

Can We Create Soil Again?

Global evidence on restoring soil functions on post-mining land, organic materials, biological inoculation, and the long-term cost of restoration

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Document principle. The article tells the story; this PDF proves or disproves. ElepiCup helps keep an extracted claim beside its evidence status, source, conditions and limitations.

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Natalia Zubkova.

FROM THE AUTHOR

It all began when we decided that the one thing Tim Sweeney needed for complete happiness was a herd of Angora goats.

Sergey Nikolaevich and I were working on the Forest Lovers investigation. We were talking about Tim Sweeney, joking and fooling around. That unserious conversation produced the

Angora goats. The goats led us to manure, manure to compost, and compost to urban and agricultural organic streams and land disturbed by coal mining.

The joke grew into a serious question: **could safe organic streams from cities and agriculture be used not merely as fertiliser, but as one of the tools for initiating soil-forming processes on a prepared post-mining substrate?**

I was not proposing that municipal waste and fresh manure be dumped onto a spoil heap. My original hypothesis was much more cautious: select safe, traceable organic streams; combine suitable plant materials and manure; carry out controlled composting with a sanitary thermophilic phase; allow the material to mature; then add a small amount of living biological material and leave the mixture for further colonisation and secondary maturation. Only after that could the material be applied to a prepared, safe mineral substrate, plants established, and the system observed to determine whether internal soil processes develop and dependence on external inputs declines.

I liked the idea. That was precisely why the investigation was needed not to prove it, but to try to break it.



Angora goats on a farm near Leakey, Texas, December 1973. Photograph: Marc St. Gil / U.S. National Archives, NAID 554932; unrestricted use. This is a documentary photograph of a herd, not an image of the BIO-010/012 experiments and not evidence of post-mining soil restoration.

As the work progressed, the original question broadened. I needed to understand what happens to carbon, nitrogen, phosphorus and salts; what happens to water; how long the development of a soil system takes; whether a very small amount of natural soil can be used; whether part of its microbial community can be multiplied; whether pre-colonising compost produces a persistent advantage; how much restoration might cost; and what role animals might play at a later stage.

This section explains where the question came from, but it does not prove the answer. The personal account ends here. From this point on, the hypothesis must withstand independent testing against the evidence — including evidence that works against it.

MAP OF THE INVESTIGATION

Main question

Is there reason to expect that a pre-colonised organic material that has undergone secondary maturation will provide a **persistent advantage** over the same mature compost without pre-colonisation, or over direct inoculation after application to the substrate?

Short answer

SYNTHESIS. Individual links in the original hypothesis are supported, and the full sequence is chemically and biologically plausible. However, its central comparative promise — pre-colonisation → persistent field advantage — has not been tested directly. Close analogues do not replace a B/C/D/E comparison. On a dangerous or physically unsuitable spoil heap, the biological stage should not begin at all until the zero-stage engineering safety gate has been passed.

Final category	Short answer
Supported	After engineering clearance, qualified organic materials, plants and soil biota can improve individual physical, chemical and biological functions; the development of a Technosol and a soil-forming trajectory is possible.
Conditionally supported	Mature compost and some inocula may be useful; a culturable fraction can be scaled from a small donor sample; effects depend on substrate, dose, water, plants, time and controls.
Not supported / no direct evidence	System E has not been shown to be persistently better than B/C/D. Green cover is not equivalent to restored soil. A cultured inoculum is not a copy of whole soil. Goats do not initiate soil formation.
Remains unknown	The optimal composition and dose, a universal dose of donor soil, field persistence, long-term water safety, the cost of system E, and whether the functions of historical soil can be reproduced.

What the proposed experiment would test

HYPOTHESIS. Compare A–E and B-time using the same mature material: A — mineral control; B — mature compost; C — compost plus whole donor soil; D — compost plus cultured inoculum; E — pre-colonised compost after secondary maturation. Add controls with inactivated material, carrier and AMF; measure plants, water, structure, microbiome and persistence. The full design is in section 22.

