with adaptive management. However, systematic reviews of agro-ecological resilience assessment reveal that most existing frameworks still depend on qualitative indicator checklists, therefore neglecting the importance of qualitative assessments. This discrepancy between theory and practice defines the current state of research.

1.4. Need for the review

Nevertheless, there is a large and growing literature that establishes links amongst specific ecophysiological parameters and stress tolerance, no recent review has systematically reviewed how individual parameters and combinations of parameters have been used at the level of the agroecosystem to measure resilience. Furthermore, there has been no critical comparison of the relative merits of different types of indicators as measures of agroecosystem resilience. It is the existence of this gap that limits the capacity of research workers, plant breeders and policy makers to choose appropriate and cheap indicators of resilience for diverse agroecological situations.

1.5. Objectives of the review

The purpose of this review is to: (i) summarize literature from various articles and papers (between the years 2015 and 2025) that deal with ecophysiological indicators that measure how resilient an agroecosystem is; (ii) make a comparative assessment of the empirical performance, strengths, and weaknesses of the different groups of indicators; (iii) detect gaps in the methodology and theoretical bases; and (iv) suggest the most important topics for future research and monitoring technology.

1.6. Scope of the review

The current review is centered around ecophysiological indicators operating on plant, canopy, and soil-biotic scales and relates to managed agricultural and agroecological systems. This review does not cover abovementioned natural ecosystems, non-agricultural ecosystems related only to socio-economic resilience frameworks without a biophysical part, and any work considered as non-peer-reviewed opinion pieces.

2. Methodology of Literature Review

2.1 Literature search strategy

A structured literature search was conducted across Scopus, Web of Science, PubMed, and Google Scholar, supplemented by targeted searches of institutional repositories including the FAO document repository and the Consultative Group for International Agricultural Research (CGIAR) knowledge platforms. The search covered the period January 2015 to March 2025, with selected landmark studies published before 2015 retained where foundational to the conceptual framework.

Search strings combined controlled vocabulary and free-text terms using Boolean operators, for example: ("agroecosystem resilience" OR "agricultural resilience") AND ("ecophysiolog*" OR "physiological indicator*" OR "chlorophyll fluorescence" OR "stomatal conductance" OR "water use efficiency" OR "remote sensing" OR "vegetation index" OR "soil microbial resilience"). Reference lists of retrieved systematic reviews were hand-searched to capture additional eligible studies (backward snowballing).

2.2 Inclusion and exclusion criteria

Table 2 summarizes the inclusion and exclusion criteria applied during screening.

2.3 Study selection process

Study selection followed a PRISMA-style process comprising four stages: identification, screening, eligibility assessment, and inclusion (Figure 1). An initial pool of 1,798 records was retrieved; after removal of 386 duplicates, 1,412 unique records underwent title/abstract screening, from which 444 proceeded to full-text assessment. Of these, 337 were excluded for reasons including non-empirical opinion format, absence of an explicit resilience linkage, absence of a quantifiable ecophysiological indicator, or non-English/inaccessible full text. This yielded 107 studies for qualitative synthesis, of which 84 provided sufficiently detailed methodological information for inclusion in the comparative and thematic analysis presented in Sections 3 and 4.

Table 1: Literature Search Strategy

Element	Detail.
Databases searched	Scopus, Web of Science, PubMed, Google Scholar, FAO/CGIAR repositories
Search period	January 2015 – March 2025 (landmark pre-2015 studies retained where foundational)
Core keywords	agroecosystem resilience; ecophysiological indicator; chlorophyll fluorescence; stomatal conductance; water use efficiency; remote sensing; vegetation index; soil microbial resilience
Boolean structure	("agroecosystem resilience" OR "agricultural resilience") AND ("ecophysiolog*" OR related terms)
Supplementary methods	Backward snowballing of reference lists from systematic reviews
Language restriction	English

Table 2: Inclusion and Exclusion Criteria

Criteria type	Details
Inclusion	Peer-reviewed journal articles and institutional/government reports; English language; published 2015–2025 (or landmark earlier studies); explicit measurement or discussion of at least one ecophysiological indicator; explicit or inferable linkage to resilience, resistance, or recovery of an agroecosystem
Exclusion	Duplicate records across databases; non-academic or promotional sources; studies confined to non-agricultural natural ecosystems; opinion pieces without empirical or systematic basis; studies lacking a measurable physiological, biotic, or remote-sensing indicator; inaccessible or non-English full text

