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RESEARCH ARTICLE

Grassland Vegetation-Soil-Enzyme Responses to Gold Mineralization Anomalies: Implications for Ecological Restoration and Net-Zero Ecosystem Management

Masroor Ahmed [1], Prabal Barua [2,*], Nahida Nargis [3], Noor Mohammad [4]

[1]*Department of Environmental Science and Engineering, Chengdu University of Technology, Chengdu, China.*
[2]*Departments of Environmental Sciences, Jahangirnagar University, Savar, Dhaka, Bangladesh*
[3]*Departments of Environmental Science and Engineering, Chang'an University, Shaanxi, China.*
[4]*Department of Organizational Operation and Human Resources Management, Chang ' an University, Shaanxi, China*
***Corresponding author:** Prabal Barua, prabalims@gmail.com

ABSTRACT

Gold-mineralized grasslands may contain spatially variable gold (Au) and associated elements such as arsenic (As) and mercury (Hg). Ecological effects are difficult to attribute because natural mineralization, mining disturbance and other sources of metal contamination may overlap. This narrative review examines vegetation, soil geochemistry and microbial enzyme activity in grasslands and related metal-affected systems. The available studies are heterogeneous and often do not measure Au, vegetation, soil properties and enzyme activity together. Studies that do not measure Au are treated as contextual evidence, not direct evidence of Au-specific effects. Unsupported cross-site Au concentrations, pooled regolith statistics, universal particle-size or dispersion ranges, plant accumulation values and enzyme diagnostic thresholds have been removed. Enzyme activities are complementary indicators of soil biological functioning, not validated Au-specific diagnostics. Restoration evidence from other ecosystems can inform hypotheses but cannot establish universal restoration outcomes for naturally mineralized grasslands. Changes in enzyme activity or SOC alone do not demonstrate net-zero performance; assessment requires repeated SOC-stock measurements, plant carbon inputs, CO_2, CH_4 and N_2O fluxes, and consideration of restoration-related emissions. The review therefore presents a conceptual monitoring agenda and testable research priorities rather than a validated causal model or universal thresholds.

Keywords: gold mineralization, grassland ecosystems, soil enzymes, vegetation–soil interactions, metal bioavailability, ecological restoration, soil carbon

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1. Introduction

Grasslands provide biodiversity, soil stabilization, water regulation and climate-related ecosystem services. Their extensive root systems and continuing organic-matter inputs contribute to terrestrial carbon cycling. Soil organic carbon (SOC) reflects the balance among plant carbon inputs, microbial decomposition and mineral-associated stabilization. Vegetation–soil–microbial interactions are therefore relevant to

restoration, but the direction and size of any carbon response must be established through measurements at the site and over time.

Geological processes create spatial variation in soil parent material, mineralogy and trace-element composition. Gold mineralization may occur with associated elements such as As, Cu, Pb, Sb, Hg or Zn, depending on the deposit. These elements have different toxicity, mobility and bioavailability, so ecological responses should not be attributed to Au alone without measurements that separate Au from co-occurring elements and other site conditions.

Vegetation growing on mineralized or metal-affected soils may respond to changes in nutrient availability, soil moisture, pH and exposure to bioavailable elements. Possible responses include changes in species composition, biomass, root traits and plant–soil interactions. Such responses are not unique to gold mineralization and should be interpreted with local reference sites and concurrent geochemical measurements.

Soil microbial communities contribute to decomposition, nutrient mineralization and carbon transformation. Their structure and activity may change under metal exposure, drought, nutrient limitation, grazing and other disturbances. The direction and magnitude of response depend on the source and mixture of stressors, soil conditions and management history; changes in microbial activity cannot, by themselves, identify Au as the cause.

Soil enzymes involved in carbon, nitrogen and phosphorus cycling can provide information about biological functioning and organic-matter transformation. Examples include β-glucosidase, cellulase, proteases, N-acetyl-glucosaminidase and phosphatases. Enzyme activity is environmentally dependent and may respond to multiple stressors. It is therefore a complementary ecological measure, not a gold-specific test or a direct measure of net carbon sequestration.

The following pathway is a conceptual hypothesis for testing, not a causal sequence established across the studies reviewed:

Possible geochemical variation → changes in soil conditions and bioavailable elements → potential vegetation and microbial responses → changes in enzyme activity and nutrient cycling → possible effects on soil-carbon dynamics.

The conceptual pathway in Figure 1 summarizes relationships that could be investigated in mineralized grasslands. It does not establish that mineralization necessarily changes vegetation or enzyme activity, or that such changes determine whether a site is a carbon source or sink. Carbon outcomes depend on plant inputs, decomposition, mineral stabilization and greenhouse-gas fluxes, all of which require direct measurement.

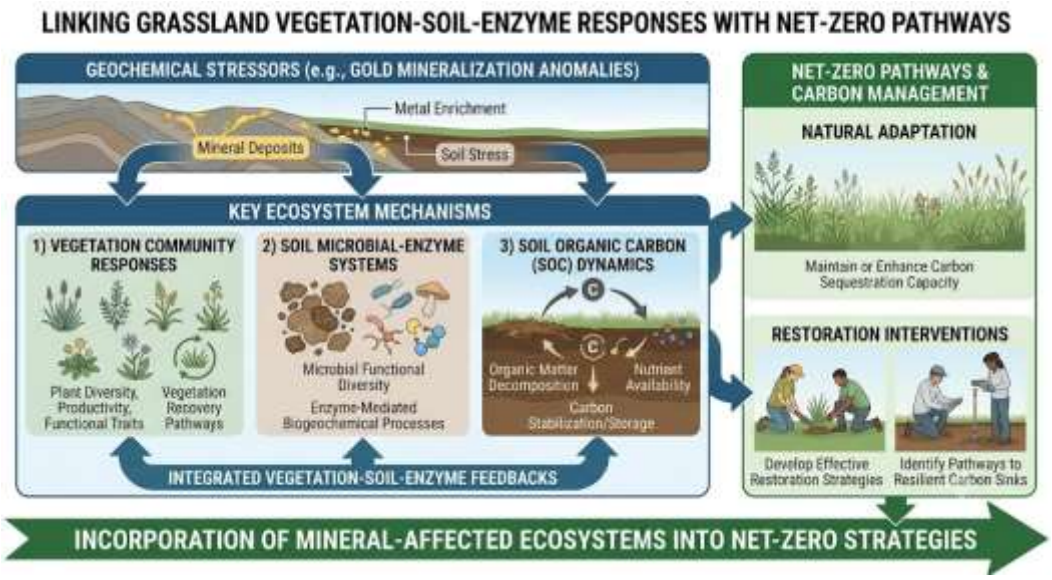


Figure 1. Conceptual diagram of possible relationships among grassland vegetation, soil processes and climate-mitigation objectives.

Grassland restoration can improve vegetation cover, soil stability and some measures of soil functioning in certain degraded ecosystems. However, results from non-mineralized grasslands or mine-affected sites cannot automatically be transferred to naturally gold-mineralized grasslands. Combining geochemical and ecological measurements may help develop site-specific monitoring, but it does not by itself establish a predictive model or a net-zero benefit.

Important gaps remain. Few studies appear to measure vegetation, Au and associated elements, soil properties and enzyme activity together at the same sites and times. The separate effects of natural mineralization, mining disturbance, co-contaminants, climate and land management are often difficult to distinguish. Direct evidence linking restoration of naturally mineralized grasslands to long-term SOC change and net greenhouse-gas balance is also limited.

This review examines (i) vegetation responses reported in gold-mineralized and metal-stressed settings; (ii) soil properties, element partitioning and enzyme activities reported in those settings; (iii) the limits of inferring carbon-cycle outcomes from these indicators; and (iv) restoration and monitoring priorities. Because the evidence includes different sites and disturbance types, the review distinguishes direct observations from contextual evidence and hypotheses requiring validation.

2. Review Methodology and Study Selection

This review article is a narrative literature review mapping evidence on vegetation, soil geochemistry and microbial enzyme activity in gold-mineralized grasslands and related metal-affected ecosystems. It is not a systematic review or meta-analysis. The manuscript previously described the evidence base as 42 peer-reviewed studies published during 2014–2025; the final included study list and publication window must be reconciled with the authors' original search records before submission. Earlier sources may be used for foundational concepts where appropriate.

The draft search strategy identifies Scopus, Web of Science Core Collection and Google Scholar as discovery platforms and uses combinations of terms relating to gold mineralization, gold anomalies, grassland vegetation, soil geochemistry, metal bioavailability, microbial enzymes, restoration and soil carbon. The exact search dates, complete platform-specific search strings and saved search outputs were not available for independent verification during revision and must be confirmed from the original records. This

description should not be treated as a reproducible systematic-review protocol until those records have been checked.