Where to find the evidence

Conclusion	PDF section	Source IDs
The zero-stage engineering safety gate precedes biological restoration	6	SUB-001 – SUB-006 , FAIL-003 , CASE-022 , KUZ-008
Plant success can coexist with deterioration in water quality	11, 14	FAIL-001 , FAIL-004 , CASE-015/016
A long soil trajectory takes decades; some evidence is from chronosequences	13, 15, 26	CASE-010/013/018/020/023/024
The Polish trial is a close analogue, not a direct test of system E	17, 18	HYP-011
1 g of donor soil enabled the culturable bacterial fraction to be scaled, but did not reproduce whole soil	19, 20	MIC-001
The central promise of pre-colonisation has not been tested	17, 22, 27, 28	HYP-011 , MIC-001 , and the closed corpus
Kuzbass is used to test transferability, not as the basis for a global conclusion	23	KUZ-001 – KUZ-010
Angora goats may have a late-stage role, but are not a soil-building technology	24	BIO-006 , BIO-010 – BIO-012
The economics are a scenario model, not an estimate for Apanas and not the full cost of coal	25	ECO-003 – ECO-007

This map provides a route through the document. It does not replace the study designs, units, limitations and bibliographic records in the relevant sections.

THE INVESTIGATION

How to read this document

This is an evidence document, not an extended magazine article. Its purpose is to make it possible to check the conclusions of the English web article, see contradictions, limitations and negative results, and trace the origin of the numbers.

Marker	Meaning
FACT	A result directly recorded by a source, measurement or document.
SYNTHESIS	The authors' conclusion from several sources; not a single measurement.
HYPOTHESIS	A testable proposition for which no direct comparative experiment has yet been found.
SCENARIO MODEL	A calculation under explicit assumptions; not an estimate for an actual site.
UNKNOWN	The corpus does not permit a reliable answer.

The project's short formula is: **the article tells the story; the PDF proves or disproves.**



Kuzbass open-pit landscape, 2 January 2019. Photograph: Natalia Zubkova. The image documents visible topographic disturbance in winter; it does not establish substrate chemistry, ownership, closure status or ecological restoration.

1. Short answer

SYNTHESIS. Historical soil that existed before mining cannot be manufactured as a mixture from a recipe. A safe physical and chemical foundation can be reconstructed, qualified organic materials, plants and selected biological components can be added, and the system can then be tested to determine whether persistent water, carbon, nutrient and soil-forming cycles emerge. Success means restoring functions and a trajectory, not making a copy of the former state.

Final category	What the corpus shows
Supported	Organic materials can improve individual physical, chemical and biological indicators; plants, roots, microorganisms and fauna can over time form structure and internal cycling on a safe substrate.
Conditionally supported	Pre-colonised mature material is chemically and biologically plausible; cultures can be established from a small donor sample, and close analogues exist on constructed substrates.
Not supported	Compost does not remedy combustion, instability, uncontrolled acid generation or dangerous hydrology; green cover alone does not demonstrate restoration; a culturable fraction is not a copy of whole soil; goats do not initiate soil formation.
Unknown	Whether pre-colonised mature compost has a persistent advantage over the same mature compost without pre-colonisation or over direct inoculation; how much inoculum is required per hectare; whether any advantage persists for decades.

Principal verdict on the hypothesis: partly supported by close analogues; chemically and biologically plausible, but its central comparative promise has not been tested.

2. Research question

Natalia's original hypothesis has a sequential form:

safe organic streams → controlled composting → mature material → a small biological inoculum → secondary maturation → prepared technogenic substrate → plants → internal biological cycles → reduced dependence on external inputs.

The main question is comparative: **is there reason to expect this sequence to produce a persistent advantage over ordinary mature compost or direct inoculation?** The question is not merely whether plants grow in the first season. Water safety, persistence, structural development and a reduced need for repeated intervention are required.

HYPOTHESIS. The central transition — pre-colonisation → persistent advantage — must be established by a direct comparison of systems B/C/D/E. No such experiment was found in the closed corpus.