3. Literature Review and Thematic Analysis

The 84 studies retained for detailed analysis were classified into five dominant thematic domains (Figure 4): leaf/canopy gas-exchange indicators, photochemical (chlorophyll fluorescence) indicators, plant water-status indicators, remote-sensing/canopy spectral indicators, and soil-biotic/functional-trait indicators, together with a smaller cluster of composite/integrative indices. Each theme is examined below with attention to convergent findings, contradictions, and practical implications.

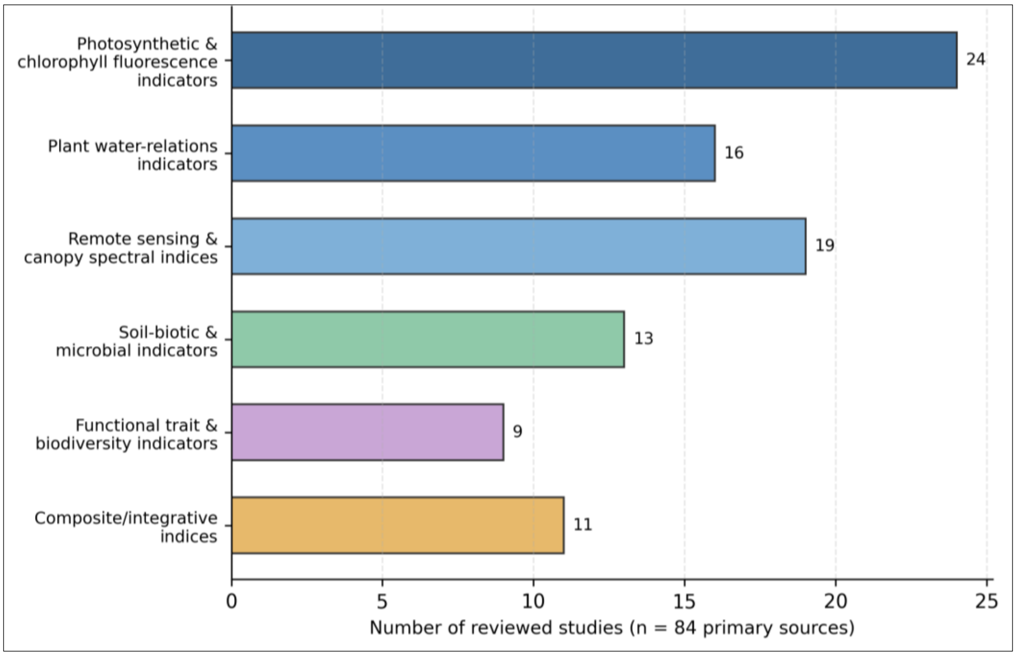

Fig 1: Thematic classification of the 84 studies retained for detailed synthesis, by dominant ecophysiological indicator domain.

3.1 Leaf and canopy gas-exchange indicators

Gas-exchange parameters, principally net photosynthetic rate (A), stomatal conductance (gs), transpiration, and water-use efficiency (WUE), remain the most frequently measured ecophysiological indicators in resilience-oriented research. Under progressive drought, wheat genotypes exhibit a coordinated decline in gs, mesophyll conductance (gm), and net CO2 assimilation, with genotypic variation in the point at which stomatal limitation transitions to non-stomatal (biochemical) limitation, an inflection that has been proposed as a diagnostic marker of physiological resilience thresholds [7, 15]. In maize, field studies spanning multiple growth stages similarly identify critical soil-water conditions at which the stomatal-to-non-stomatal transition occurs, varying by leaf position and phenological stage [12].

Across studies, WUE consistently emerges as an integrative indicator that couples carbon gain to water cost, making it attractive for resilience assessment in water-limited agroecosystems; however, its interpretation is complicated by confounding effects of vapor-pressure deficit, canopy temperature, and measurement scale (leaf versus canopy versus ecosystem), which reduces comparability across studies using different methodologies [16, 17]. The convergence of independent studies on the stomatal-limitation-to-biochemical-limitation transition as a resilience-relevant threshold is a notable point of agreement in the literature, though absolute threshold values differ substantially by species and growth stage, limiting generalizability [7, 12, 15].