Studies were considered relevant when they addressed one or more review domains: vegetation and plant–soil interactions; soil geochemistry or element bioavailability; microbial communities or enzyme activity; or restoration, soil carbon and greenhouse-gas outcomes. Studies from mining-affected or other metal-stressed systems were retained only as contextual evidence where direct studies of naturally mineralized grasslands were limited. Their findings are not treated as direct evidence of natural Au anomalies.

Studies were excluded from direct Au-specific interpretation when they did not measure Au, did not report interpretable empirical findings, or examined mining waste and mixed-metal contamination without a defensible link to natural mineralization. The cited studies differ in ecosystem, exposure source, sampling design and endpoints; therefore, their numerical results were not pooled or treated as weighted averages. No effect-size meta-analysis or formal risk-of-bias assessment was performed.

The synthesis is organized thematically and separates direct gold-system observations, contextual analogical evidence and hypotheses that remain to be tested. Before resubmission, the authors should verify the final included-study list, search dates and strings, all retained quantitative values, and reference metadata against the original records and primary publications.

3. Results and Discussions

3.1. Gold Mineralization Basics

Weathering of primary hypogene deposits can liberate structurally bound Au from sulfide minerals such as arsenopyrite and pyrite. Oxidative dissolution, colloid formation and groundwater-mediated transport are possible processes in some mineralized settings, but their depth, particle size and lateral extent vary with geology, hydrology, redox conditions and mineralogy. These processes should not be assigned a universal depth or dispersion distance without site-specific measurements.

Pedogenic processes in grassland soils are influenced by pH, organic matter, clay mineralogy and wetting–drying cycles. These properties can affect sorption, colloid transport and the mobility of Au and associated elements, but the available evidence does not justify a universal depth or lateral extent for dispersion halos across grassland and forest systems (Ma et al., 2025; Campillo-Cora et al., 2025; Száková et al., 2025). Table 1 summarizes a proposed vertical sequence of supergene processes rather than a universal profile. The oxidation zone may contain altered sulfides and Fe–Mn oxides that sorb or redistribute trace elements such as As, Sb, Pb and Cu. The distribution of Au and associated elements varies with parent material, hydrology, redox conditions and mineralogy; the profile should therefore be interpreted as a conceptual synthesis, not a site-independent diagnostic rule.

Table 1. Conceptual supergene zones, possible geochemical processes and candidate indicators (depths and associations are site-specific)

Weathering Zone	Illustrative depth (site-specific)	Dominant Geochemical Conditions	Key Reactions / Processes	Dominant Minerals & Secondary Phases	Au Form / Fineness	Diagnostic Geochemical Indicators	Typical Enrichment / Depletion	Reference
Oxidation Cap / Gossan	0–2	Strongly oxidizing; acidic to circum-neutral	Oxidation of sulfides; $Fe^{2+} \rightarrow Fe^{3+}$; formation of Fe oxyhydroxides and sulfate phases	Hematite, goethite, jarosite, scorodite, Mn oxides	Au(0) with locally Ag-rich relics; commonly high-fineness residual Au	Fe, Mn, As, Sb, S, Hg, Cu; low sulfide-S; high Fe^{3+}/Fe^{2+}	May occur; requires site-specific measurement	Newsome & Falagan (2021)
Oxidized Supergene Blanket	2–10	Oxidizing; variable Eh and pH	Dissolution of sulfides followed by adsorption/coprecipitation onto Fe–Mn oxides	Goethite, hematite, jarosite, MnO_2, native Au, secondary Cu minerals	Fine native Au; Au nanoparticles may occur	Au, Ag, As, Sb, Hg, Cu, Fe, Mn; Au/Ag ratio	Strong Fe–Mn and metalloid accumulation; Hg may be redistributed	Szkov et al. (2025)
Fe–Mn Oxide Enrichment Zone	1–8	Oxidizing; high sorption capacity	Metal adsorption on Fe/Mn oxyhydroxides: Mn++FeOOH→M□– □FeO OHM^{n+}+FeOOH \rightarrow M\!-\!FeOOH	Goethite, lepidocrocite, hematite, pyrolusite	Fine-grained/residual Au associated with Fe–Mn oxides	Fe, Mn, As, Sb, Pb, Zn, Cu, Au	As–Sb and transition metals commonly enriched relative to parent material	Li et al. (2025)
Supergene Cu–Au Zone	5–20	Moderately oxidizing to transitional	Oxidation and remobilization of Cu; downward transport and secondary enrichment	Chalcocite, covellite, malachite, azurite, goethite	Native Au and electrum; locally liberated Au grains	Cu, S, Fe, Au, Ag; Cu/S ratio	Cu and Au may show secondary enrichment below oxidation front	Recent supergene mineralizatio n literature
Argillic / Clay-Altered Zone	5–15	Acidic to moderately acidic	Hydrolysis of feldspars and silicates; intense clay formation	Kaolinite, gibbsite, illite, smectite	Fine residual Au and electrum relics	Al, Si, K, Fe; elevated clay fraction; low Ca–Mg	Mobile base cations depleted; Al–Fe residual enrichment	Liu et al. (2025)
Leached Saprolite	>10	Strong chemical weathering; acidic to neutral	Removal of mobile elements; residual concentration of immobile phases	Kaolinite, gibbsite, goethite, quartz, Fe oxides	Au–Ag electrum relics; residual/coarse Au	Au, Fe, Al, Ti, Zr; depletion of Ca, Mg, Na, K	Major-element depletion may reach high levels; Au may become residually concentrated	Liu et al. (2025)

Weathering Zone	Illustrative depth (site-specific)	Dominant Geochemical Conditions	Key Reactions / Processes	Dominant Minerals & Secondary Phases	Au Form / Fineness	Diagnostic Geochemical Indicators	Typical Enrichment / Depletion	Reference
Transitional Redox Front	~8–20	Rapidly changing Eh; variable pH	Reduction/oxidation cycling; dissolution–reprecipitation of Fe and Mn phases	Goethite, hematite, Mn oxides, secondary sulfides	Liberated native Au; fine Au particles	Fe^{2+}/Fe^{3+}, Mn, S, As, Sb, Au, Hg	Strong element redistribution across redox boundary	Newsome & Falagan (2021)
Partially Weathered Sulfide Zone	15–30	Weakly oxidizing to reducing	Progressive pyrite/arsenopyrite oxidation; preservation of primary sulfides	Pyrite, arsenopyrite, chalcopyrite, pyrrhotite with secondary Fe oxides	Native Au, electrum, Au inclusions in sulfides	S, Fe, As, Au, Cu, Zn, Pb, Ag	Primary sulfide-associated Au preserved; limited supergene redistribution	Newsome & Falagan (2021)
Primary Sulfide / Hypogene Zone	>20–30	Reducing; relatively stable	Primary hydrothermal mineralization; limited weathering	Pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, quartz, carbonate	Au in sulfide inclusions and electrum; variable fineness	Au, Ag, As, Sb, Cu, Pb, Zn, S	Represents the principal geochemical background/source zone	Newsome & Falagan (2021)
Hg-Rich Weathering Domain	Variable	Oxidizing; strong Hg mobilization potential	Hg oxidation, volatilization, adsorption and redistribution	Hg-bearing Fe oxides; locally Hg sulfides/relicts	Au may occur with Hg-rich alteration halos	Hg, Au, As, Sb, Fe, Mn	Hg can show substantial depletion from primary zones and enrichment in oxide horizons	Szkov et al. (2025)
As–Sb Metalloid Enrichment Zone	Variable	Oxidizing; high Fe-oxide sorption	Oxidation and adsorption/coprecipitation of As and Sb	Scorodite, Fe oxyhydroxides, Sb oxides/secondary phases	Fine residual Au associated with Fe oxides	As, Sb, Fe, Mn, Au, S	As and Sb commonly form strong pathfinder anomalies	Ma et al. (2025)

Some studies of mineralized environments discuss microbial biofilms and particle morphologies as possible contributors to Au transformation. However, the evidence summarized here does not establish a common timing, frequency or microbial pathway across grassland systems. Reported morphologies and biological interpretations should be treated as source-specific observations rather than universal properties of grassland gold systems.

The studies considered here cover different geological settings and ecological questions. The cited literature does not support assigning a common Au concentration or anomaly radius to every grassland or metal-affected site. Studies of lead–zinc mines, open-pit coal mines, general grassland degradation and restoration are contextual evidence only unless the original study directly measured Au in a natural mineralization setting. Table 2 therefore records each source's scope and limitation; no unsupported Au concentration or spatial halo is inferred.