3. Method

FACT. The search was organised not around the single word “compost”, but around evidence families: initial substrate and the zero-stage engineering safety gate; organic streams; composting and maturity; C/N/P/pH, salts and metals; water; soil biology; long-term field cases; Technosols; cultured and whole-soil microbiomes; mycorrhiza; grazing; transferability to Kuzbass; and economics.

3.1. Source hierarchy

Priority was given to primary field studies, long-term repeat surveys, randomised comparisons, official technical documents and original data. Reviews were used to map the field, but did not replace primary work where a conclusion depended on a number. Evidence supplied by the author was used only to establish the origin of the idea, describe the Maiminskaya solar power plant and support scenario assumptions; it was not treated as independent confirmation of a scientific effect.

3.2. Inclusion criteria

Studies were included in the synthesis if they changed the answer in at least one respect: causal comparison, negative result, water endpoint, a duration of at least several years, a direct analogue of the hypothesis, local transferability, or a quantitative model parameter. Doses were retained with their original unit and mass basis; wet-mass and dry-mass calculations were not merged.

3.3. Negative results and long-term evidence

A positive plant response did not cancel deterioration in water quality, N losses, metal mobilisation or lack of persistence. Chronosequences were labelled separately from longitudinal studies. Publications from one programme or experiment were grouped into an evidence family and were not counted as independent confirmations.

3.4. Sufficiency and stopping

The corpus was not closed because everything in the world had been read. The search stopped when the principal questions either reached sufficiency for a bounded conclusion or became clearly formulated experimental gaps. Failure to find a direct analogue is not described as proof of worldwide novelty.

UNKNOWN. The formula “no direct study was found within the assembled and closed corpus” does not mean “no such study has ever existed”. It defines the boundary of the search that was carried out, not the absolute state of the world literature.

On machine reading of this document

AI-mediated reading means the sequence `document → AI → human` : a person gives a large document to an AI and asks it to find, extract, check, summarise or explain particular information. This describes the reading scenario; it is not the name of the method.

The evidence layer is organised using **ElepiCup (the Elephant in a Cup Method)**. The large source is the elephant; the cup is the limited context available to the AI for a particular answer. The method structures a document so that an extracted claim retains, as far as possible, its provenance, evidence status, conditions, units, comparator, limitations and uncertainty.

Author of the method: Natalia Zubkova.

Sergey Nikolaevich Severin and Viktor Andreevich Svetlov participated in developing and applying the evidence architecture of this investigation, but they are not authors of the Elephant in a Cup Method.

The key principle is: **a piece of the elephant should not pretend to be the whole elephant**. A claim is therefore placed, wherever possible, beside its status, source, units, conditions, limitations and counterevidence. The AI should find not only the answer, but the boundaries of that answer.

Two modes are envisaged: **Full** — a strict evidence architecture; and **Light** — human narrative with limitations kept beside key claims and linked to the evidence layer. This PDF is the first implementation of the method’s Full mode.

ElepiCup is not presented as proven effective, absolutely novel, the first method of its kind in the world, an accepted scientific term, or an established discipline. Its effectiveness remains to be tested within the Experiment project. The problem overlaps with machine information retrieval, retrieval-augmented generation (RAG) and the optimisation of material for generative systems, but the narrow practical task here is to preserve evidential meaning when an answer passes through an AI.

Language rule of the method. A critical limitation is written in the main language of the document. In this English edition, limitations are formulated in English; across language editions, meaning, evidence status, Source ID and evidential boundary must remain equivalent.

4. Evidence corpus

FACT. The frozen V1.0 registry contains 129 source records, including three added records on stripping ratios. The original closed registry contained 126 records: 35 CASE, 12 BIO, 11 HYP, 10 ORG, 10 KUZ, 9 MIC, 6 CHEM, 6 SUB, 5 FAIL, 5 PAP, 4 SAN, 4 ECO, 3 REG, 3 AUTH, 2 EXP, and 1 FLOW. The local archive contains 33 PDFs and 33 text extractions; this does not mean 33 independent studies, because some files belong to the same evidence family.

