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Clean Enough for Whom? Multispecies Justice and the Redefinition of Success in the Green Remediation of Pharmaceutical-Contaminated Soils

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ABSTRACT: Green and sustainable remediation has become the dominant normative frame for soil clean-up, and pharmaceutical residues have become one of its more demanding objects. Yet the criteria by which a contaminated soil is judged successfully remediated remain almost entirely chemical and resource-based: the concentration of the parent compound relative to a threshold, achieved at an acceptable footprint of energy, emissions, water and waste. This article argues that these criteria are not merely incomplete but systematically silent about the organisms on which the outcome most directly falls, and that the silence is produced rather than accidental. Three displacements structure the argument. First, chemical removal and ecological recovery are separable outcomes: mineralisation, transformation, sequestration as non-extractable residue and translocation into biomass are all recorded as removal, though only the first constitutes detoxification. Second, the boundaries of environmental justice are examined and found to exclude soil biota by default rather than by argument, an exclusion that recognition-based and critical accounts of justice give reason to revisit. Third, the predicate "green" is shown to be indexed to a human scale of accounting, such that interventions reducing energy use may nonetheless simplify the communities they act upon. Heidegger's analysis of technology as a mode of revealing supplies an account of why the metric gap persists under repeated correction: the removal-rate criterion expresses a prior disclosure of soil as standing-reserve. Against this, a Multispecies Remediation Justice framework is proposed, organised around distributive, recognition, procedural and restorative dimensions and operationalised as a four-tier reporting ladder. Two further cases — Ephemeroptera distribution mapping and energy-saving retrofit of traditional kilns — establish that the tension recurs across monitoring and production technologies. The article closes with amendments to green remediation certification, impact assessment and monitoring disclosure.

1. INTRODUCTION

A remediation project ends when someone with the authority to do so declares that it has ended. That declaration is stated in technical language, but it is an exercise of authority before it is a measurement: it fixes when obligation ceases, when observation stops, and whose account of the site becomes the official one. In practice it rests on a small number of quantities — the concentration of the target contaminant against a regulatory action level, the cost of reaching it and, increasingly, the energy, greenhouse gas, water and waste burdens incurred along the way. Where all four are satisfactory, the site is released and the soil re-enters the register of usable land.

The rise of green and sustainable remediation (GSR) over the past two decades has transformed the third of these quantities

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and left the first two largely undisturbed. Frameworks developed by the United States Environmental Protection Agency, the Sustainable Remediation Forum and the Interstate Technology and Regulatory Council converge on a set of core elements — energy, air emissions, water resources, materials and waste — through which the environmental footprint of a clean-up is to be reduced (Sang et al., 2022). The achievement is real: a remedy avoiding excavation, transport and incineration is materially preferable to one that does not. But it is also bounded in a way that has attracted little scrutiny. Every one of those core elements is a quantity of human resource consumption. None registers what becomes of the organisms living in the soil under treatment.

For most contaminant classes this omission can be defended as a reasonable simplification. For pharmaceuticals it cannot. Pharmaceutical and personal care product residues reach agricultural and peri-urban soils through biosolids application, livestock manure, wastewater irrigation and manufacturing effluent, and they arrive with properties that distinguish them from legacy hydrocarbons or metals: they are biologically active by design, they act at low concentrations, and their principal targets are the organisms that mediate soil function. A technology aimed at such compounds intervenes in a system whose biological components are simultaneously the receptors of harm, the agents of degradation, and the medium through which the outcome will be judged — and yet only the second of these roles enters the record.

The question in the title is therefore not rhetorical. Cleanliness is a comparative property, and every comparison specifies a beneficiary. Where the standard derives from food safety and land reuse, the soil is clean for people, and its condition for the earthworms, fungi and bacteria that constitute it is a matter on which the record is silent. Critical environmental justice scholarship has insisted that such silences are not gaps in knowledge but arrangements of visibility, sustained because they distribute the burden of proof in a particular direction. Those required to demonstrate harm are those least able to do so, and here they cannot speak at all. What follows takes that asymmetry, rather than any deficiency of technique, as the object of analysis.

Four contributions are intended. The first is diagnostic: chemical removal and ecological recovery are separable outcomes, and current success criteria cannot distinguish them (Section 4). The second is normative: the vocabulary of environmental justice is extended to the remediation site in a way that includes soil organisms without collapsing into implausible claims about the standing of individual microbes (Section 5). The third is explanatory: Heidegger's analysis of modern technology accounts for why the metric gap is stable rather than accidental, and why greening does not by itself close it (Section 6). The fourth is constructive: a Multispecies Remediation Justice framework with an associated reporting ladder is set out, probed against two further cases at different scales, and translated into amendments to existing policy instruments (Sections 7–9).

The argument is conceptual and normative rather than experimental, and it is also reflexive. Two of the technologies examined below are ones the authors have themselves built: a bacterial isolate developed for the degradation of a pharmaceutical residue, and a distribution-mapping programme for freshwater indicator insects. Both were designed and reported under exactly the evaluative conventions criticised here, and they are used in Sections 6 and 8 as worked cases rather than as illustrations of other people's practice. The remaining empirical basis is a structured synthesis of three literatures that rarely meet: the soil science of pharmaceutical contamination and its remediation; environmental, ecological and multispecies justice theory; and the policy literature on green and sustainable remediation.

2. SCOPE AND METHOD

This is a framework-development paper supported by a scoping synthesis rather than a systematic review, and it claims no exhaustive coverage of the literatures it draws on.

Three bodies of work were searched: the fate and ecological effects of pharmaceutical residues in soil, with the technologies proposed for their remediation; justice theory as applied to nonhuman entities, spanning ecological and multispecies justice, rights of nature, and nonhuman stakeholder theory; and assessment frameworks for green and sustainable remediation, with the critical literature on scale in environmental governance and on restoration standards.

Sources were retained where they bore on four questions: what pharmaceutical residues do to soil organisms; what remediation technologies do to them; how success is defined and by whom; and on what basis nonhuman interests might enter an assessment. Priority went to reviews, framework documents and standards, since the object of analysis is the structure of evaluation rather than any particular result.

Two boundaries should be stated. The article proposes categories and indicator types rather than numerical criteria, since defensible thresholds for biological indicators require empirical derivation and jurisdiction-specific negotiation. And the illustrative material in Figures 1 and 5 is schematic, representing relationships documented in the cited literature rather than measurements from a single site.