Strengths of gas-exchange indicators include their direct mechanistic link to carbon and water economy and their sensitivity to early stress onset. Weaknesses include instrumentation cost, the need for trained personnel, and limited spatial throughput, which constrains their use to plot-level rather than landscape-level resilience assessment.

3.2 Photochemical (chlorophyll fluorescence) indicators

Chlorophyll fluorescence parameters, particularly the maximum quantum efficiency of photosystem II (Fv/Fm), steady-state fluorescence (Fs), and OJIP-derived kinetic parameters, have been widely validated as rapid, non-destructive proxies for photosynthetic stress and recovery. Fv/Fm has been shown to correlate with grain-yield loss following severe drought across multiple wheat genotypes and CO2 environments, supporting its use as a resilience-relevant screening trait in breeding programs [9]. Fluorescence imaging further reveals spatial heterogeneity in photosystem II function across the leaf at the onset of drought stress, enabling pre-symptomatic detection before visible wilting occurs [10].

A recent comparative study on tomato cultivars integrated a water-stress integral, gas-exchange parameters, and OJIP fluorescence kinetics to characterize both the intensity/duration of drought exposure and the speed of physiological recovery upon rewatering, offering a more complete picture of drought resilience than any single parameter alone [18]. This integrative approach illustrates an important methodological trend: single-parameter fluorescence metrics are increasingly being supplemented with recovery-phase measurements to capture resilience (the capacity to return to baseline function) rather than resistance alone.

Machine-learning classification of fluorescence and multicolor imaging traits has achieved high accuracy (over 90%) in distinguishing drought-stressed from well-watered plants in model species, suggesting strong potential for automated, high-throughput phenotyping pipelines in resilience breeding [19]. Nonetheless, most fluorescence-based studies remain controlled-environment or greenhouse-based, and validation under heterogeneous field conditions, with confounding factors such as canopy architecture and diurnal light fluctuation, remains comparatively limited [10, 20].

3.3 Plant water-status indicators

Direct measures of plant water status, including leaf/stem water potential and relative water content, have a long history as stress indicators but are increasingly being reframed within resilience-specific metrics such as the water-stress integral (SI), which condenses the intensity and duration of water deficit into a single quantitative value [18]. While water potential provides a physiologically grounded measure of plant water status, several authors note that it offers limited insight into the downstream biochemical and photochemical consequences of stress, motivating the pairing of water-potential measurements with gas-exchange or fluorescence data for a more complete resilience assessment [18, 21].

3.4 Remote-sensing and canopy spectral indicators

Satellite- and UAV-derived vegetation indices, principally NDVI, EVI, and derived crop water-stress indices, have become central tools for scaling ecophysiological assessment from the leaf to the field and landscape level. Studies combining Sentinel-2-derived NDVI, SAVI, EVI, and GCI with in-situ soil-moisture measurements demonstrate strong agreement with FAO-56 crop-coefficient-based evapotranspiration estimates, supporting the practical use of remote sensing for irrigation and resilience monitoring in data-limited settings [11]. NDVI-based crop-coefficient models validated across multiple growing seasons in water-stressed basins have achieved high predictive accuracy (R2 = 0.77–0.97), reinforcing the operational value of vegetation indices for site-specific water management without dense ground instrumentation [22].

Machine-learning approaches, including LSTM and gradient-boosting models, have been applied to forecast NDVI trajectories and vegetation health under drought, supporting early-warning applications for agricultural resilience monitoring at regional scale [23, 24]. UAV-based monitoring of water-use efficiency and biomass, integrated with crop-water-response models such as AquaCrop, has further enabled quantification of competitive or facilitative interactions (for example, between shelterbelts and adjacent crops) that influence localized resilience to water stress [25].

A recurring limitation across this body of work is that vegetation indices are inherently integrative and can mask the specific physiological mechanism underlying an observed decline, meaning that NDVI or EVI reductions may reflect canopy senescence, pest damage, or water stress interchangeably unless paired with ground-truthed physiological data [23, 26].