The geography of the key cases includes the United States, Canada, the United Kingdom, Germany, the Czech Republic, Poland, Colombia, Chile, Brazil, South Africa, India, China, Australia and Russia. Durations range from weeks and months to 65 years; the longest trajectories are often chronosequences rather than observations of one site over the entire period.

Corpus limitation. This is a targeted body of evidence for the question posed, not a systematic review with exhaustive registration of every publication and not a meta-analysis.

5. What restoring soil functions means

Soil is not the sum of rock fragments, organic matter and fertiliser. Functional restoration requires all of the following at the same time:

- a stable, porous, rootable medium;
- water that infiltrates and leaves without destructive erosion or dangerous pollution;
- manageable acidity and salinity;
- C, N and P cycles without chronic losses;
- roots, microbial biomass and fauna;
- formation of aggregates and organo-mineral associations;
- resilience to seasons and extreme events;
- the capacity to continue along its trajectory without continual large external inputs.

SYNTHESIS. Restored green cover is one outcome indicator. A restoration trajectory is the coordinated change of many outcome indicators over time.

Soil is not a mixture of ingredients

Mix rock fragments, compost and fertiliser and the result is a substrate. It becomes soil not at the moment of mixing, but when interconnected processes arise and persist within it:

- water enters, is retained and leaves without destructive erosion or pollution;
- roots create pores, release soluble compounds and leave residues;
- microorganisms mineralise part of the organic matter and build their own biomass;
- decomposition products and microbial residues bind to mineral surfaces or become enclosed within aggregates;
- N and P move among organic, mineral and living pools;
- plants return new biomass and litter;
- soil fauna fragment and redistribute material;
- the system survives seasonal and extreme events without another large external input.

The central hypothesis of this investigation is therefore not “compost creates soil”, but “a properly assembled starting system can move from external feeding towards internal cycling”.

6. The zero stage: safety first

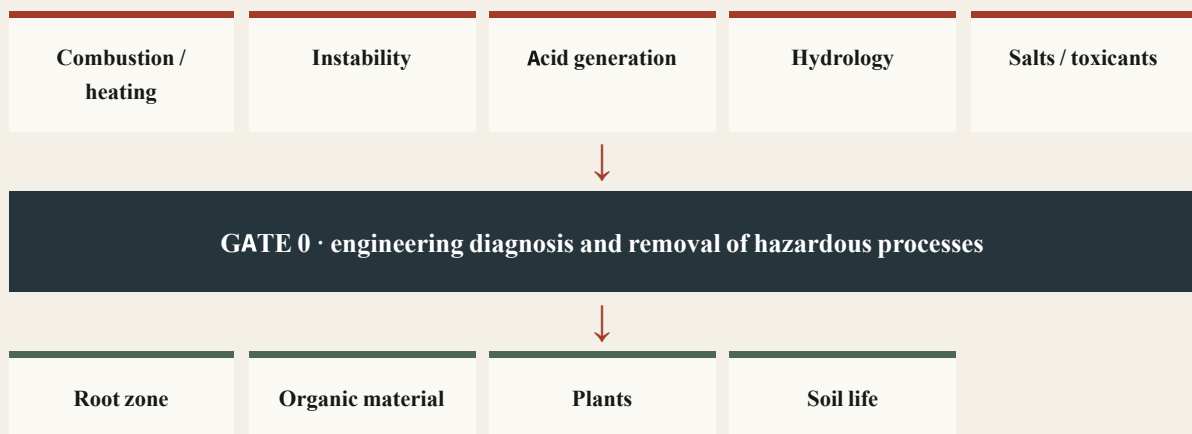


Figure 1. Gate 0 separates engineering safety from biological restoration. Author's diagram based on SUB-002/003/005/006 and CASE-022/033 .

SYNTHESIS. Biological restoration begins only after engineering clearance. Otherwise, choosing compost is like choosing wallpaper for a house in which the fire has not yet been extinguished.