3. Pharmaceuticals in soil and the standard remedial response

3.1 Entry, persistence and effect

Pharmaceutical compounds reach terrestrial systems through several simultaneous routes: sewage sludge applied to land, manure from intensive livestock production, irrigation with treated or partially treated wastewater, and manufacturing effluent. Once in soil, behaviour is governed by sorption to organic matter and clays, pH-dependent speciation and microbial transformation. Persistence varies by orders of magnitude across compound classes, and the assumption that a compound has gone because it can no longer be extracted has become difficult to sustain (Section 4.1). Global analysis of soil metagenomes places antibiotic resistance genes across a wide range of habitats, with higher abundance in agricultural than non-agricultural soils, indicating that pharmaceutical pressure on soil communities is not localised (Zheng et al., 2022).

The documented effects are consistent in direction if variable in magnitude. Antibiotic exposure reduces prokaryotic diversity, shifts fungal community composition, enriches resistance determinants and mobile genetic elements, and depresses plant growth-promoting taxa, linking microbial change to plant performance through a mechanism independent of direct phytotoxicity. Veterinary pharmaceuticals affect arbuscular mycorrhizal symbioses in compound-specific and sometimes opposing ways, so that a mixture cannot be predicted from its constituents. Soil invertebrates respond at concentrations overlapping the upper range of field observations, with non-steroidal anti-inflammatory drugs and lipid-lowering agents among the more acutely toxic classes tested (Zhang et al., 2024; Nwankwo et al., 2025).

The significance of these findings depends on what soil biodiversity does. Combined observational and microcosm evidence associates the diversity of bacteria, fungi, protists and invertebrates with multiple ecosystem functions simultaneously — nutrient cycling, decomposition, plant production, and suppression of pathogenicity (Delgado-Baquerizo et al., 2020). Experimental simplification impairs multifunctionality, with the sharpest losses where groups such as mycorrhizal fungi and nematodes are suppressed (Wagg et al., 2014). Soil biodiversity is thus not an ornamental property of a site but the mechanism by which the site does anything at all, and it is vulnerable to precisely the compounds under discussion.

3.2 The remedial repertoire and its success criteria

Three families of technology are advanced as green alternatives to excavation and thermal treatment. Bioremediation applies indigenous or introduced microorganisms, sometimes with biostimulation, to degrade the target compound in situ. Phytoremediation uses plant uptake, rhizosphere degradation and, in constructed wetland configurations, associated microbial processes; reviews of antibiotic removal by these means document substantial efficiencies alongside persistent uncertainty about effects on resistance genes (McCorquodale-Bauer et al., 2023). Mycoremediation exploits the broad oxidative capacity of ligninolytic fungi. Recent work on antibiotic-polluted agricultural soils integrates source diversity, bioavailability modulation and ecological impact within a single treatment design (Olanrewaju & Bezuidenhout, 2025), and contamination by resistant bacteria and their genes has been recognised as posing challenges that conventional approaches do not address (Li et al., 2023).

What unites these technologies at the level of assessment is the criterion by which they are judged. Removal efficiency of the parent compound is the primary endpoint; cost and duration are the operational constraints; and under GSR frameworks, footprint metrics break ties between otherwise equivalent options. Sang et al. (2022), reviewing the American policy system and its case record, find that the EPA, SURF-US and ITRC frameworks respectively promote green remediation, sustainable remediation and their combination, evaluated through energy, emissions, water, materials and waste. The frameworks differ in emphasis. None requires that a project demonstrate the recovery of the biological community whose loss the treatment may have caused.

4. First displacement: chemical removal is not ecological recovery

4.1 The mass balance problem

The proposition that a contaminant has been removed conceals a distinction between at least four fates, only one of which is destruction.

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Mineralisation converts the compound to carbon dioxide, water and inorganic ions. This is detoxification in the strict sense, and it is what the word "degradation" is usually taken to name.

Transformation yields structurally related products which frequently retain the pharmacophore responsible for the parent compound's activity. Analyses of pharmaceutical transformation products establish that they can reach concentrations comparable to or exceeding those of the parent, that they may be more persistent, and that toxicity is not reliably reduced by transformation (Celiz et al., 2009). Work on advanced oxidation makes the point sharply: substantial disappearance of the parent compound was accompanied by no mineralisation, so that the correct description was transformation rather than degradation (Zilberman et al., 2023). Earlier surveys of pesticide transformation products found that products are usually less toxic than parents but identified a minority in which they are not (Sinclair & Boxall, 2003) — and a minority suffices, since the compounds falling into it are unknown at the point of decision.

Sequestration produces non-extractable residues. A unified treatment distinguishes three types: type I, comprising the parent substance or xenobiotic transformation products sequestered or entrapped, with demonstrated potential for release; type II, covalently bound to soil organic matter and considered strongly bound; and type III, biogenic residues incorporated into microbial biomass (Kästner et al., 2018). Only types II and III can be regarded as a safe sink. Type I is a reservoir whose remobilisation depends on conditions that a project neither controls nor monitors after closure, and the uncertainties attending the toxicity of non-extractable residues remain substantial (Harmsen et al., 2019). Isotope-labelling work confirms that standard analysis cannot easily separate a hidden hazard from a safe sink (Lennartz et al., 2024).

Translocation moves the compound rather than altering it. Plant uptake concentrates residues in harvestable tissue whose disposal the site record does not track; leaching transfers them to groundwater; volatilisation transfers them to air. Each is recorded, at the treated horizon, as removal.

Figure 1 sets out the consequence. A fate partition in which mineralisation and stabilised residues together account for a minority of the applied mass — a proportion consistent with the ranges reported across the studies cited above — is entirely compatible with a reported removal efficiency approaching completeness. The two numbers measure different things.