Table 2. Evidence audit of cited grassland and metal-affected studies and their relevance to Au-specific claims

Site / source	Source topic	Au evidence status	Other evidence retained	Appropriate use / limitation	Reference
Qixia Mountain, China	Lead–zinc mining and heavy-metal pollution	Au not reported in cited source as identified by reviewer	Metal pollution / microbial context only	Contextual metal-stress evidence; cannot support Au concentration or Au halo	Li et al. (2025)
Hulun Buir, China	Soil stoichiometry near opencast coal mine	Au not reported in cited source as identified by reviewer	Soil stoichiometry and enzyme activity	Contextual disturbance evidence; cannot support natural Au-mineralization claims	Bi et al. (2024)
Galicia, Spain	Trace-metal forms in grassland soils	Au, As and Hg not reported in source abstract per reviewer	Source-reported trace metals only	No Au value or Au anomaly should be attributed	López-Mateo et al. (2023)
Uruguayan grasslands	Grassland soil microbiome comparison	No Au measurement established in manuscript source record	Grassland microbiome context	No metalliferous setting or Au plume assumed	Giménez (2025); verify reference
Alpine degraded grassland	Ecological restoration study	No Au measurement established in manuscript source record	Vegetation recovery; soil / microbial restoration context	Cannot support Au decline or Au gradient	Shu et al. (2023)
Karst vegetation / degraded valley	Vegetation and soil-enzyme response	No Au measurement established in manuscript source record	Plant / phosphatase response only if supported by source	Cannot support Au concentration or mineralization halo	Gan et al. (2025); verify reference
Otago, New Zealand	Surficial arsenic redistribution above gold-mineralized zones	No plant Au value inferred; use only source-reported data	As redistribution and geochemical context	Does not establish plant Au accumulation	Blake et al. (2019)
Shewushan, China	Plant–soil geochemistry in a gold lateritic deposit	Potential direct gold-system evidence; exact values must be verified	Plant–soil geochemistry as source reports	Check original tables and units before retaining numbers	Qin et al. (2021)
Mining / metal-stress literature	Microbial and soil responses under metal exposure	Au not necessarily measured	Enzyme and microbial responses	Cannot establish Au-specific sensitivity	Campillo-Cora et al. (2025); Nikolova et al. (2023)
Review-level synthesis	Cross-study framework	No new measurement; no pooled Au value	Conceptual links only	Not a primary dataset or measured gradient	Authors' synthesis

The source material available for this review does not provide a traceable, harmonized dataset supporting a pooled sample size of n = 248 or the depth-specific means and standard deviations previously listed. Those pooled values have therefore been removed rather than presented as observed data. Table 3 now summarizes the data requirements for a defensible cross-site regolith comparison. A quantitative depth profile should be added only after each value is traced to a primary source and units, sampling depths, analytical methods and sample sizes are reconciled.

Table 3. Data requirements and traceability limits for cross-site regolith comparisons

Data element	Required reporting	Current review status	Reason for requirement	Interpretation rule	Evidence source
Sampling horizon / depth	Exact depth interval and sampling design	No harmonized cross-site profile retained	Depth varies by soil, weathering and site design	Compare only within traceable studies	Primary study methods
Au concentration	Measured value, unit, detection limit, method and QA/QC	No pooled mean or range calculated	Not all cited studies measured Au	Do not assign Au values to contextual studies	Primary study results
As / Hg / other elements	Element-specific values and speciation / extractable fraction where available	Study-specific only	Total concentration does not equal bioavailability	Do not pool unlike fractions or units	Primary study results
Soil properties	pH, organic matter, texture, Fe–Mn oxides, CEC, moisture	Not consistently available across studies	These properties affect retention and mobility	Report covariates alongside metal concentrations	Primary study methods/results

A cross-site depth gradient cannot be inferred from the currently traceable source set. Depth-related patterns should be evaluated within individual studies that report measured Au and associated elements at documented depths, with local background values, analytical methods and detection limits.

Table 4 presents qualitative hypotheses about climate and possible dispersion pathways. It is not a pooled dataset: numerical estimates for Au colloids, As mobilization, redox potential or runoff are not reported unless verified in a source that directly measured them.

Table 4. Qualitative climatic controls and variables for evaluating possible dispersion pathways

Setting / climatic context	Potential dispersion process	Variables to measure	Possible ecological relevance	Evidence status	Reference / note
Arid steppe	Windblown dust and surface redistribution may occur	Wind exposure, particle size, soil moisture, mineralogy, Au and pathfinders if measured	Dust deposition may affect surface soils	Qualitative hypothesis; no universal rates assigned	Site-specific primary studies required
Semi-arid prairie	Seasonal infiltration, runoff and capillary processes may influence transport	Rainfall, runoff, groundwater, redox, dissolved/particulate fractions	May alter metal mobility and root-zone exposure	Not a pooled cross-site gradient	Site-specific primary studies required
Humid grassland	Runoff, leaching and redox cycling may influence redistribution	Rainfall, soil saturation, Eh, pH, Fe–Mn phases and measured elements	May change sorption and bioavailability	Not a pooled cross-site gradient	Site-specific primary studies required

Overall, Table 4 highlights variables that may influence dispersion pathways. These relationships are conceptual and site-dependent; the table should not be interpreted as establishing universal thresholds or measured quantitative gradients.

No standardized or independently validated threshold is established by this review for identifying Au mineralization from soil enzyme activity, vegetation indices or electrical conductivity alone. Individual study values should be interpreted within their local context. Enzyme responses may vary with pH, moisture, temperature, organic matter, nutrient availability and mixtures of contaminants; they are complementary measures of soil functioning, not Au-specific diagnostic tests.

Table 5 summarizes reported gold morphotypes and proposed formation processes. Particle-size ranges and formation interpretations vary by source and analytical method and should not be treated as universal patterns.

Table 5. Summary of reported gold morphotypes and proposed formation processes

Au Morphotype	Typical Size	Putative Formation Mechanism	Microbial Association / Process	Common Substrate or Association	Diagnostic Evidence	Reported Occurrence / Frequency	Grassland / Environmental Setting	Interpretation for Au Cycling	References
Spheroidal Au nanoparticles	~0.01–0.10 µm	Reduction of dissolved/complexed Au and subsequent nucleation	Bacterial enzymatic/metabolic reduction; extracellular reduction	Cell surfaces, extracellular polymeric substances (EPS), Fe oxides	TEM/SEM, EDS, nanoscale Au-rich particles	Not quantified consistently across studies	Steppe, prairie and organic-rich surface soils	May be consistent with biological influence; not diagnostic alone	Newsome & Falagan (2021)
Bacteriomorphic Au particles	~0.05–1.0 µm	Biofilm-mediated nucleation, aggregation and templating	Microbial biofilms and EPS-mediated sorption/reduction	Bacterial cells, biofilms, Fe/Mn oxides	SEM morphology, Au-rich EDS signatures, organic coatings	Not quantified consistently across studies	Arid and semi-arid steppe	Possible interpretation requiring site-specific evidence	Székov et al. (2025)
Irregular / aggregated nanoparticles	~0.05–2 µm	Coalescence of primary nanoparticles and surface-bound Au	Microbial reduction followed by aggregation	EPS, clay minerals and organic residues	TEM/SEM, EDS, surface chemistry	Frequently reported	Moisture-variable grassland soils	Represents secondary growth and stabilization of biogenic Au	Review synthesis
Flaky / porous Au-rich aggregates	~0.1–500 µm	De-alloying, dissolution–reprecipitation and aggregation	Indirect microbial modification; biofilm and organic-matter effects	Electrum, sulfide relics, Fe oxides and clay	SEM/EDS, Au–Ag distribution, surface texture	Not quantified consistently across studies	Tussock and temperate grassland	Indicates supergene alteration combined with biological surface modification	Liu et al. (2025)
Au–Ag electrum relics	~1–500 µm	Preferential Ag dissolution and residual Au enrichment	Indirect microbial/biogeochemical influence	Weathered sulfides, quartz and Fe oxides	Au/Ag ratio, SEM–EDS, microprobe	Common in weathered Au systems	Temperate and alpine grasslands	Records chemical weathering and residual Au enrichment rather than direct biogenic precipitation	Liu et al. (2025); Blake et al. (2019)
Fe-oxide-associated Au	Nano- to sub-mm	Adsorption, coprecipitation and reduction on Fe oxyhydroxides	Microbial Fe cycling can indirectly influence Au retention	Goethite, ferrihydrite, hematite	Sequential extraction, SEM–EDS, Fe-mineralogy	Frequently reported	Oxidized and ferruginous grassland regolith	Important mechanism for near-surface Au immobilization and redistribution	Newsome & Falagan (2021)
Clay/EPS-associated Au	Nano- to µm-scale	Surface adsorption and aggregation	Microbial EPS provides reactive binding sites	Kaolinite, illite, smectite and organic coatings	XRD, SEM–EDS, surface spectroscopy	Commonly associated with fine fractions	Clay-rich steppe and saprolite	Indicates coupled biological–mineral retention of Au	Review synthesis