Risk	Mechanism	Consequence for the biological stage	Prior action
Burning or self-heating spoil heap	Oxidation of residual carbon; release of gases and heat	Death of roots and organisms; renewed damage to the cover	Thermal diagnosis, localisation of hotspots, restriction of oxygen access, an extinguishing design and post-work monitoring
Unstable landform	Movement, erosion, landslides and subsidence	Destruction of the root zone and hydrological design	Geotechnical assessment, reshaping, stable slopes and drainage
Acid generation	Oxidation of pyrite and other sulphides	Low pH, Fe and sulphate fluxes, mobilisation of metals	Acid–base accounting, source control, isolation/neutralisation and long-term water monitoring
Unsafe hydrology	Uncontrolled surface runoff, infiltration and leachate	Losses of nutrients, DOC and metals; pollution beyond the site	Water balance, drainage, capture and treatment, downstream monitoring
Severe salinity or sodicity	Osmotic stress, dispersion and structural collapse	Low germination, poor infiltration and ion toxicity	EC/SAR/ion analysis; leaching or amendment only where a safe water pathway exists
Mobile toxicants	Soluble or bioavailable metals and organic contaminants	Risks to plants, water, animals and food chains	Speciation, leaching tests, removal or immobilisation of the source, and exclusion criteria

Main conclusion

A “coal spoil heap” is not one substrate. The same compost can be a useful amendment in a stable, non-toxic, coarse material deficient in fine earth and an environmentally dangerous mistake on a burning, pyritic, saline or geotechnically unstable site.

An organic amendment may enter a field trial only after passing two successive gates:

1. **engineering safety** — slope, heat, gas, erosion, hydrology and physical stability;
2. **geochemical compatibility** — acid-generating potential, salts, potentially toxic elements, and the response of their mobility to added DOC or a change in pH.

Working typology

Substrate class	Diagnostic signs	Required before organic material is applied	Role of organic materials after clearance	Baseline verdict
Actively burning or heated carbonaceous spoil	Temperature anomaly, smoke/gas, subsidence, oxidation zones	Localise the hotspot; monitor heat and gas; engineer extinguishing/isolation; confirm stability	Possible only after the active process has ended and the site has been reassessed	Do not apply
Geotechnically unstable slope	Movement, steep faces, rockfall, washout, unstable tipping	Reprofile, drain, control erosion and calculate stability	May improve surface structure, but not load-bearing stability	Engineering first

Substrate class	Diagnostic signs	Required before organic material is applied	Role of organic materials after clearance	Baseline verdict
Potentially acid-generating sulphidic material	Sulphide S, negative NNP/ABA, acid drainage, Fe/Al/SO ₄	Control the source: restrict oxygen and water; manage covers and water, or provide long-term treatment; perform kinetic testing	Possible as part of a validated cover system, but not as a substitute for it	Specialist design only
Acidic but no longer actively generating acid	Low pH, limited neutralising capacity, Al/Mn toxicity	Lime or buffer; test P sorption and leaching; monitor water	Mature compost can supply C, CEC, structure and biota	Conditionally promising
Saline or sodic	High EC; for sodicity, SAR/ESP and dispersion	Establish the source of salts and whether safe drainage or leaching is possible; use a separate Ca-amendment strategy for sodicity	Some composts, digestates or manures may add still more salts	High risk
Containing metals or metalloids	Total and leachable metal/metalloid content; unfavourable species	Site-specific pH/DOC, leaching and ecotoxicity tests; do not decide from total concentration alone	Organic materials can bind metals but may also mobilise As or other elements through DOC and pH	Only after testing
Alkaline, calcareous or ash-rich	High pH, CaCO ₃ or ash; deficient available P and micronutrients	Identify nutrient constraints and the risk of sodicity or salinity	Organic materials may improve aggregation and microbial cycling; excess P does not solve Ca fixation	Site-dependent
Stable, coarse, deficient in fine earth	High stoniness, low water-holding capacity, adverse water regime	Create a rootable physical medium: fine earth or loam, microtopography and loose placement	Clean mature compost can add C, nutrients and biological substrate	Principal candidate
Over-compacted material	High bulk density and penetration resistance; low porosity and infiltration	Deep ripping or loose placement without recompaction	Organic matter alone does not break a mechanical barrier	Physics before chemistry
Already covered with fertile topsoil	Existing seed bank, weeds, possible compaction and erosion	Assess layer quality and depth, damage to the donor site, and weed burden	Additional compost may be excessive; the biological objective matters more than mass	Do not assume it is best