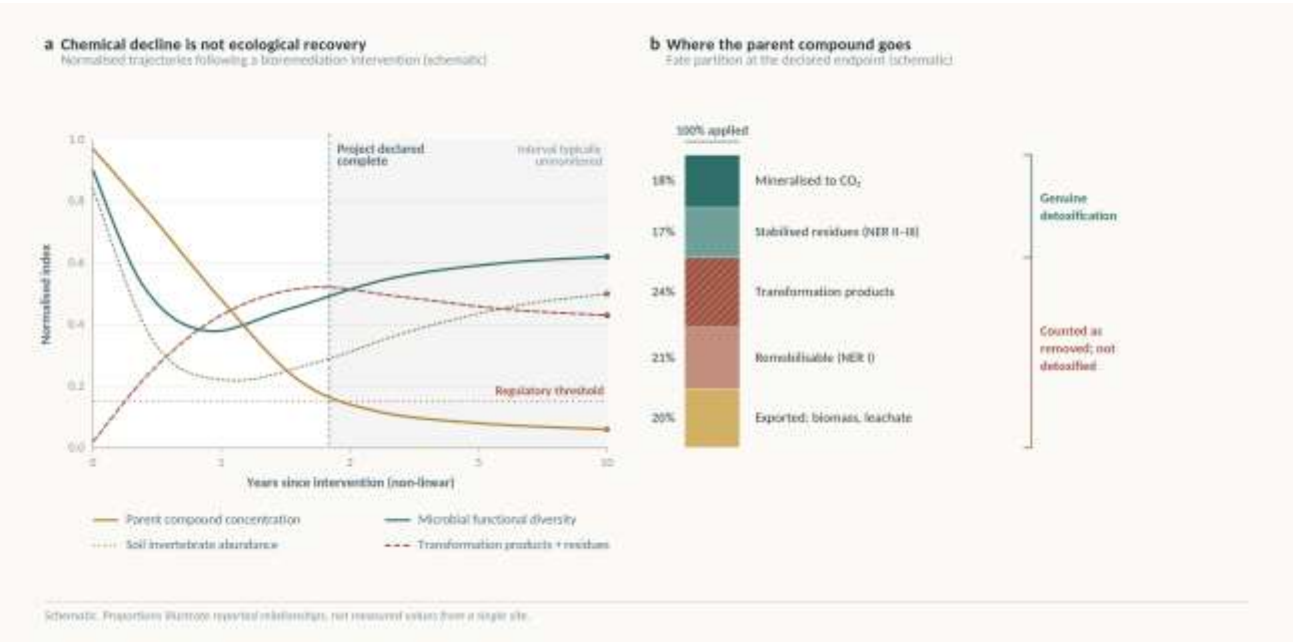

Figure 1. Two ledgers of remediation success. (a) Normalised trajectories following a bioremediation intervention: the parent compound crosses the regulatory threshold and the project is declared complete, while microbial functional diversity and invertebrate abundance remain below baseline and the burden of transformation products and mobilisable residues plateaus rather than falling. (b) Fate partition of the applied compound at the declared endpoint; only mineralisation and stabilised non-extractable residues constitute detoxification. Schematic: proportions illustrate relationships reported across the cited literature rather than measurements from a single site.

4.2 What the concentration metric cannot register

Even where mineralisation is genuine, a fall in concentration carries no information about the state of the community that achieved it.

Three gaps matter. The first is functional redundancy: a community may retain its capacity to perform a measured process while having lost the taxonomic breadth that allows it to continue performing that process under changed conditions. Redundancy is insurance, and its loss is invisible to any assay of current rates. The second is network structure: multifunctionality depends not only on which taxa are present but on the interactions among them, and experimental simplification shows discontinuous responses in which function is maintained until a threshold is passed and then falls sharply (Wagg et al., 2014). A project measuring function at a single time point cannot know which side of such a threshold it has left the soil on. The third is temporal: recovery from disturbance is slow relative to the timescale of a remediation contract, and the interval in which it would become observable falls after monitoring ceases. A stalled trajectory and a completed one are, under current reporting, the same datum.

The distinction this supports is between decontamination, the reduction of a chemical concentration in a matrix, and ecological restoration, the re-establishment of the relations that the matrix supported. Standards for ecological restoration handle exactly this through a reference model against which recovery is scored on a graduated scale rather than assessed pass or fail (Gann et al., 2019). Remediation has no equivalent instrument, and the vocabulary of "clean-up" obscures the fact that one is needed. The point is not that decontamination is unimportant, but that it has been allowed to stand as proxy for a much larger claim it does not license.

5. SECOND DISPLACEMENT: WHO COUNTS AS A SUBJECT OF JUSTICE

5.1 The human frame and its default boundary

Environmental justice scholarship has developed a differentiated account of what justice requires, moving beyond distribution to include recognition of membership in the moral and political community, the capabilities required for functioning and flourishing, and inclusion in decision-making — dimensions that Schlosberg (2007) argues are interrelated and jointly necessary, and which he extends explicitly toward relations between human communities and nonhuman nature. Agencies have begun to absorb the vocabulary, with recognitional and capabilities dimensions proposed as additions to assessment practice (Eisenhauer et al., 2021).

Applied to contaminated land, this apparatus has been productive: it identifies which communities bear disproportionate exposure, whose knowledge is admitted into site characterisation, and who is present when remedial options are appraised. What it has not done is identify who else is present at the site.

The exclusion of soil organisms from justice claims in remediation is, so far as the literature discloses, not the conclusion of an argument. No one has argued that soil biota lack morally relevant interests and that their exclusion therefore follows. They are absent because the frameworks were built for other purposes and the question was never put — a different situation from settled disagreement, and for reform a more tractable one.

5.2 The multispecies turn

The multispecies justice literature puts the question directly. Celermajer et al. (2021) set out theoretical approaches, areas of application and a research agenda for extending justice beyond the human, and the companion body of work develops the implications for climate futures (Tschakert et al., 2021), for the imaginative register in which alternatives are articulated (Thaler, 2022), for the moral significance of relations between species (Bendik-Keymer, 2022), and for the legal forms recognition might take, including through the rights of nature movement (Fitz-Henry, 2022). The programmatic ambition is a shift in the boundary of the just community from human individuals to animals, plants, microorganisms, ecosystems and the relations among them.

Two features bear on remediation. The first is the treatment of scale: the framing that runs from the individual organism to the planetary is presented not as a range of possible resolutions but as a set of decisions with distributive consequences. The second is the priority of recognition over distribution. One cannot allocate burdens fairly among parties one has not identified as parties. This ordering locates the failure earlier than it is usually located: not in the weighing of interests but in the enumeration of who has them. Parallel work in organisational theory makes the operational version of the same move, arguing that nonhuman nature is typically approached as an undifferentiated whole and that taking it seriously requires particularising nonhumans as stakeholders with distinct vulnerabilities and needs (Kortetmäki et al., 2023). That demand is exactly what a project fails to meet when it records "soil microbiota" as a single line item denoting degradation capacity.

5.3 The objection from absurdity, and a reply

The obvious objection is that this line of argument overreaches. If soil bacteria are subjects of justice, then every act of tilling, planting or walking is a prima facie injustice; the position appears to generate obligations no one could discharge, and a framework that generates them is not a serious guide to policy.

The objection has force against one version of the position and none against another. It succeeds against a claim that individual microorganisms bear rights analogous to those of persons — a claim that would indeed make ordinary agriculture impossible and that nothing here requires. It fails against the claim actually needed, which attaches justice considerations not to organisms severally but to functional relations and habitat continuity.