Au Morphotype	Typical Size	Putative Formation Mechanism	Microbial Association / Process	Common Substrate or Association	Diagnostic Evidence	Reported Occurrence / Frequency	Grassland / Environmental Setting	Interpretation for Au Cycling	References
Organic-coated Au particles	~0.05–100 μm	Complexation, adsorption and localized reduction	Microbial biomass, humic substances and EPS	Humus, plant residues and microbial biomass	SEM/TEM, C–Au association, spectroscopy	Reported mainly in A horizons	Organic-rich grassland topsoil	Suggests strong influence of organic matter on Au mobility and stabilization	Review synthesis
Sulfide-derived Au particles	~1–500 μm	Oxidative dissolution of pyrite/arsenopyrite followed by Au liberation	Microbial oxidation may accelerate sulfide weathering	Pyrite, arsenopyrite, chalcopyrite	SEM–EDS, mineral liberation, S/Fe chemistry	Common in mineralized regolith	Gold-bearing steppe and tussock systems	Represents liberation of previously sulfide-hosted Au during weathering	Blake et al. (2019)
Nugget-like / coarse Au particles	>500 μm	Mechanical concentration, residual enrichment and physical reworking	Secondary biological surface modification rather than primary formation	Quartz, Fe oxides, gravels and weathered bedrock	SEM morphology, grain texture, Au–Ag chemistry	Not quantified consistently across studies	Alluvial and reworked grassland settings	Primarily reflects physical and chemical redistribution; microbial origin should not be assumed	Gong et al. (2025)
Nanoparticulate Au associated with As–Fe phases	<1 μm	Au reduction and adsorption/coprecipitation during Fe–As cycling	Microbial redox transformations indirectly control Au retention	Scorodite, goethite, ferrihydrite and organic coatings	TEM/SEM–EDS, Au–As–Fe associations	Reported in oxidized mineralized soils	Metalliferous grasslands	Links microbial redox activity with Au–As immobilization and remobilization	Ma et al. (2025); Newsome & Falagan (2021)
Secondary Au coatings / surface enrichment	Sub-μm to several μm	Dissolution–reprecipitation and surface nucleation	Microbial reduction and organic-mediated precipitation may contribute	Primary Au grains, electrum and Fe oxides	High-resolution SEM, surface Au enrichment, Au–Ag zoning	Common in weathered grains	Supergene grassland profiles	Indicates repeated near-surface Au mobilization and reprecipitation	Review synthesis

Studies summarized in Table 5 describe different Au particle forms and possible biogeochemical processes. Particle morphology and proposed formation pathways vary by source and analytical method. These observations do not establish that a particular particle size, biological process or formation pathway is universal in mineralized grasslands.

Table 6. Candidate monitoring indicators and validation status; no universal Au-specific thresholds are established by this review

Candidate indicator	What it measures	Threshold status in this review	Required validation	Appropriate interpretation
Au concentration	Element concentration in soil / regolith	No universal threshold established	Primary-source verification, local background, method and detection limit	Geochemical variable; not inferred from studies that did not measure Au
As concentration / speciation	Total or bioavailable arsenic	No universal threshold established	Separate total from extractable/speciated fractions; record co-contaminants	Potential pathfinder / toxicant depending on context
Hg concentration / speciation	Total or bioavailable mercury	No universal threshold established	Confirm source measurement, units and speciation	Do not assume co-occurrence or ecological effect without data
Electrical conductivity (EC)	Salinity / soluble-ion proxy	No Au-specific threshold established	Calibrate by soil type and measure relevant ions	General soil-condition variable, not an Au diagnostic
Dehydrogenase activity (DHA)	Microbial oxidative metabolism	No Au-specific threshold established	Standardized assay, controls, replication and external validation	Complementary biological-condition indicator
Shannon diversity	Community diversity index	No Au-specific threshold established	Consistent sampling and taxonomic resolution	Ecological response metric; not specific to Au
Z-score / composite index	Standardized deviation from a defined reference	No validated composite cut-off established	Define reference population, variables, weights and independent test set	Exploratory only until validated

Figure 2 is a conceptual synthesis of reported regolith patterns, dispersion pathways and particle morphologies. Its components come from different sources and locations; the figure should not be interpreted as a globally validated detection model or as proof that the processes occur together at every site.

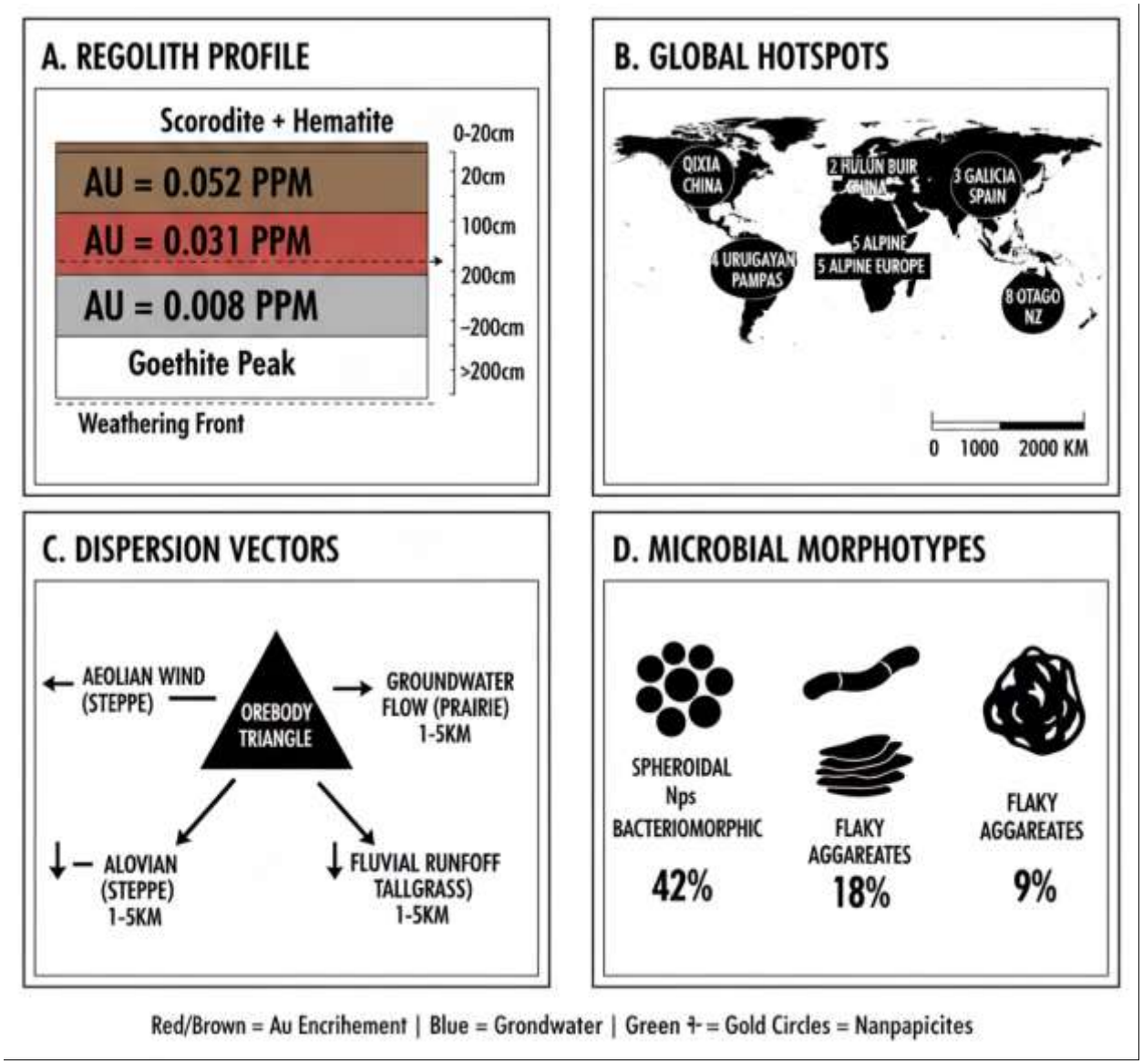


Figure 2. Integrated model synthesizing regolith profiles, dispersion vectors, microbial morphotypes, and global hotspots.

3.2. Vegetation Responses

The mineralization of gold also imposes physiological stress on grassland vegetation, leading to biomass loss, altered root architecture, and the accumulation of metals in the dominant grasses. Dominant plants (e.g., Miscanthus) in the Shewushan gold deposit showed leaf Au up to 0.15 mg/kg (Table 6), and the bioaccumulation factors of related As and Sb had a value of more than 1. It was selectively taken up by both foliar and root uptake at a neutral pH. Equally, Ebyan (2024) found the concentration of Au as 0.02-0.12 mg/kg in wild vegetation in gold-prospected zones, where Stipa spp. were detected. Showing 2.3-fold higher levels than controls due to nanoparticle adhesion on leaf surfaces (Fig 3).