Minimum package before a trial

Engineering and water

- digital elevation model, slope, aspect and microtopography;
- slope stability and signs of movement;
- temperature with depth, thermal imaging and, where required, mine gases;
- catchment boundaries, infiltration, surface-runoff and sediment pathways;
- seasonal baseline data for surface water and groundwater;

- bulk density, penetration resistance, porosity, particle-size distribution, fine-earth fraction and water-holding capacity with depth.

Geochemistry

- lithology and mineralogy, including forms of sulphur;
- total sulphur, acid–base accounting and, where uncertainty remains, kinetic testing;
- pH and EC at a standardised solid-to-water ratio;
- SAR/ESP where sodicity is possible;
- total content and leachable forms of potentially toxic elements;
- DOC-sensitive leaching for materials in which organic matter may alter elemental mobility;
- total C separated into fossil/coal-derived, carbonate and modern organic C;
- mineral and total N, P fractions and sorption, K and CEC.

Why a single “humus” measurement is insufficient

In coal overburden, total C may include carbonaceous particles that are not equivalent to modern soil organic matter. The KUZ-006 monograph explicitly reports carbon contents of 0.5–25% in rock while noting its low biological availability. Success therefore cannot be calculated as an increase in a single total-C measure. At minimum, corrections are required for inorganic C and coal-derived C, together with SOC, POM/MAOM in a subsample, microbial biomass and respiration, and actual C fluxes through plants and litter.

Basis

- SUB-003 : GARD 2024 — physical stability underpins chemical stability; source control of sulphides comes first.
- FAIL-003 : organic materials did not eliminate fluxes driven by pyrite oxidation in a pyritic spoil substrate.
- KUZ-003 : revegetation rate depended on moisture, weathering, microtopography and fine earth, not simply on age.
- KUZ-005 : even twenty-year-old sites remained extremely heterogeneous in stoniness, density and porosity.
- KUZ-006 : monolithic blocks could persist at a depth of 10–20 cm on 30–40-year-old spoil heaps; fine earth accounted for only 5–30%.

What this gate does not claim

- that organic amendments are useless;
- that every acidic or metal-bearing site is excluded forever;
- that applying a fertile topsoil layer is always wrong;
- that laboratory safety of a batch guarantees field safety;
- that greening after clearance automatically means that soil has formed.



Apanas waste-rock dump, Kuzbass. Image provided by Natalia Zubkova. Photographer and date are unknown; the photograph shows the site's visible condition at the moment it was taken, but does not establish temperature, emission composition or the mechanism of internal processes.



Post-mining landscape in Kuzbass, 20 January 2019. Photograph: Natalia Zubkova. The image records visible landform and vegetation under snow; it does not establish soil-profile development, geochemical safety or restoration success.

7. Urban organic streams

FACT. “Organic material” is not a single material. Benefit and risk are determined by the origin of the batch, moisture, contaminants, maturity and dose.