The distinction can be stated precisely. What is owed is not the survival of any particular bacterium but the persistence of the conditions under which the assemblage can continue to constitute itself: the maintenance of functional guilds, the availability of habitat structure, the continuity of symbiotic partnerships, and the capacity of the community to recover from disturbance. On this construal, ploughing a field is not an injustice, because the relations reconstitute themselves; sterilising it durably, or replacing a diverse assemblage with an engineered monoculture whose persistence is unknown, is a candidate for one.

Two consequences follow. The unit of assessment becomes the community and its functions rather than the individual, which brings the claim within reach of existing measurement, since functional diversity, guild abundance, symbiotic establishment and recovery trajectory are quantities soil ecology already knows how to estimate. And the framework becomes comparative rather than absolute. It does not prohibit intervention; it requires that where two interventions achieve comparable chemical outcomes, the one foreclosing fewer relations be preferred, and that where a faster remedy forecloses more, the trade be recorded rather than concealed.

This is a weaker position than the strongest multispecies justice claims. It is also considerably harder to dismiss, and it is sufficient for everything that follows.

5.4 The enclosure of the countable

Figure 2 represents the result. Assessment practice forms a set of nested bands: contaminant concentration at the centre; footprint metrics around it; human-facing outcomes such as land reuse, cost and community around those. A boundary of mandatory reporting encloses the three. Outside it lie microbial functional diversity, mycorrhizal and rhizosphere symbioses, invertebrate populations, transformation-product ecotoxicity, resistance-gene reservoirs, trophic linkages to adjacent compartments, and post-closure recovery trajectory.

Nothing prevents a project from measuring items in the outer band, and some do. But because they lie outside the boundary, measuring them is a cost carrying no corresponding credit, and declining to measure them carries no penalty. The incentive structure follows from the boundary, and the boundary is what a justice framework has to move.

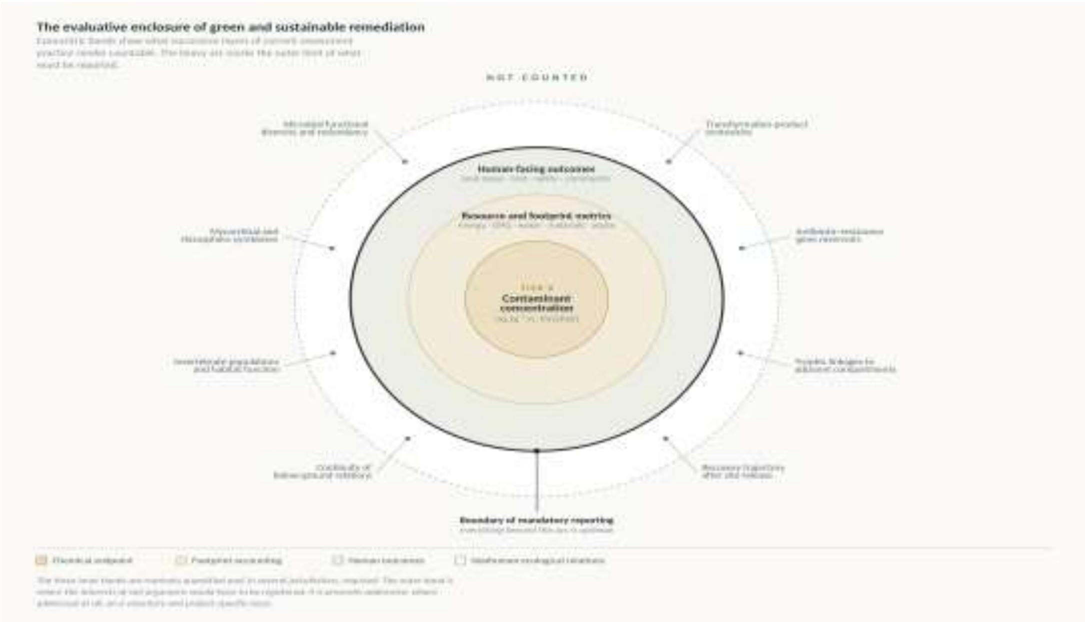

Figure 2. The evaluative enclosure of green and sustainable remediation. Concentric bands represent successive layers of what current assessment practice renders countable, from contaminant concentration at the centre through resource-footprint accounting to human-facing outcomes. The heavy arc marks the outer limit of mandatory reporting. Items in the outer field — microbial functional diversity, mycorrhizal and rhizosphere symbioses, invertebrate populations, transformation-product ecotoxicity, resistance-gene reservoirs, trophic linkage and post-closure recovery — may be measured but need not be.

6. THIRD DISPLACEMENT: "GREEN" IS INDEXED TO A SCALE, AND THE METRIC WAS NEVER NEUTRAL

6.1 Efficiency gains that are not ecological gains

The predicate "green" as deployed in remediation denotes a comparative reduction in resource consumption and emissions relative to a conventional alternative. It is a real property and a useful one. It is also a claim about an accounting boundary rather than about the treated system.

Three examples make the gap concrete, the first of them our own. In earlier work we isolated an aerobic strain, Burkholderia sp. Z-3, from medical wastewater and characterised its capacity to degrade levodopa, a therapeutic residue whose toxicity toward aquatic organisms and mammalian cells motivated the study; degradation was resolved to the molecular level through gene cloning, enzyme expression, chromatographic identification of intermediates and computational docking (Jiang, in preparation). Judged by the conventions of that literature the work was complete: a novel degrader, a characterised pathway, a quantified removal rate. Judged by the criteria developed here it was not, because no measurement was made of what the inoculum did to the community it entered. That omission was not an oversight in execution but a faithful application of the reporting conventions the field supplies, which is precisely the point at issue.

The literature indicates that the omission matters. A critical appraisal by Mawarda et al. (2020) concludes that microbial inoculation frequently does affect resident communities, framing introduced strains as invisible invaders whose non-target effects have been assumed negligible rather than demonstrated so, and a meta-analysis of 335 studies confirmed measurable effects on native community properties, conditioned by environmental stress and by whether the inoculant was native to the site (Sun et al., 2024). Neither result implies that bioaugmentation should be abandoned; both imply that its effects on the community are a proper object of assessment, and at present they are not one.

Phytoremediation relocates the accounting problem. A plant accumulating a pharmaceutical residue has removed it from the soil horizon and concentrated it in harvestable tissue, at which point disposal arises in a form the site record does not track. Where constructed wetlands are the configuration, removal efficiencies for antibiotics can be substantial while effects on resistance determinants remain incompletely characterised (McCorquodale-Bauer et al., 2023): greener by the footprint metric, unresolved by the ecological one.