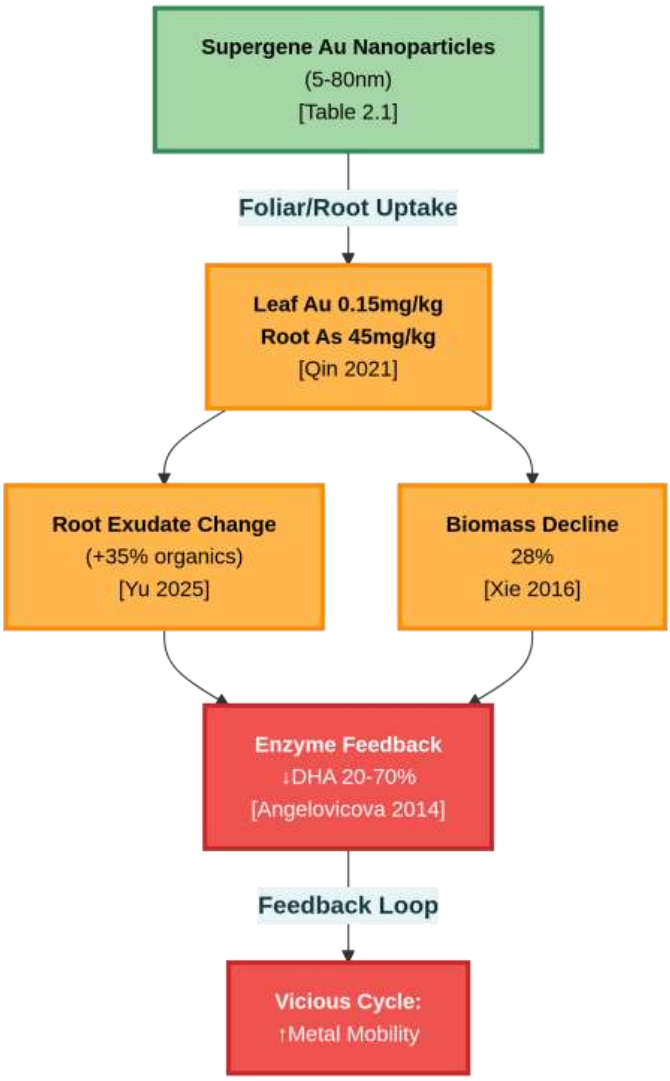


Figure 3. Conceptual synthesis of vegetation and soil-enzyme observations reported across separate mineralized or metal-affected studies. Arrows indicate proposed relationships for testing; the figure does not demonstrate a single causal pathway. No quantitative leaf-Au ratio is inferred from this figure.

Root exudates may influence metal mobility in the rhizosphere, but effects depend on plant species, element mixtures and soil conditions. Studies reporting plant responses or surface redistribution of As provide context; observations from different sites do not establish a single causal sequence for gold-mineralized grasslands. Table 7 summarizes the evidence status for plant Au and As accumulation in the cited settings. Values are not pooled, and the table distinguishes direct gold-system evidence from contextual studies that did not report plant Au.

Table 7. Evidence status for plant Au and As accumulation in cited gold-related and metal-affected settings

Location / source	Plant / ecosystem evidence	Au in plant tissue	As in plant tissue	BAF	Use in this review	Reference / verification note
Shewushan gold lateritic deposit, China	Plant–soil geochemistry in a gold lateritic deposit	Retain only values directly stated in Qin et al. (2021); no unverified value reproduced	Retain only values directly stated in source	Not calculated here	Potential direct gold-system evidence; verify original table and units	Qin et al. (2021)
East Otago / Macraes, New Zealand	Study concerns surficial arsenic redistribution above gold-mineralized zones	No plant Au value inferred from the cited source	Soil / sediment As evidence only where directly reported; not a plant value	Not calculated	Evidence for geochemical As redistribution, not plant Au accumulation	Blake et al. (2019)
Qixia Mountain, China	Lead–zinc mine pollution / metal ecology	Not reported in source as identified by reviewer; removed	No plant As value retained unless directly reported	Not calculated	Contextual metal-stress evidence only	Li et al. (2025)
Hulun Buir grassland, China	Grassland soil stoichiometry near an opencast coal mine	Not established in cited source; removed	Not established in cited source; removed	Not calculated	Contextual coal-mine / grassland evidence only	Bi et al. (2024)
Galicia grassland soils, Spain	Forms of toxic and trace metals in grassland soils	Au, As and Hg not reported in source abstract per reviewer; removed	No plant-root value inferred	Not calculated	Contextual soil-metal evidence only	López-Mateo et al. (2023)
Cross-study synthesis	Plant–soil transfer framework	No cross-site numeric range reported	No cross-site numeric range reported	Not calculated	Values can be added only after primary-source extraction and unit harmonization	Authors' synthesis

The available sources do not provide a consistently comparable set of plant Au concentrations and bioaccumulation factors across the listed locations. Unverified values have therefore been removed. A bioaccumulation factor should be calculated only when matched plant-tissue and soil concentrations, units, locations and analytical methods are reported in the same study.

Plant tissue data may contribute to biogeochemical assessment where a study directly measures plant Au or associated elements and provides appropriate controls and analytical detail. General vegetation responses or soil As measurements alone do not demonstrate plant Au uptake. Root uptake, internal translocation and surface particle adhesion must be distinguished through documented washing procedures, tissue localization or suitable elemental analysis.

Vegetation responses reported in degraded grasslands, croplands and metal-affected sites may help identify candidate variables for future study, but they cannot be combined as if they were observations of the same natural Au-mineralization process. Percent changes in diversity, leaching or genetic variation are retained only when their original source, endpoint and study context have been verified; they are not used here to infer a universal grassland response.

3.3. Soil Bioavailability Mechanisms

The mobility and bioavailability of Au and associated elements depend on mineralogy, pH, redox conditions, organic matter, hydrology and the chemical form of each element (Fig 4). Dissolved complexes, particles, secondary biogenic particles and elements sorbed to mineral surfaces are distinct forms and should not be conflated. The current evidence does not justify universal claims about Au particle sizes, lateral dispersion distances, depth ranges, surface enrichment factors or electrical-conductivity thresholds across grassland systems.

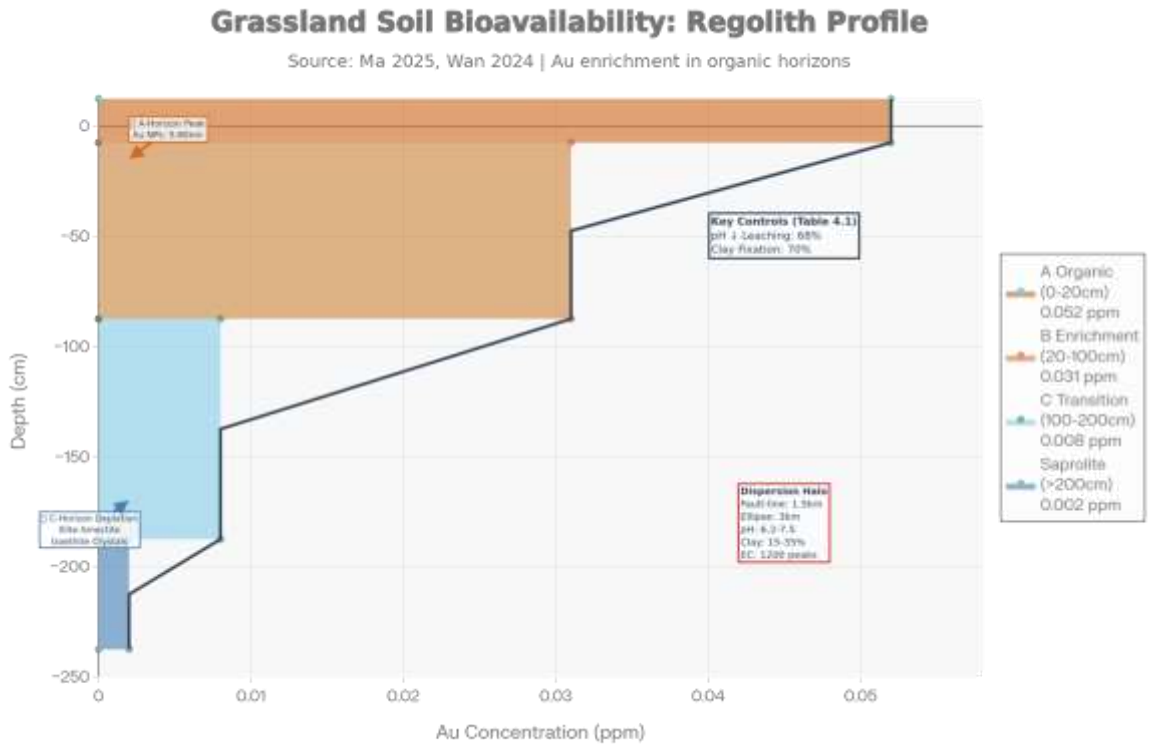


Figure 4. Overlay of grassland soil bioavailability mechanisms on regolith profile and dispersion halo, integrating pH/clay controls from multi-site data

Soil pH, clay mineralogy, cation-exchange capacity and Fe–Mn oxides can affect metal partitioning, but the direction and strength of those effects depend on the element and soil. The cited Galicia and Qixia studies are not treated as direct evidence for Au concentrations unless the primary source explicitly reports Au measurements. Their relevance is limited to the variables and metals actually measured in those studies.