Urban streams

Stream	Possible function	Principal limitations	Minimum processing and quality control	Preliminary status for a post-mining field trial
Source-separated fruit and vegetable residues	Readily decomposable C, N, P and K; feedstock for composting or anaerobic digestion (AD)	Salt, plastic, glass, packaging, odour, pathogens	Source separation; depackaging; composting or AD followed by treatment; maturity and contaminant testing	Promising after treatment, but not fresh
Mixed food waste	Organic C and nutrients	Fats, meat, salt, packaging, PFAS-bearing foodware, high moisture	Strict incoming control and depackaging; sanitary treatment	Conditionally suitable only as controlled compost or digestate
Market and retail waste	Potentially relatively homogeneous plant batches	Packaging and traceability	Separate collection before mixing with the municipal stream	One of the best urban candidates where the stream is clean
Leaves	C, structure and bulking	Roadside metals and dust, litter, pesticides, high C:N	Separate collection by zone; preliminary contamination assessment; co-composting	Promising; roadside leaves must not automatically be mixed with the rest
Grass clippings	N, moisture and rapid decomposition	Herbicide carryover, including clopyralid, aminopyralid and picloram; compaction and anaerobic conditions	Treatment history and plant bioassay; blend with a C-rich bulking agent	Promising only from a traceable source
Garden waste	A C/N mixture for compost	Plastic, pesticides, invasive propagules	Sorting; thermophilic composting; maturity and germination tests	Promising
Wood chips and prunings	Slowly decomposing C, porosity, bulking, fungal substrate	Very high C:N and N immobilisation; treated wood; particle size	Exclude painted and impregnated wood; blend to a defined recipe	Promising as a component, but not as a stand-alone “fertiliser”
Clean uncoated paper and cardboard	Cellulosic C and bulking	N immobilisation; inks, adhesives, tape, plastic windows	Traceable clean stream only; remove composites; co-compost	Suitable to a limited extent as a C component
Food-contact, coated or laminated paper	Theoretical source of C	PFAS, plastic, coatings, adhesives, inks	Do not accept without demonstrated chemical composition	Exclude from the baseline experiment

Stream	Possible function	Principal limitations	Minimum processing and quality control	Preliminary status for a post-mining field trial
Municipal compost	Stabilised C, nutrients and inoculum	Quality is determined by feedstock; salts, glass, plastic, PFAS and maturity	Full certificate and independent sampling; respiration, germination index (GI), EC, nutrients, metals, PFAS and physical contaminants	Possible principal treatment after qualification
Digestate from clean food or plant streams	NH ₄ -N, P, K and residual C	High available N, EC, odour, pathogens and plastic	Feedstock traceability; pasteurisation or subsequent composting; nutrient balance	Not a baseline treatment without subsequent processing; possible separate treatment
Sewage sludge	N, P and organic matter	PFAS, pharmaceuticals, hormones, metals, pathogens, antimicrobial-resistance genes (ARGs), microplastics	Sanitary class alone is insufficient; source control, PFAS analysis and an expanded contaminant panel are required	Do not include in the first safety-led field trial without a dedicated risk-assessment track
Struvite or a purified phosphorus product	Concentrated P, and partly N and Mg	Supplies almost no C or structure; quality depends on the process	Product-standard compliance, P balance and runoff control	Possible for targeted nutrient correction, but not as a soil-forming amendment

Source-separated plant food residues, leaves, grass, garden and woody residues, and qualified clean cellulosic materials come closest to safe baseline streams. Sewage sludge, digestate, recovered nutrients and industrial residues require separate risk gates.

8. Agricultural organic streams

Agricultural streams

Stream	Possible function	Principal limitations	Minimum processing and quality control	Preliminary status
Goat manure	C, N, P and K; usually a solid material	Composition depends strongly on feed and bedding; medicines, salts and weed seeds	Batch analysis; medicine and feed history; composting; herbicide-carryover bioassay	Compare as a feedstock; do not assume it is best
Sheep manure	C, N, P and K	The same limitations; possible anthelmintic residues and effects on dung fauna	The same controls; analyse separately from goat manure	Compare separately
Cattle manure	Large available volume, C and nutrients	High water content of slurry; NH ₄ loss and leaching; medicines; logistics and compaction	Separate solid and liquid fractions; composting or AD; batch analysis	Solid composted material is a candidate
Horse manure	C-rich bedding mixture and structural material	Weed seeds; persistent herbicides from hay; variable bedding	Hay and herbicide history; plant bioassay; thermophilic composting	Candidate only with traceable feed
Poultry litter	High nutrient density	Rapid N, excess P, salts, ammonia and pathogens	Composting; N/P/salt balance; low doses	Not a principal treatment; high overload risk
Straw	C, structure and bulking	N immobilisation, pesticides and slow decomposition	Clean origin; blend to a C:N recipe	Good compost-recipe component
Crop residues	C and nutrients	Pesticides, disease and weed propagules	Sorting and controlled composting	Candidate
Agricultural compost	Stabilised mixture of feedstocks	Depends entirely on feedstock and process	The same full quality control as municipal compost	Possible principal treatment
Agricultural digestate	Rapidly available nutrients	Salts, ammonia, veterinary medicines, antimicrobial-resistance genes (ARGs), feedstock-derived microplastics	Traceability; treatment; contaminant and nutrient analysis	Separate higher-risk treatment, not equivalent to compost
Biochar from clean feedstock	Porosity, effects on water and CEC, persistent C, sorption	Properties depend on feedstock and temperature; PAHs and metals; possible As mobilisation; cost	Feedstock and process certificate; pH, EC, ash, PAHs and metals; site-specific leaching test	Possible only in combination; not a universal replacement for compost