Consortium design and biostimulation raise the question in its purest form. To engineer a community for degradation efficiency is to select for a functional trait across a population, and selection has a cost measured in the traits not selected for. Where the engineered assemblage is more efficient and less diverse than the one it displaces, the project has traded ecological insurance for kinetic performance, and the trade appears in the record only as an improvement.

6.2 Scale as a political variable

Environmental governance scholarship established some time ago that the scale at which a problem is defined is not given by the problem. Bulkeley (2005) argues that space and scale are too readily treated as pre-given containers, and that an adequate account must attend to the politics of scale and of networks rather than assuming decisions cascade down a natural hierarchy. Applied here the point is direct: whether a project is evaluated at the scale of the treated horizon, the field, the catchment or the decade is a decision, made by particular parties, and it determines the answer.

A remedy appearing successful at the scale of the plot and the contract period may appear otherwise at the scale of the catchment and the decade, because that is where translocated residues and delayed recovery become visible. Selecting the narrower scale is not a technical necessity but a choice with a beneficiary, and the beneficiary is generally the party bearing the cost of the wider one. Scale, in other words, is where the distributive question is settled before it is asked.

6.3 Enframing and standing-reserve

The recurrence of this pattern across otherwise unrelated technologies suggests it is not a series of local oversights. Heidegger's analysis of modern technology supplies a candidate explanation.

The claim in "The Question Concerning Technology" is that technology is not primarily an instrument but a mode of revealing — a way in which entities are disclosed in advance as being of a certain sort. Modern technology reveals under the mode Heidegger calls Ge-stell, enframing, in which entities appear as Bestand, standing-reserve: stock held in readiness, ordered and calculable, awaiting call-up. As Huttunen and Kakkori (2022) summarise the position, the difficulty is not that technological thinking exists but that calculative thinking has become the only form of thinking, so that nature and ultimately the human being appear exclusively as standing-reserve.

The application is close to exact. A soil disclosed as standing-reserve is a soil whose relevant properties are those that can be ordered: contaminant load, treatment cost, time to threshold, and the capacity of the resident biota to perform degradation on demand. Under this disclosure the microbial community is not overlooked through carelessness. It is present, but present as capacity — as an electrical grid is present as available power. What cannot appear is the community as something with a continuing existence of its own, because that is not a mode in which standing-reserve is available.

This explains a feature of the metric gap that mere oversight would not. Were the exclusion of soil organisms an accident of drafting, one would expect it to be corrected once pointed out, and the correction to be uncontroversial. What is observed instead is that ecological indicators, where they appear at all, appear as optional supplements rather than requirements, and that proposals to make them mandatory meet resistance framed in terms of proportionality and cost. That is what one expects when indicators are asked to do something the framework was not built to do.

Critically, the greening of remediation does not by itself alter the disclosure. To reduce the energy consumed in ordering a standing-reserve is to order it more efficiently. Efficiency is the native virtue of enframing, not an escape from it. This is why a technology can be greener on every published metric and still exemplify the problem described here.

6.4 Sparing, and the objection from quietism

Heidegger does not counsel abandoning technology, and the reading offered here does not either. What he opposes is the monopoly of one mode of revealing. The alternatives he names — Schonen, sparing or safekeeping, and Gelassenheit, releasement — describe a comportment in which one uses technology while allowing entities to show themselves as what they are rather than only as what they are for.

The standard objection to invoking these notions in policy contexts is that they are quietist: evocative about attitude, silent about action, and therefore useless to anyone drafting a standard. The objection is fair as an observation about the primary

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texts and mistaken as an inference about what can be built from them.

A mode of disclosure has an operational signature. What a technology is permitted to reveal determines what is measured; what is measured determines what can be reported; what can be reported determines what can be contested. Sparing, translated into the idiom of assessment, is not a mood but an indicator set — one in which the continued existence of the soil community appears as a criterion of success rather than as an input to it. Figure 3 sets the two configurations side by side for the Z-3 case, holding the engineering constant and varying only the disclosure. The same inoculum, dose and application method yield different questions, different counted entities, different decision rules and different endpoints. The framework in Section 7 is best understood as the institutionalisation of that second column: an attempt to specify what sparing would consist in if it had to be written into a reporting requirement.