Transport may differ among grassland, cropland and forest soils because of differences in soil structure, moisture, management and geochemistry. The current sources do not support a single percentage difference in leaching or a universal transport pathway. Such comparisons should be reported only where the cited study directly measured the relevant process under comparable conditions. Soil stoichiometry and nutrient cycling observations do not by themselves demonstrate Au-specific effects (Table 8).

Table 8. Soil and environmental controls on metal bioavailability: review-based synthesis

Factor	Grassland condition / typical range	Cropland contrast	Expected effect on Au/As bioavailability	Mechanistic interpretation	Reference / evidence
Soil pH	Site-specific; report measured pH	Frequently more acidic in intensively managed or strongly weathered cropland soils	**pH-dependent**; generally lower mobility of many cationic metals at higher pH, while As behavior can differ by species and mineral surface	Controls protonation, mineral surface charge, dissolution, and metal sorption	Peijnenburg et al.; Peijnenburg (2025)
Clay content	Site-specific; report measured clay fraction	May be higher or dominated by kaolinitic fractions depending on soil type	**↓ mobility / ↑ retention** with increasing reactive clay surfaces	Clay minerals provide sorption and ion-exchange sites	López-Mateo et al. (2023)
CEC (cmolc kg^{-1})	Approximately **18–22** in the proposed grassland range	Approximately **10–15** in the proposed cropland comparison	**Higher CEC generally favors retention** of cationic metals such as Cd and Pb; Au behavior is more complex	Greater density of negatively charged exchange sites	Peijnenburg (2025)
Fe–Mn oxides	Common in mineral grassland soils and weathered profiles	Variable; affected by drainage and cultivation	**Strong retention of As** under oxidizing conditions; can also retain other trace metals	Surface adsorption and inner-sphere complexation on Fe/Mn oxides	Peijnenburg (2025);
Soil organic matter (SOM)	Often relatively stable under permanent grassland	Frequently disturbed or reduced by intensive cultivation	**Can decrease or increase bioavailability**, depending on metal and dissolved organic matter	Complexation, sorption, and formation of soluble metal–organic complexes	Peijnenburg et al.
Redox potential (Eh)	Generally more stable under permanent grassland but strongly controlled by moisture	Often modified by drainage, tillage, and irrigation	**Strong control of As mobility**; reducing conditions can alter Fe oxides and release associated As	Fe/Mn oxide reduction and changes in As oxidation state	Peijnenburg (2025)
Soil moisture	Seasonal variation; often higher under dense grass cover	Strongly modified by irrigation and drainage	**Can alter metal availability and plant uptake**	Changes pore-water chemistry, redox status, and diffusion	González-Alcaraz et al.
Electrical conductivity (EC)	Variable; site-specific	Can become elevated in irrigated or salt-affected cropland	**May modify metal mobility and competition**	Ionic strength affects adsorption–desorption and metal speciation	López-Mateo et al., 2023

Factor	Grassland condition / typical range	Cropland contrast	Expected effect on Au/As bioavailability	Mechanistic interpretation	Reference / evidence
Soil texture	Frequently loam to sandy-loam in grassland systems, but highly site-specific	Often altered by cultivation and erosion	Fine-textured soils generally have **greater retention capacity**	Surface area and mineral-associated sorption	López-Mateo et al., 2023
Dissolved organic matter	Influenced by litter decomposition and root activity	Strongly affected by manure, fertilizer, and crop residues	**Can either mobilize or immobilize metals**	Formation of soluble or strongly bound metal–organic complexes	Peijnenburg (2025)
Root activity / rhizosphere processes	High and relatively continuous under permanent grassland	Seasonal and crop-dependent	**May increase local metal availability and uptake**	Root exudates, pH changes, microbial activity, and ligand production	Peijnenburg et al. 2000
Plant species	Species-specific grassland communities such as *Leymus*, *Stipa*, *Miscanthus*	Crop species generally selected and intensively managed	**Strong species-specific effect on accumulation**	Differences in root uptake, translocation, tolerance, and rhizosphere chemistry	Peijnenburg (2025)
Metal speciation	Strongly controlled by local mineralogy and redox conditions	Often affected by fertilizers and amendments	Determines the **bioavailable fraction** rather than total concentration	Different chemical species have different mobility and uptake potential	Peijnenburg (2025)
Gold mineralization intensity	Naturally heterogeneous along mineralized gradients	Usually less relevant except in contaminated agricultural areas	**Higher mineralization can increase Au–As exposure**	Parent material, sulfide oxidation, weathering, and secondary mineral formation	Blake, et al., 2019

Soil pH, cation-exchange capacity, clay minerals, Fe–Mn oxides, organic matter, moisture and redox conditions can jointly influence metal retention and mobility. Increasing clay content or exchange capacity may increase retention for some cationic elements, whereas arsenic behavior depends strongly on speciation and interactions with oxide minerals. These are general soil-chemical principles and should be applied to each element and site rather than assumed to predict Au bioavailability.

Plant exposure depends not only on total soil concentration but also on dissolved or extractable fractions, soil properties and species-specific uptake. Total concentration should therefore not be used alone as a proxy for biological exposure. The Galicia study is cited here only for the metal fractions and extraction methods that it actually reports. The review does not infer Au, As or Hg concentrations from that source unless those elements and values are explicitly present in the original paper.

3.4. Enzyme Inhibition & Bioindicators

Soil enzymes can help characterize microbial functioning in metal-affected soils, but reductions in activity do not identify Au as the cause. Studies of Cu, Pb, Zn or mixed-metal contamination are contextual evidence and must not be presented as direct evidence of Au-specific effects. Enzyme activity is affected by soil pH, moisture, temperature, organic matter, nutrients, substrate availability and co-contaminants. Any quantitative percentage change should be attributed only to the endpoint and site measured in the cited primary source.

3.5. Mechanisms of Inhibition

The review does not establish a dose–response relationship between Au nanoparticles and soil enzyme inhibition. Particle size, chemical form, concentration, exposure route and the presence of associated elements must be documented before attributing oxidative stress or enzyme responses to Au. The Hulun Buir source concerns an open-cast coal-mine setting and is not evidence of natural gold mineralization unless Au was directly measured and the study design supports that interpretation.

3.6. CNP Stoichiometry Responses

Microbial nutrient limitation and enzyme stoichiometry can be informative in degraded grasslands, but they are not specific to gold mineralization. Ratios and percentage changes from separate studies should not be pooled or used to infer a common mechanism unless the measures, sampling designs and units are comparable.

The previous sentence concerning geometric “length” and “angle” checks was unrelated to this ecological discussion and has been removed. Interpretation of enzyme responses should instead account for nutrient availability and other site conditions.

3.7. Grassland-Specific Bioindicators

Grassland monitoring may include dehydrogenase, β-glucosidase, phosphatases and urease as complementary measures of microbial metabolism and nutrient cycling. The review does not support the claim that these enzymes are unique to grasslands, resistant to low-dose Au, or capable of predicting mineralization with a universal accuracy range.

3.8. Prospecting and Restoration Applications

Enzyme measurements are not validated non-invasive prospecting tests for gold mineralization. The previously stated Au/DHA thresholds and diagnostic-performance estimates are not supported by traceable validation data and have been removed. Enzyme assays may be included in ecological monitoring alongside geochemistry and vegetation measurements, with site-specific controls.

Soil enzymes can be useful indicators of soil biological condition in some metal-affected ecosystems. Their interpretation is non-specific and requires concurrent measurements of soil chemistry, bioavailable elements, vegetation and environmental covariates. Table 9 summarizes enzyme activities that may provide complementary information on microbial respiration and C, N and P cycling. Au mineralization may co-occur with other elements, but enzyme responses are not specific to Au and can be influenced by pH, organic matter, moisture, temperature, substrate availability and co-contaminants.