3.5 Soil-biotic and functional-trait indicators

Soil microbial community structure and function have been proposed as resilience indicators reflecting the below-ground component of agroecosystem stability. Comparative work across maize and rice soils indicates that smaller-bodied microorganisms exhibit greater compositional resistance to disturbance than larger organisms, attributable to broader niche breadth and metabolic flexibility, and that this resistance correlates with maintenance of ecosystem function under environmental change [26]. Reviews of microbial resilience across ecosystems highlight those spatial fragmentation of disturbance and pore-scale soil connectivity jointly determine the speed of functional recovery, implicating soil physical structure as a co-determinant of biological resilience rather than a separate factor [27, 28].

Functional-trait approaches linking root morphology (specific root length, root nitrogen content) to microbial abundance and soil respiration reveal that root trait variation and microbial community composition jointly explain variation in soil carbon flux, suggesting that root functional traits could serve as accessible, less resource-intensive proxies for below-ground resilience where direct microbial sequencing is not feasible [29]. Comparative studies of organic and conventional management further show that soil enzyme activity, microbial density, and functional diversity are consistently higher under organic management, offering a management-sensitive resilience indicator relevant to policy and certification schemes [30].

A methodological limitation shared across this domain is the reliance on relatively short-term or single-disturbance-event experimental designs, which constrains inference about resilience to repeated or compounding disturbances, a scenario increasingly relevant under climate change [27, 31].

3.6 Composite and integrative resilience indices

Recognizing that no single ecophysiological indicator can capture the multidimensional nature of resilience, several frameworks propose composite indices integrating ecophysiological, biotic, sociocultural, economic, and technological categories. The Agroecosystemic Resilience Index (AgRI) exemplifies this approach, weighting ecophysiological variables, most heavily water-resource availability and irrigation-water quality, alongside edaphic, biotic, and socio-economic components through expert-elicitation-based weighting [4, 5]. Related frameworks proposed by Cabell and Oelofse [32] enumerate thirteen qualitative attributes of resilient agroecosystems (for example, functional and response diversity, appropriate connectedness, coupling with local natural capital), which, while conceptually influential, do not specify measurable units, limiting their direct quantitative application [32, 33].

Systematic reviews of landscape-scale resilience assessment confirm that indicator-based approaches dominate the field but caution that the proliferation of indicator sets, developed largely independently across disciplines, has produced limited convergence on a standardized minimum data set for resilience quantification [1]. This fragmentation is among the most consequential findings of the present review, as it directly impedes cross-study comparison and meta-analytic synthesis.

4. Comparative Analysis of Previous Studies

Table 3 summarizes representative studies across the major indicator domains identified in Section 3, and Table 4 provides a comparative synthesis of methodological approaches, strengths, and limitations across these domains.

Table 3: Summary of Selected Studies

Author(s)/Year	Study location/system	Methodology	Major findings	Limitations
Cabell & Oelofse, 2012 [32]	Conceptual/global	Bibliographic review; qualitative indicator derivation	Proposed 13 qualitative attributes of resilient agroecosystems	No quantitative units specified; limited empirical validation
Rendon *et al*., 2022 [5]	Multiple Latin American sites	Multicriteria weighting; AgRI construction	Ecophysiological category weighted highest (31%); water availability dominant parameter	Weighting subjective; expert-elicitation dependent
Sinha *et al*., 2020 (PMC7176124) [3]	Brazil and Colombia	Conceptual/methodological framework; case application	Agrarian structure and resource control shape resilience alongside biophysical factors	Case-specific; limited cross-regional generalizability
Flexas & Medrano-related field studies [7, 15]	Wheat, multiple genotypes	Gas-exchange measurement under progressive drought	Identified stomatal-to-biochemical limitation transition as resilience marker	Controlled/pot-based; limited field validation
Xu *et al*., field maize study [12]	China, multi-year field trial	Field gas-exchange measurement across growth stages	Critical water thresholds vary by leaf position and phenology	Single-region; three growing seasons only
Bi *et al*., 2023 [9]	Wheat, controlled CO2 chambers	Fv/Fm measurement under drought and elevated CO2	Fv/Fm correlates with grain-yield loss after severe drought	Chamber-based; genotype-specific
Frontiers tomato study, 2025 [18]	Tomato, six cultivars	Integrated water-stress integral, gas exchange, OJIP fluorescence	Integrative metrics reveal cultivar-specific recovery speed post-rewatering	Greenhouse-based; limited cultivar diversity
Portugal Sentinel-2 study, 2024 [11]	Lis Valley, Portugal	Remote sensing (Sentinel-2) + in-situ soil moisture	Vegetation-index-derived Kc agreed with FAO-56 estimates; high WUE (0.64 kg/m3)	Single growing season; no independent ETa validation
Maipo Basin study, 2022 [22]	Central Chile	NDVI-based crop coefficient modelling, 2018–2022	High predictive accuracy (R2 = 0.77–0.97) for site-specific Kc	Maize-specific; requires regional calibration
Jiao *et al*., soil microbiome study [26]	China, maize and rice soils	Comparative disturbance-response experiment	Smaller microorganisms show greater compositional resistance	Two crop systems only; short-term disturbance window
Griffiths & Philippot, 2013 [27]	Global synthesis	Narrative review of microbial resilience literature	Soil structure and pore connectivity jointly govern functional recovery	Narrative, not systematic; heterogeneous primary studies