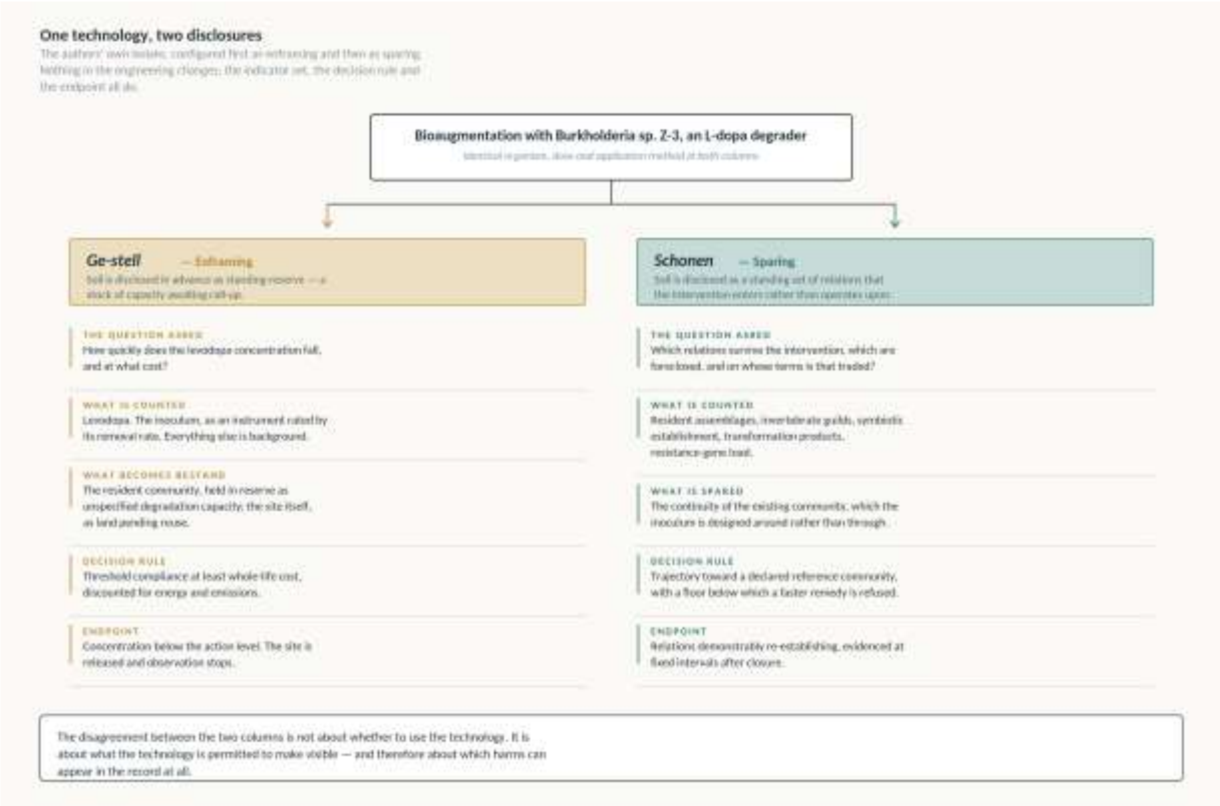

Figure 3. One technology, two disclosures. Bioaugmentation with Burkholderia sp. Z-3, the L-dopa-degrading isolate described in Section 6.1, configured first under enframing (Ge-stell) and then under sparing (Schonen). The organism, dose and application method are identical in both columns. What differs is the question asked, the entities counted, the decision rule and the endpoint — which is to say, everything that determines what can subsequently appear in the record as a harm.

7. A MULTISPECIES REMEDIATION JUSTICE FRAMEWORK

The framework organises the foregoing into four dimensions, each stated as a question a project must answer and attached to a candidate reporting indicator. Figure 4 presents it in full; the discussion here gives the reasoning behind each dimension and the associated implementation ladder.

7.1 Distributive justice

How are the residual burdens of the intervention apportioned — between human communities, and between taxa and functional groups within the soil?

The distributive question is usually asked about communities near the site and about future land users. Extended, it asks where the contaminant mass went and who received it. Section 4 established that a substantial fraction is typically transformed, sequestered or translocated rather than destroyed, and that these fates are recorded as removal. The corresponding indicator is a full fate mass balance disaggregated by receiving compartment, together with change in the abundance of at least three functional guilds relative to an untreated reference plot. The requirement is demanding but not novel, since isotope-labelling methods and reference-plot designs are both established. What is new is the obligation to report the partition rather than the aggregate.

7.2 Recognition justice

Are soil organisms registered as entities with interests of their own, or only as instruments and as media through which risk reaches people?

Recognition is prior to distribution because unenumerated parties cannot be allocated anything. The failure mode is specific: microbiota appear in the record solely as degradation capacity, so taxa performing no useful work are not enumerated and therefore cannot be shown to have been harmed. This is not a measurement problem but a consequence of what the record is for. The indicator is a mandatory pre-intervention biological baseline together with an explicit reference-community model, deposited before the remedy is selected. The sequencing matters: a baseline collected after selection can only characterise, whereas one collected before it can constrain. This is the device by which restoration standards make recovery assessable (Gann et al., 2019), and its absence from remediation practice is the single most consequential gap the framework identifies.

7.3 Procedural justice

Who holds the authority to declare a soil restored, and on whose evidence does that declaration rest?

At present the endpoint is proposed by the party bearing the cost of meeting it, verified against a single chemical criterion, and approved by a regulator whose remit is framed in terms of human health and land use. No party represents the interests of the affected biota, so those interests have no procedural route into the decision even where acknowledged in principle. The indicator has two components: a named proxy assessor for nonhuman receptors within the impact assessment, and disclosure of the sampling design, taxonomic coverage and monitoring frequency on which any biological claim rests. The proxy mechanism has precedent in the rights of nature literature and in guardianship arrangements for ecosystems (Fitz-Henry, 2022), and the requirement to particularise the represented parties follows Kortetmäki et al. (2023). The disclosure component matters independently, for reasons Section 8.1 develops: a biological claim whose sampling basis is undisclosed is not assessable.

7.4 Restorative justice

Is the object of repair the usability of the land, or the web of relations that the contamination and the remedy together disturbed?

This is where remediation and restoration diverge most sharply. Remediation treats success as a threshold crossed at a moment; restoration treats it as a trajectory scored against a reference model at intervals. A stalled recovery and a completed one are therefore indistinguishable, since both terminate at the same declaration. The indicator is a recovery trajectory reported at fixed post-closure intervals on a graduated scale. The instrument exists: the five-star recovery-wheel logic of the international restoration standards requires only adaptation of its attributes to below-ground systems (Gann et al., 2019). The obstacle is institutional rather than methodological, since post-closure obligation is precisely what site release is designed to terminate.

7.5 The implementation ladder

The four dimensions are cumulative rather than alternative, and Figure 4 expresses their implementation as a four-tier ladder in which each tier presupposes the one below it. Tier 0 reports parent-compound concentration against a threshold; this is current practice, and nothing in the framework displaces it. Tier 1 adds the abundance and diversity of resident microbial and invertebrate assemblages, measured before intervention and at closure, which amplicon sequencing and standardised invertebrate assays make the least demanding addition. Tier 2 adds process rates — respiration, nitrogen turnover, decomposition, symbiotic establishment — because structural data alone can mislead: composition may shift while function is maintained, or function may degrade while composition appears stable. Tier 3 adds the trajectory toward the declared reference community, reported after closure and scored rather than merely passed.

Two features of the ladder are deliberate. It is proportionate, in that Tier 1 might reasonably be required of all projects and Tiers 2 and 3 of projects above a sensitivity threshold defined by land use, contaminant class or proximity to protected habitat. And it is incremental, so that a regulator may adopt Tier 1 without committing to Tier 3, which gives a defensible path for jurisdictions unwilling to move in a single step.

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Applied retrospectively to the Z-3 study of Section 6.1, the ladder is diagnostic rather than merely critical. That work reported Tier 0 in full and nothing above it. Tier 1 would have required amplicon profiling of the treated matrix before inoculation and at the end of incubation, which is neither costly nor methodologically novel once the sampling is planned in advance. Tier 2 would have required a respiration or nitrogen-turnover assay run alongside the degradation kinetics already being measured, using the same sampling points. Tier 3 would have required extending observation beyond the point at which levodopa became undetectable, which is where the study stopped, and comparing the resulting community against an uninoculated control maintained for the same period. The instructive feature is that the first two additions were available at the time at marginal cost, and were not made, because nothing in the reporting expectations of the field asked for them. A framework of this kind earns its place if it makes such omissions visible before the work is designed rather than after it is published.