Table 9. Soil enzyme indicators and their validation status in grassland soil assessment

Bioindicator / Parameter	Enzyme / Process Represented	Response under Mining/Metal Stress	Ecological Interpretation	Potential Use in Gold-Mineralized Grasslands	References
Dehydrogenase activity (DHA)	Microbial respiratory activity and intracellular redox processes	Often decreases under heavy-metal contamination	Indicates reduced microbial metabolic activity	Complementary indicator of soil biological condition; not Au-specific	Angelovičová et al. (2014); Bi et al. (2024)
β-glucosidase (β-Glc)	Cellulose decomposition and C cycling	Frequently inhibited under metal stress	Indicates disruption of microbial C acquisition	May help characterize decomposition processes; not Au-specific	Nikolova et al. (2023); Campillo-Cora et al. (2025)
Acid phosphatase	Organic-P mineralization	Response depends on P availability and metal stress	Indicates microbial/plant P acquisition pressure	Useful for identifying P limitation in degraded grasslands	Daunoras et al. (2024); Bi et al. (2024)
Alkaline phosphatase	P acquisition under neutral–alkaline conditions	May change with P limitation and environmental stress	Reflects P cycling and nutrient demand	Useful alongside acid phosphatase for P limitation assessment	Daunoras et al. (2024)
Urease	Organic-N transformation	Can decline under severe contamination or environmental stress	Indicates disturbance of N cycling	Useful for evaluating N-cycle recovery after mining	Daunoras et al. (2024)
Catalase	Decomposition of hydrogen peroxide / oxidative stress response	Can change under metal-induced oxidative stress	Indicates microbial oxidative stress	Complementary indicator of metal-related stress	Daunoras et al. (2024)
Microbial biomass C	Size of active microbial pool	Often reduced in contaminated soils	Indicates loss of microbial functional capacity	Useful as a supporting biological indicator	Campillo-Cora et al. (2025)
Microbial biomass N	Microbial N storage and cycling	May decline or become imbalanced	Indicates alteration of N cycling	Useful with enzyme stoichiometry	Bi et al. (2024)
Enzyme C:N:P stoichiometry	Relative microbial investment in C, N and P acquisition	Shifts under nutrient limitation and environmental disturbance	Indicates changes in microbial nutrient limitation	Useful for diagnosing ecosystem functional stress	Bi et al. (2024)
DHA:β-Glc ratio	Microbial respiration relative to C-decomposition activity	May change with metal and substrate stress	Indicates changes in microbial functional allocation	Potential composite indicator	Proposed synthesis
Multi-enzyme index	Integrated microbial functioning	Potentially integrative, but requires validation	Provides an integrated soil-health signal	Potentially useful for restoration monitoring, with site-specific validation	Peijnenburg (2025); Campillo-Cora et al. (2025)

Soil enzyme activity can complement conventional geochemical and vegetation assessments by indicating aspects of soil biological functioning. Dehydrogenase, β-glucosidase, urease and phosphatases are

not validated Au-specific indicators, and no universal threshold or diagnostic sensitivity is established by the evidence reviewed here. Their interpretation requires site-specific baselines and concurrent measurements of soil properties and bioavailable metals.

3.9. Restoration Strategies

Restoration responses depend on disturbance type and severity, substrate, water and nutrient availability, native vegetation, and management history. Evidence from alpine grasslands, mine wastes and other metal-affected soils may inform hypotheses, but it does not establish that active restoration is universally superior to passive recovery in naturally mineralized grasslands. Claims about fixed recovery periods or a universal increase in SOC have been removed; comparative, site-specific monitoring is needed.

Restoration outcomes vary with the type and severity of disturbance, substrate, water and nutrient availability, native vegetation, and management history. Evidence from alpine grasslands, mine wastes and other metal-affected soils may inform options for mineralized grasslands, but it cannot establish that active restoration is universally superior to passive recovery or prescribe universal recovery times. Comparative, site-specific monitoring is needed to determine which approaches restore vegetation, soil biological function and carbon stocks most effectively.

Studies of rehabilitated platinum tailings and other mine-affected substrates provide analogical evidence about possible recovery of soil biological functions, not direct evidence for naturally gold-mineralized grasslands. Reported enzyme activity and recovery times depend on the source study's substrate, methods, reference condition and restoration history; no universal recovery period is inferred here.

Results from coal-mining areas, karst valleys and other disturbed grasslands are retained only as contextual examples. They do not establish a common recovery percentage or time course for gold-mineralized grasslands. Climate, soil moisture, nutrients, element mixtures and management may alter the response, and each cited quantitative result requires verification against its primary source.

4. Implications for Sustainable Grassland Management and Net-Zero Transition

Grasslands are relevant to climate and land-management policy because their vegetation and soils participate in carbon cycling. Natural mineralization, mining and other disturbances should be distinguished: they differ in exposure pathways and ecological effects. Metal exposure may affect microbial activity, but the direction and magnitude depend on the elements present, their bioavailability and the wider soil environment.

The synthesis indicates that soil enzyme activities may provide useful complementary information about biological functioning. However, the evidence is drawn from heterogeneous studies and does not establish a consistent early-warning threshold for mineralized grasslands.

Evidence from restoration studies is mixed and ecosystem-specific. Active interventions may accelerate some vegetation or soil responses under particular conditions, while passive recovery may be appropriate elsewhere. The current review does not support universal percentage benefits for reseeding, fertilization or microbial recovery in gold-mineralized grasslands. Restoration outcomes should be evaluated using site-specific vegetation, soil-carbon and greenhouse-gas measurements.

Climate change may interact with metal mobility and soil biological processes through changes in moisture, temperature, pH, redox conditions and microbial community composition. The direction and size of these interactions are context-dependent and require field observations or controlled experiments rather than extrapolation across unrelated ecosystems.

This review identifies vegetation, soil chemistry and enzyme measurements as possible complementary components of monitoring frameworks for naturally mineralized and mining-affected grasslands. The available evidence does not establish a validated decision-support framework or demonstrate policy effectiveness.

The potential management contribution is to encourage integrated site assessment rather than to claim proven net-zero benefits. Biological indicators can complement geochemical and vegetation data, but enzyme-based assessment is not a substitute for measurements of soil-carbon stocks, plant carbon inputs and greenhouse-gas fluxes.

Future studies should quantify relationships among enzyme activity, microbial diversity, vegetation and SOC accumulation, while measuring soil CO_2 emissions, CH_4 and N_2O fluxes and restoration-related emissions. Remote sensing, GIS and ecosystem modelling may help scale validated field observations, but require transparent training data and independent validation (Table 10).

Table 10. Potential management implications and evidence gaps for vegetation–soil–enzyme interactions

Net-Zero Theme	Vegetation–Soil–Enzyme Process	Major Findings	Implications for Net-Zero	Research Gap	References
Grassland carbon sequestration	Soil microbial activity regulates decomposition and stabilization of soil organic carbon (SOC). Enzymes such as β-glucosidase, dehydrogenase and phosphatase control carbon turnover.	Grasslands store approximately one-third of global terrestrial carbon, most of which is contained in soils. Reduced microbial activity decreases carbon stabilization and long-term SOC storage.	Conserving soil biological activity enhances carbon sequestration and supports nature-based climate mitigation.	Long-term quantification of SOC responses under metal stress remains limited.	Lal (2004); Conant et al. (2017); Bhaduri et al. (2022); Gong et al. (2025)
Soil health and ecosystem functioning	Heavy metals suppress extracellular enzyme activities, microbial respiration and nutrient cycling.	Enzyme responses under mining-related metal contamination vary by soil and exposure conditions; a common percentage range cannot be inferred from this review.	Soil enzyme monitoring may complement broader site assessment; early-warning performance is not established here.	Standardized biological thresholds across grassland ecosystems are lacking.	Angelovicova et al. (2014); Nikolova et al. (2023); Wang et al. (2023); Campillo-Cora et al. (2025)
Climate change resilience	Climate warming and altered precipitation modify microbial communities, enzyme activity and metal mobility.	Drought and warming alter phosphatase and dehydrogenase activity while changing heavy-metal bioavailability.	Climate-adaptive restoration can improve resilience of degraded grasslands.	Coupled climate–metal interaction models remain scarce.	Daunoras et al. (2024); Liu et al. (2025); Wang et al. (2025)
Ecological restoration	Revegetation stimulates root exudation, microbial recovery and SOC	Active restoration increases SOC, accelerates enzyme recovery and restores microbial nutrient balance more rapidly	Restoration may support carbon storage, but net climate effects require direct SOC and greenhouse-gas	Long-term monitoring (>20 years) across climatic regions is needed.	Gong et al. (2025); Garaiyurrebaso et al. (2017); Yu et al. (2025); Shu et al. (2023)

Net-Zero Theme	Vegetation–Soil–Enzyme Process	Major Findings	Implications for Net-Zero	Research Gap	References
	accumulation.	than passive restoration.	measurements.		
Sustainable mining management	Enzyme bioindicators detect ecological disturbance before severe vegetation decline occurs.	Enzyme responses provide sensitive indicators of ecosystem stress and restoration success around mining areas.	Biological monitoring supports environmentally responsible mining and rehabilitation planning.	Integration into environmental regulations remains limited.	Haghighizadeh et al. (2024); Newsome & Falagan (2021); McLagan et al. (2025)
Nature-based solutions (NbS)	Restored grasslands recover biodiversity, microbial diversity and carbon cycling simultaneously.	Biodiversity recovery improves ecosystem stability, carbon retention and resilience against future disturbances.	Supports global Net Zero through ecosystem restoration and biodiversity conservation.	Limited studies quantify carbon credits from restored mining landscapes.	Gong et al. (2025); Bhaduri et al. (2022); UNEP (2024); IPCC (2023)
Carbon monitoring technologies	Integration of enzyme bioindicators with hyperspectral remote sensing and GIS improves ecosystem assessment.	Combining biological and remote-sensing indicators is a research opportunity requiring independent field validation.	Supports digital monitoring of carbon sequestration and restoration under Net Zero programmes.	AI-assisted monitoring frameworks remain largely experimental.	Wang et al. (2023); Liu et al. (2025); Yu et al. (2025)
Environmental policy and SDGs	Vegetation–soil–enzyme indicators support ecosystem-based environmental management.	Integrated biological monitoring aligns with sustainable land management and ecosystem restoration initiatives.	Contributes directly to SDG 13 (Climate Action), SDG 15 (Life on Land), and global Net Zero strategies.	Harmonized international monitoring frameworks are still lacking.	United Nations (2015); IPCC (2023); FAO (2022); UN Decade on Ecosystem Restoration (2021)

Table 10 summarizes potential management implications and evidence gaps. These are research priorities, not demonstrated net-zero outcomes. Enzyme activity is not an Au-specific diagnostic, and increases in enzyme activity do not necessarily indicate greater soil-carbon storage because enzymes also mediate decomposition.