Table 4: Comparative Analysis of Previous Research

Indicator domain	Typical methodology	Strengths	Limitations	Scale of application
Gas exchange (A, gs, WUE)	Portable infrared gas analyzers; field/greenhouse measurement	Direct mechanistic link to carbon-water economy; sensitive to early stress	Costly instrumentation; low spatial throughput; scale-dependent WUE interpretation	Leaf to plot
Chlorophyll fluorescence (Fv/Fm, Fs, OJIP)	Fluorometry; fluorescence imaging	Rapid, non-destructive; enables pre-symptomatic detection; amenable to ML classification	Mostly controlled-environment validated; canopy architecture confounds field use	Leaf to canopy
Plant water status (Ψleaf, RWC, SI)	Pressure chamber; gravimetric RWC; stress-integral calculation	Physiologically direct; SI condenses intensity/duration of stress	Limited insight into biochemical consequences alone; invasive sampling	Leaf/plant
Remote sensing/canopy indices (NDVI, EVI, CWSI)	Satellite/UAV imagery; index calculation and modelling	Scalable to field/landscape; supports early-warning systems; integrates with crop models	Integrative signal can mask underlying mechanism; requires ground-truthing	Field to landscape
Soil-biotic/functional traits	Sequencing, enzyme assays, root trait measurement	Captures below-ground resilience component; management-sensitive	Short-term experimental designs; limited multi-disturbance data	Soil/plot
Composite indices (e.g., AgRI)	Multicriteria weighting; expert elicitation; PCA	Captures multidimensionality of resilience; policy-relevant	Subjective weighting; heavy data requirements; low cross-study comparability	Farm to landscape