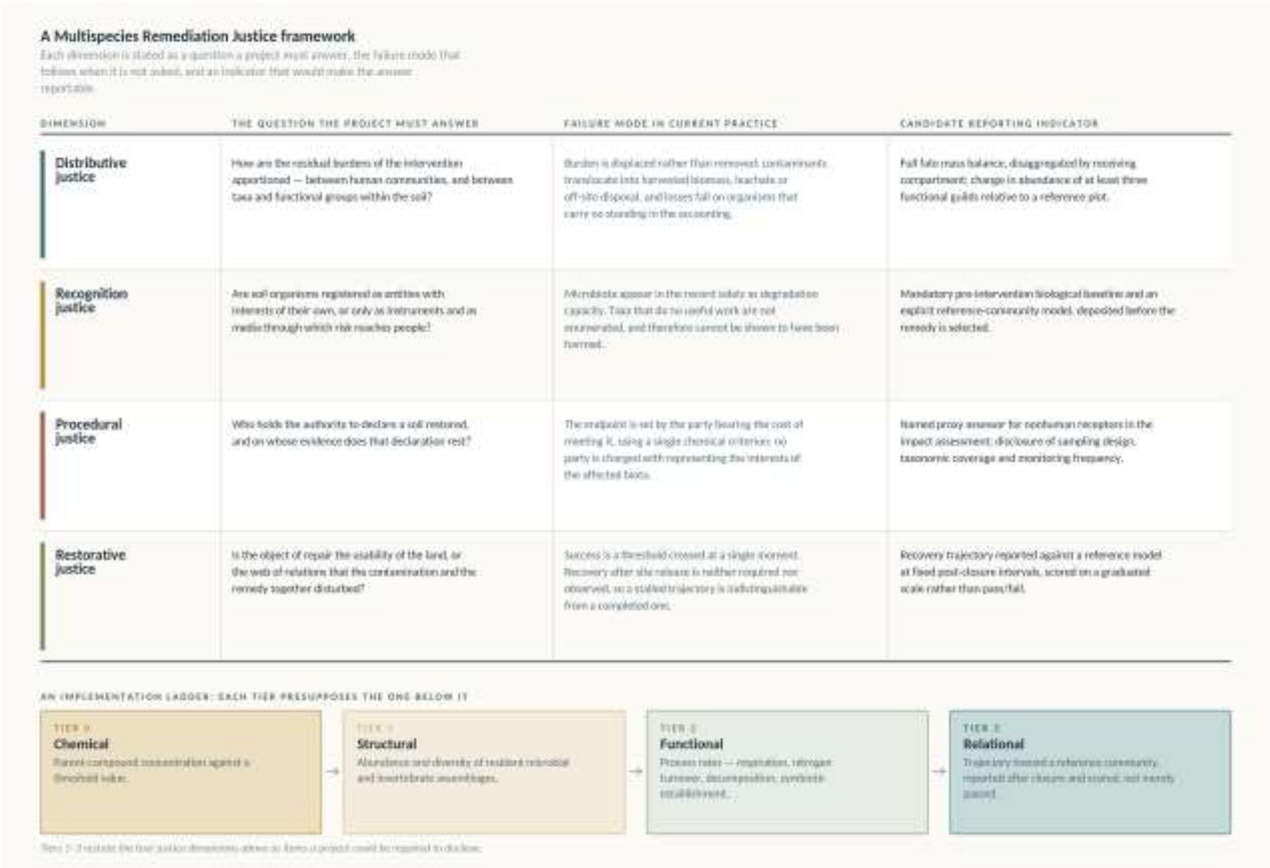

Figure 4. The Multispecies Remediation Justice framework. Each of the four justice dimensions is expressed as a question a project must answer, the failure mode that follows when it is not asked, and a candidate reporting indicator. The lower band sets out the implementation ladder: Tier 0 corresponds to current practice, and Tiers 1 to 3 give the successive additions required to make the four dimensions reportable. The tiers are cumulative and are intended to be applied proportionately to site sensitivity.

8. CROSS-SCALE ILLUSTRATION: MONITORING AND PRODUCTION TECHNOLOGIES

If the pattern identified above belongs to a mode of disclosure rather than to soil remediation in particular, it should recur where the subject matter differs and the disclosure does not. Two further cases probe this; Figure 5 sets out the comparison.

8.1 Monitoring: Ephemeroptera distribution mapping

Mayfly larvae are among the most widely used indicators of freshwater condition, valued for sensitivity to oxygen depletion and organic pollution. Their standing rests on a substantial methodological literature: Bauernfeind and Moog (2000) set out requirements for assessing ecological integrity from mayfly community structure and emphasise that interpretation depends heavily on sampling strategy, while Menetrey et al. (2008) examine their performance in lentic systems and find their diversity relatively poorly represented despite high occurrence.

The second of our own cases sits here. Following the description of Vietnamella chebalingensis from larval material (Luo et al., 2020), we sampled the type locality in Chebaling National Nature Reserve, reared nymphs through to the winged adult stage under laboratory conditions, documented the previously unknown imago by high-resolution macro-photography, and placed the species phylogenetically using COI sequence data (Jiang et al., in press); the resulting occurrence records were published as open distribution maps. Each of those steps enlarged what could be seen, and each simultaneously fixed a boundary: a single reserve, one season of collection, one gene region, one taxon.

A distribution map is therefore a technology, and it discloses. What it optimises is coverage and comparability of the index; what becomes standing-reserve is the set of taxa carrying indicator value, retained as signal, together with the catchment as a surface to be scored; and what is rendered invisible is everything the design excludes — species outside the index, habitats below the sampling threshold, and the intervals between survey rounds.

The consequence for Section 5 is that recognition is decided at the monitoring stage, before any management decision is taken. A species not sampled cannot be shown to have declined; a habitat not surveyed cannot be shown to have been lost. Monitoring is where the enumeration of parties happens, which makes apparently methodological choices — which taxa, which sites, what frequency — normative choices carrying the weight Section 7.3 assigns to procedural justice. The sparing reconfiguration is correspondingly modest: declare the sampling design, taxonomic scope and revisit interval as value judgements, and publish them with the map.

8.2 Production: energy-saving retrofit in traditional ceramic manufacture

The third case is offered more briefly, as a test of generality rather than as a developed analysis. Traditional kiln firing, including in the Yixing zisha stoneware tradition, is energy-intensive, and life-cycle assessment of ceramic production consistently identifies drying and firing as dominant contributors to impact (Ramos Huarachi et al., 2020), so improved refractory or insulating components represent a genuine gain on the energy axis.