Soil biological activity is relevant in grasslands exposed to metal stress, including where Au-associated elements such as As, Pb and Hg occur. Reduced activity of dehydrogenase, β-glucosidase, urease or phosphatases may indicate altered microbial functioning and nutrient cycling, but responses are not unique to metal exposure. Enzyme measurements should be interpreted alongside soil chemistry, bioavailable metal fractions, vegetation data and environmental covariates.

Climate change and metal exposure may interact through changes in soil moisture, temperature, pH, redox conditions and microbial community composition. The direction and magnitude of these interactions remain context-dependent. Management options such as native revegetation, soil amendments or moisture conservation should be selected only after site-specific assessment of ecological risks and potential effects on metal mobility.

Ecological restoration may support grassland recovery by rebuilding native vegetation, stabilizing soil and improving below-ground biological functioning. Whether these changes increase SOC stocks or produce a net climate benefit must be measured rather than inferred from enzyme activity alone. Monitoring should distinguish vegetation recovery, SOC stock change, ecosystem carbon balance and net greenhouse-gas balance.

Enzyme measurements can add a biological dimension to routine monitoring of soil chemistry, water quality and vegetation condition. Their value is as complementary indicators of soil functioning; they are not specific tests for Au mineralization, and any interpretation should be supported by site-level baselines and multiple lines of evidence.

Grassland conservation and restoration may contribute to climate mitigation, but their net effect depends on avoided carbon losses, changes in SOC stocks, plant carbon inputs, CO_2 emissions, CH_4 and N_2O fluxes, and emissions associated with restoration activities. Carbon storage or increased enzyme activity alone is not evidence of carbon neutrality. Existing grasslands should be protected where this avoids degradation, while restoration outcomes should be evaluated using a whole-system carbon and greenhouse-gas perspective.

Remote sensing, GIS, hyperspectral observations and machine-learning methods may help integrate vegetation condition, soil properties, metal concentrations and enzyme measurements across landscapes. Such approaches require training data and independent field validation; the bracketed reference tags have been removed pending verification and replacement with complete author–date citations.

5. Conclusions and Recommendations

This narrative review finds that vegetation, soil properties and microbial enzyme activity are potentially informative, complementary dimensions for assessing grassland responses in gold-mineralized and other metal-affected settings. The reviewed studies are heterogeneous, and direct measurements of all three components under a common design are limited. The synthesis therefore supports a conceptual framework for testing relationships, not a validated causal model or a universal account of natural Au mineralization.

Vegetation can influence rhizosphere chemistry and organic-matter inputs, while soil pH, clay minerals, cation-exchange capacity, Fe–Mn oxides, moisture and redox conditions affect metal retention and bioavailability. Total Au or As concentration alone is therefore insufficient to predict plant uptake or ecological response. Future assessments should measure bioavailable fractions and relevant soil properties alongside vegetation and enzyme data.

Soil enzymes may serve as complementary bioindicators of soil biological condition. Dehydrogenase, β-glucosidase, urease and phosphatases reflect different aspects of microbial metabolism and nutrient cycling, but their activities are influenced by pH, temperature, moisture, organic matter, substrate availability and co-contaminants. The reviewed evidence does not validate Au-specific diagnostic thresholds or sensitivity estimates.

Soil biological functioning is relevant to carbon cycling, but enzyme activity can promote both organic-matter decomposition and nutrient release; its increase does not necessarily imply net SOC accumulation. The climate implications of restoration require direct measurement of plant carbon inputs, SOC stocks over time, soil CO_2 emissions, CH_4 and N_2O fluxes, and the emissions associated with management activities.

The review proposes using vegetation, soil geochemistry and enzyme activity together as a conceptual monitoring framework for grassland responses in mineralized and metal-affected settings. Its predictive value, causal pathways and operational thresholds require testing with coordinated field sampling, controlled experiments and independent validation. Any application to net-zero planning should include direct carbon-stock and greenhouse-gas accounting.

The review's contribution is to organize evidence on vegetation responses, soil geochemistry and microbial enzyme activity in the specific context of gold-mineralized grasslands, while distinguishing that evidence from findings in mining-affected or otherwise metal-contaminated ecosystems. This comparison generates testable questions about Au and associated elements, but it does not establish that the three components form a universally verified causal system.

The evidence does not support using enzyme activity to prospect for deeply buried gold or assigning universal detection sensitivity or specificity across geographically distinct landscapes. Enzyme measurements may help characterize biological condition at the soil surface, but their interpretation should be combined with local geochemical baselines, vegetation observations and validated analytical methods.

Future studies should quantify associations among vegetation, soil properties, enzyme activities and Au-associated elements using coordinated sampling. They should measure total and bioavailable fractions of Au, As, Pb, Hg and other relevant elements, along with pH, organic matter, cation-exchange capacity, clay mineralogy, Fe–Mn oxides, moisture and redox conditions. Such designs would help distinguish direct evidence, cross-study association and causal hypotheses.

Future field studies should test whether enzyme activities provide reliable indicators of ecological stress in gold-mineralized and mining-affected grasslands. Studies should combine dehydrogenase, β-glucosidase, urease and phosphatase assays with vegetation measurements, soil geochemistry and bioavailable metal fractions, and should report sample sizes, controls, methods and uncertainty. Independent validation is needed before proposing thresholds.

Future research should examine how warming, drought and rainfall variability affect plant–microbe interactions, metal mobility and enzyme activity. Controlled experiments paired with field observations and repeated seasonal sampling would help identify which responses are consistent across sites and which depend on local conditions.

Remote sensing, GIS and machine-learning methods could help map vegetation condition and integrate field measurements of soil properties, metal concentrations, biomass and enzyme activity. These approaches should be developed using transparent training data and tested against independent field observations before use in restoration planning or mineral exploration.

Restoration research should evaluate more than plant cover. Repeated measurements of native vegetation, SOC stocks, microbial activity, enzyme activity and bioavailable metals are needed to assess recovery. Comparisons of active restoration and natural recovery should account for initial site conditions, restoration costs and potential greenhouse-gas effects rather than assuming one approach is universally preferable.

Standardized monitoring protocols are needed for mineralized grasslands. Studies should report sampling locations and depths, plant tissue type, sample preparation, extraction and assay methods, units, detection limits, quality assurance, environmental covariates and uncertainty. Common protocols would improve comparison among studies, but should not obscure important differences among soil types and mineralization settings.

Priority research gaps and agenda. Four gaps emerge from the literature: (1) a shortage of field studies that measure vegetation, total and bioavailable Au/associated elements, soil properties and enzyme activity at the same sites and sampling times; (2) limited separation of natural mineralization signals from mining disturbance, co-contaminants, climate and land-management effects; (3) inconsistent sampling, analytical and enzyme-assay protocols, with few independent tests of indicator performance across soil types and regions; and (4) insufficient long-term evidence linking restoration treatments to native-vegetation recovery, soil-carbon stock change and full greenhouse-gas balance. Priorities are therefore coordinated multi-season

field campaigns with reference sites and adequate replication; controlled experiments that isolate Au from As, Hg and other co-occurring stressors; harmonized reporting of methods, detection limits and uncertainty; external validation of any proposed indicator thresholds; and restoration trials that compare natural recovery with active interventions while tracking costs, ecological outcomes, SOC and CO_2, CH_4 and N_2O fluxes. Remote-sensing or machine-learning tools should be developed only where they can be trained and independently validated against these field measurements.

6. Limitation of the Study

This is a narrative synthesis rather than a systematic review or meta-analysis. The included studies differ in ecosystem type, disturbance source, sampling design and analytical method; evidence from mine-affected sites is not assumed to represent natural gold-mineralization anomalies. The review does not validate Au-specific enzyme thresholds, diagnostic sensitivity, a causal vegetation–soil–enzyme pathway, or a net-zero outcome. Numerical values and reference metadata should be checked against the original publications before publication, and climate claims require direct carbon-stock and greenhouse-gas measurements.

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