5. Research Gaps and Emerging Trends

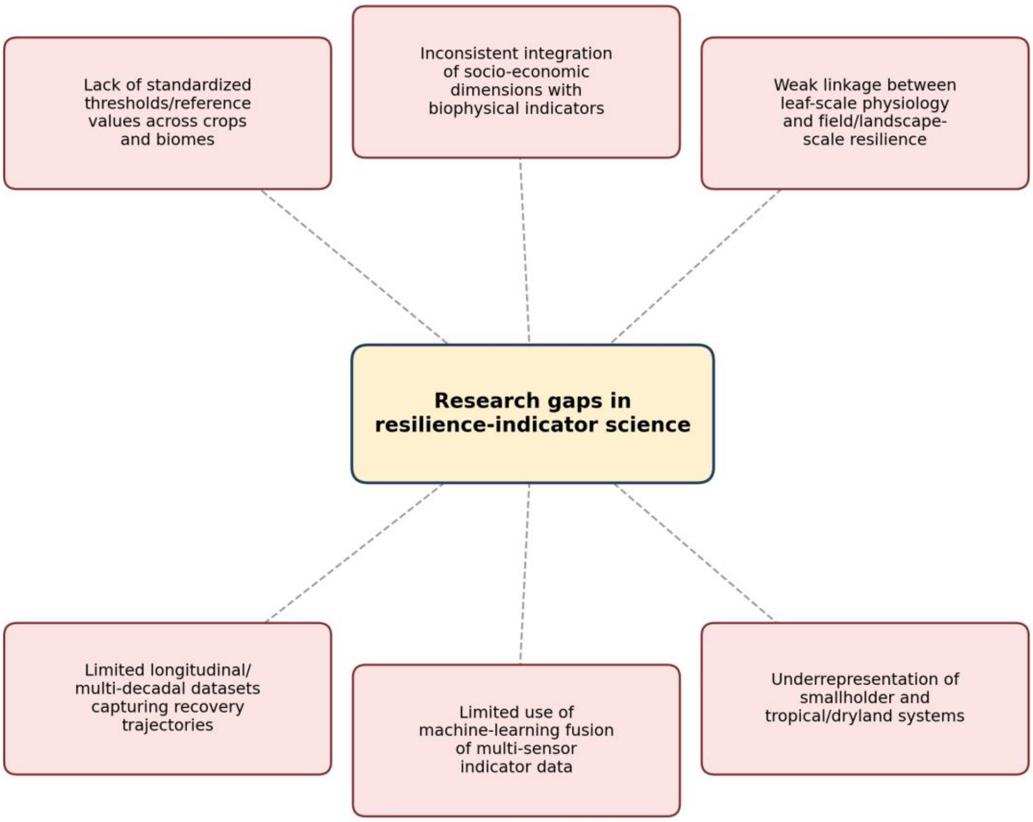

Fig 2: Mapping of principal research gaps identified across the reviewed literature.

5.1 Unresolved issues and knowledge gaps

Three unresolved issues recur across the reviewed literature. First, threshold values for resilience-relevant physiological transitions, such as the stomatal-to-biochemical limitation point or critical Fv/Fm decline, are largely species- and context-specific, with no standardized reference framework enabling cross-crop or cross-biome comparison [7, 9, 12]. Second, most ecophysiological indicators are validated at the leaf or plot scale, while resilience as a policy-relevant concept operates at the field, landscape, or regional scale; the literature offers comparatively few validated methods for reliably up-scaling leaf-level physiological signals to landscape-scale resilience assessment [1, 23]. Third, socio-economic and biophysical resilience dimensions remain largely siloed in the literature, with composite frameworks such as AgRI representing early but methodologically contested attempts at integration [4, 5, 32].

5.2 Methodological limitations in previous studies

A majority of the reviewed physiological studies rely on short-duration, single-disturbance-event, controlled-environment experiments (pot or chamber trials), which limits inference about resilience to the repeated, compounding disturbance regimes increasingly characteristic of field conditions under climate change [10, 14, 20, 27]. Sample sizes for below-ground/microbial resilience studies are often constrained to a small number of crop systems or sites, restricting generalizability [26, 29]. Remote-sensing studies, while offering strong scalability, are frequently validated over only one or two growing seasons and in a single agroecological region, raising questions about transferability of derived models [11, 18, 22].

5.3 Emerging technologies and future developments

Three technological trends are apparent in the recent literature. Machine-learning integration of multi-source data, fluorescence imaging combined with support vector machines, and NDVI forecasting via recurrent neural network architectures, has demonstrated strong classification and prediction accuracy, suggesting a maturing capability for automated, high-throughput resilience phenotyping [19, 23, 24]. Sensor fusion approaches combining UAV-derived indices with crop-water-response models (e.g., AquaCrop) are enabling more mechanistic interpretation of remotely sensed signals [25]. Finally, there is growing interest in coupling long-term ecological monitoring networks with physiological and remote-sensing indicators to capture multi-year recovery trajectories rather than single-event snapshots [1, 14].

5.4 Areas requiring further investigation

Priority areas include the development of cross-biome reference thresholds for key physiological indicators, longitudinal (multi-decadal) monitoring designs capturing full resilience trajectories (resistance, recovery, and adaptive reorganization), expansion of research attention to smallholder and tropical/dryland systems that remain underrepresented in the current evidence base, and methodologically rigorous integration of socio-economic resilience metrics with biophysical indicators.