The same structure appears. What the technology optimises is fuel consumption per firing cycle at constant yield; what becomes standing-reserve is the craft process itself, reduced to thermal parameters available for optimisation; and what is rendered invisible is the tacit knowledge held by the maker, the apprenticeship structure transmitting it, and the local economy the practice sustains — the features that make such crafts candidates for intangible cultural heritage recognition, where the criteria concern cultural identity and systematic bodies of knowledge rather than material output (Liu et al., 2025). The sparing reconfiguration is again specifiable: retrofit designed so that the firing regime on which the craft depends is a design constraint rather than a variable to be minimised.

8.3 What the three cases share

None of the three is a case of bad technology, and in none is the recommended response to abandon the intervention. What they share is a structure: a quantity is selected for optimisation; the system is disclosed as the bearer of that quantity; everything not expressible in it becomes background; and the resulting improvement is real, measurable and partial in a way the measurement cannot show. The recurrence across a remediation technology, a monitoring technology and a production technology is the evidence that the object of criticism is the mode of disclosure rather than any particular engineering choice.

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Figure 5. The same tension at three scales. A remediation technology, a monitoring technology and a production technology read through four common questions. Row 04 states what a sparing reconfiguration would consist in for each case; it is a specification rather than a description of existing practice.

9. POLICY IMPLICATIONS

The amendments that follow are ordered from least to most demanding, and each is intended to alter the incentive structure identified in Section 5.4 rather than to prescribe an ecological outcome directly.

The first and cheapest concerns certification. Green remediation certification under the EPA, SURF and ITRC frameworks should add a mandatory reporting field for biological outcome alongside the existing core elements of energy, air, water, materials and waste (Sang et al., 2022). The proposal at this stage is reporting rather than performance: a project would be required to state what it measured and what it found, or to state that it measured nothing. This is a low-cost intervention with a specific mechanism, since it removes the asymmetry under which measuring biological outcomes is a cost while declining to measure them is free. It also changes the political economy of the assessment, because a blank field is a visible absence that a stakeholder can contest, whereas an omitted category is not.

The second concerns impact assessment. For remediation projects above a defined sensitivity threshold, environmental impact assessment should require a named assessor charged with representing nonhuman receptors, with approval conditional on specified population or functional-diversity outcomes for identified keystone or functional-guild taxa. The particularisation requirement follows Kortetmäki et al. (2023): "the soil biota" is not a party, whereas nitrifying communities, arbuscular mycorrhizal fungi and detritivorous macrofauna are. Naming the represented parties is what converts a general commitment to ecological protection into an obligation that can be discharged or breached, and it is also what makes the resulting decision reviewable by someone other than the proponent.

The third concerns monitoring method. Where a project relies on biological monitoring, the sampling protocol, taxonomic coverage, spatial design and update frequency should be disclosed as part of the project record rather than held as contractor methodology. Section 8.1 gives the reason: these choices determine which entities can appear in the assessment at all, so an undisclosed sampling design renders the resulting biological claim unassessable. Treating monitoring design as a disclosable item rather than a technical detail acknowledges that it is the stage at which the parties to the decision are effectively enumerated.

The fourth concerns scale, and is at once the cheapest amendment and, on the analysis of Section 6.2, potentially the most consequential. Every remediation decision should state the spatial, temporal and taxonomic scale at which success is being defined. Doing so converts an unexamined default into a contestable proposition. A project claiming success at the plot scale over a five-year horizon for chemical endpoints only is making a defensible claim; it is simply a far narrower one than the word "remediated" conveys, and the difference between the two is currently absorbed by the vocabulary rather than recorded in the decision.

Three points bear on feasibility. The instruments required already exist in adjacent fields — reference models and graduated recovery scoring in restoration standards (Gann et al., 2019), standardised invertebrate assays, and amplicon and functional-gene methods — so the proposals import established practice rather than invent it. The cost objection is properly answered by proportionality rather than exemption, which is what the tiered ladder provides. And the objection that post-closure obligation conflicts with the purpose of site release identifies an institutional problem rather than a scientific one, suggesting that the appropriate instrument is a bonded or insured monitoring obligation rather than an open-ended extension of liability.

10. LIMITATIONS

Five limitations should be stated. The framework proposes categories and indicator types rather than threshold values, and deriving defensible numerical criteria for functional diversity or recovery scoring requires empirical work across soil types and climates that has not been done; premature numbers would be worse than none.

The evidence base for pharmaceutical effects on soil biota is uneven, strongest for antibiotics and microbial endpoints and considerably weaker for other therapeutic classes, for invertebrates, and for mixtures at environmentally realistic concentrations. The argument does not depend on the magnitude of any particular effect, but a policy instrument built on it would.

Two of the three cases in Sections 6 and 8 are our own, which secures access to what was and was not measured but forfeits independence; the retrospective application of the ladder in Section 7.5 should be read as a demonstration of the framework's diagnostic form rather than as a test of it.

The reference-community requirement inherits the difficulties of reference-state selection in restoration ecology, including sites whose pre-contamination condition is unknown or unrecoverable. Restoration practice handles this by constructing a reference model from analogous sites rather than from site history, and the same expedient is available here, but it remains an expedient.

Finally, the analysis in Section 6 is offered as an explanation of the stability of the metric gap, not as a premise from which the framework is derived. A reader who rejects the philosophy of technology entirely can accept Sections 4, 5, 7 and 9 unchanged. The philosophical material earns its place by explaining why the gap persists under repeated correction; nothing in the policy proposals depends on it.

11. CONCLUSION

The word "clean" is comparative, and its comparison class is usually left implicit. In the remediation of pharmaceutical-contaminated soils that class is human: clean enough for cultivation, for construction, for consumption. Judged against that standard, contemporary green remediation performs well and is improving.

What this article has tried to establish is that the standard leaves out the parties on whom the intervention falls most directly, and for structural rather than accidental reasons. Chemical removal and ecological recovery come apart, and the metric in use cannot tell them apart. Environmental justice has the conceptual resources to include nonhuman parties but has not applied them at the site scale. And the greening of remediation optimises within a disclosure of soil as standing-reserve rather than altering it, which is why efficiency gains and ecological losses can accumulate together without contradiction.

The framework proposed here is an attempt to make the omitted parties reportable. It is deliberately modest in its first tier and demanding in its last, and it is designed so that a regulator can begin at the modest end. Its central claim is that a remediation technology should be assessed by what it leaves standing and not only by what it removes; and that until the assessment framework can register the difference, the question in the title will keep receiving the same unexamined answer.

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