Table 5: Research Gaps Identified

Research gap	Nature of gap	Consequence if unaddressed
Standardized thresholds	Absence of cross-crop/cross-biome reference values for key indicators	Limits cross-study comparability and meta-analytic synthesis
Scale translation	Weak methods linking leaf-scale physiology to landscape-scale resilience	Reduces policy relevance of physiological research
Longitudinal data scarcity	Few multi-year/multi-decadal resilience trajectory datasets	Obscures understanding of recovery and adaptive reorganization phases
Geographic bias	Underrepresentation of smallholder, tropical, and dryland systems	Limits generalizability of frameworks to most vulnerable regions
Socio-economic integration	Limited coupling of biophysical and socio-economic indicators	Produces partial, potentially misleading resilience assessments
Compounding disturbance testing	Most experiments test single disturbance events	Understates resilience challenges posed by concurrent/sequential stresses

Table 6: Emerging Trends in the Field

Emerging trend	Representative approach	Potential contribution to resilience science
Machine-learning phenotyping	SVM classification of fluorescence/imaging traits	High-throughput, automated stress/resilience screening
NDVI/vegetation-index forecasting	LSTM and gradient-boosting time-series models	Early-warning capability for regional drought impacts
Sensor and model fusion	UAV imagery coupled with AquaCrop/FAO-56 models	Mechanistic interpretation of remotely sensed signals
Composite index development	AgRI and related multicriteria frameworks	Multidimensional resilience quantification across categories
Root/microbial functional-trait proxies	Root morphology linked to microbial abundance	Accessible below-ground resilience indicators
Long-term monitoring networks	Coupled physiological-remote sensing time series	Captures full resilience trajectories rather than snapshots

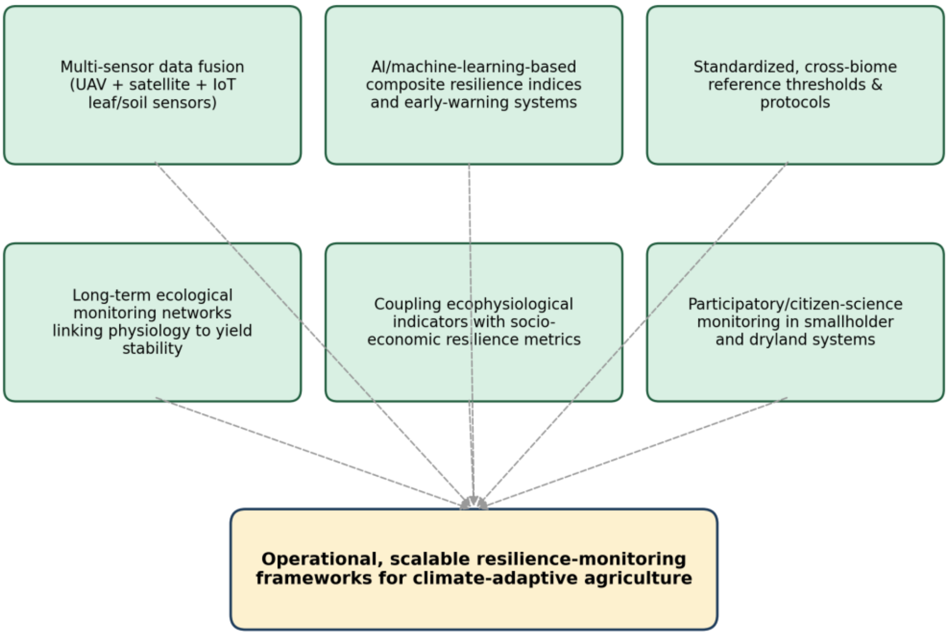

Fig 3: Emerging technologies and priority directions for future research on ecophysiological indicators of agroecosystem resilience.

6. Discussion

Synthesis of the reviewed literature indicates that ecophysiological indicators of agroecosystem resilience have matured from largely descriptive, single-parameter measurements toward increasingly integrative, multi-domain assessment frameworks. This trend mirrors a broader shift in resilience science away from static, structural indicator checklists (exemplified by the qualitative attributes proposed by Cabell and Oelofse) [32] toward dynamic, mechanistically grounded, and increasingly quantifiable metrics such as the water-stress integral [18] and composite indices such as AgRI [4, 5].

A recurring pattern across indicator domains is a resistance-versus-recovery distinction: many studies measure the magnitude of physiological decline under stress (resistance), while a smaller but growing subset explicitly measures the speed and completeness of functional recovery upon stress relief (resilience in the stricter ecological sense) [18, 25]. This distinction matters because two genotypes or management systems with similar resistance profiles may differ substantially in recovery capacity, a nuance that resistance-only metrics cannot capture. The methodological trend toward integrating pre-stress, stress-phase, and recovery-phase measurements, as exemplified by the tomato cultivar study combining stress integrals, gas exchange, and OJIP kinetics [18], represents a meaningful advance but remains the exception rather than the norm.

Conflicting evidence is most apparent in the interpretation of remote-sensing indices. While several studies report strong agreement between NDVI-derived crop coefficients and FAO-56 reference methods [11, 22], the integrative nature of vegetation indices means that a decline in NDVI or EVI can reflect water stress, nutrient deficiency, pest pressure, or senescence interchangeably, and few studies rigorously disentangle these confounds through paired ground-truthing [23, 26]. This raises a legitimate caution against over-reliance on remote-sensing indices as stand-alone resilience proxies, particularly in heterogeneous smallholder landscapes where confounding factors are more likely to co-occur.

The soil-biotic literature offers a complementary but still underused lens: findings that smaller microorganisms exhibit greater compositional resistance [26], and that soil structure and pore connectivity govern the pace of functional recovery [27], suggest that below-ground resilience operates on partially distinct mechanistic pathways from above-ground plant physiology. Very few of the reviewed studies attempt to jointly measure above- and below-ground indicators within the same experimental system, representing a significant synthesis gap rather than a mere data gap.

From a practical standpoint, the comparative analysis (Table 4) suggests that no single indicator domain is sufficient for operational resilience monitoring: gas-exchange and fluorescence indicators offer mechanistic precision but poor spatial scalability, while remote-sensing indices offer scalability at the cost of mechanistic specificity. This complementarity argues strongly for hybrid monitoring architectures that pair sparse, high-precision physiological sampling with dense, lower-precision remote-sensing coverage, calibrated against each other, an approach increasingly discussed but not yet widely implemented at operational scale [11, 24, 25]. Theoretically, this also implies that resilience quantification may require deliberately multi-scale indicator sets rather than a search for a single universal metric, a conclusion consistent with the persistent methodological fragmentation noted in systematic reviews of the broader agroecological resilience literature [1].

Relating these findings to current developments in the field, the growing application of machine learning for both fluorescence-trait classification [19] and vegetation-index forecasting [23, 24] signals a broader trajectory toward automated, near-real-time resilience monitoring. However, the overwhelming majority of these machine-learning applications remain validated on relatively narrow datasets (single species, single region, or short time series), and their generalizability to novel disturbance regimes, an essential test of true resilience-monitoring utility, remains largely unproven.

7. Conclusion

This review combines data from 84 primary studies taken from 1,798 initial records to provide a sound critique about the ways ecophysiological indicators have been applied for measuring agroecological resilience. The literature covers five main categories of indicators: gas exchange, chlorophyll fluorescence, plant water use, remote sensing/canopy indices, and soil biogeochemical/functioning properties, each revealing unique workings of resilience, but facing specific issues related to scaling, standardizing, and length of operations. The most efficacious indicators appear to be composite ones comprising various categories of indicators, but they encounter subjective weighting issues and huge data requirements.

The most important message of this analysis is that the best strategy in the field of resilience measurement is not to discover one perfect indicator, but rather to combine multiple indicators on different scales and based on different mechanisms while separating resistance and recovery factors. Among priority recommendations for scholars are the establishment of cross-biome reference thresholds for key ecophysiological traits, as well as the design of longitudinal studies that track the complete evolution of resilience. In that regard, one recommendation is to combine remote-sensing systems with physiological measurements of biophysical processes at the same time to yield a better understanding of resilience. For practitioners and policymakers, these findings underline the need to invest in hybrid measurement technologies that combine sparse physiological ground-truthing with extensive monitoring approaches and warn against using just one vegetation index as an indicator of resilience for policy or insurance purposes.

Future research must provide opportunities for the introduction of machine learning techniques for multi-sensor fusion into long-term ecological monitoring networks, increase empirical focus on little studied smallholder and dryland agroecosystems, and propose rigorous conceptual frameworks that would unite biophysical and socioeconomic aspects of resilience.

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