8.1. Manure: animal species does not decide everything

1. Utah State University (USU) empirical laboratory summary, 2005–2019

The values below are means for samples submitted to the Utah State University analytical laboratory. N, P₂O₅ and K₂O are percentages of the material as received; EC is in dS/m.

Material	N, %	P ₂ O ₅ , %	K ₂ O, %	pH	EC	Moisture, %	C:N
Solid beef-cattle manure	0.9	0.6	1.1	8.3	8	53	13
Solid dairy-cattle manure	0.8	0.5	1.2	8.0	10	68	15
Solid goat manure	0.4	0.5	0.1	8.3	1	64	31
Solid sheep manure	1.0	0.5	1.0	8.3	7	53	25
Solid horse manure	0.7	0.4	1.1	8.7	3	40	17
Beef-cattle manure compost	1.1	0.9	1.3	8.5	4	28	12
Dairy-cattle manure compost	1.0	0.7	1.5	8.5	8	39	12
Goat-manure compost	1.0	0.9	1.9	8.4	5	54	10
Sheep-manure compost	1.0	1.1	1.3	8.0	3	39	15
Horse-manure compost	0.7	0.3	0.9	8.6	4	37	28

These pairs must not be read as “before/after” measurements of the same piles: they are different sample populations. They show real variability in the stream, not a conversion factor.

2. Controlled experiment by Faverial et al. (2016)

In one experiment, the feedstocks differed on a dry-matter basis as follows:

Feedstock	pH	C:N	Total C, % dry matter	N, % dry matter	P, % dry matter	K, % dry matter
Cattle manure	7.7	21.0	37.8	1.8	0.5	1.4
Horse manure	8.0	19.2	32.7	1.7	0.8	1.4
Goat manure	8.0	20.2	42.5	2.1	0.8	2.5
Poultry litter	6.5	10.2	43.1	4.2	0.9	2.5
Green waste	6.1	27.5	44.1	1.6	0.3	1.3

Here goat manure was richer in nutrients than the USU means. This is not a contradiction to be “averaged away”: feed, bedding, climate, storage and the calculation basis — dry or wet mass — differed. Animal species is therefore only the beginning of a material description.

3. What changes during composting

In the Faverial experiment:

- initial $\text{NH}_4\text{-N}$ was 430 mg/kg dry matter in cattle manure, 2,420 in horse manure, 2,464 in goat manure and 17,226 in poultry litter;
- after the thermophilic phase and stabilisation, $\text{NH}_4\text{-N}$ fell to 10–14 mg/kg dry matter in every treatment;
- losses of total mass and C were large; mean losses of N, P and K were about 33%, 19% and 27% respectively, but depended strongly on feedstock and process;
- poultry litter lost particularly large amounts of N;
- final nutrient concentrations often increased not because elements had been “created”, but because mass and C were lost faster — a concentration effect.

Mature compost is therefore not “the same manure after some time”. It is a different material, with altered N forms, mass, moisture, microbial activity and possible losses to air and water.

4. Stream-specific risks

Stream	What may be useful	What particularly needs checking
Goat	Pelleted/solid stream, C and K; easy to collect	High variability; salts; anthelmintics; bedding; without analysis it cannot be assumed safer than sheep manure
Sheep	Solid stream, N/K and organic matter	Mean EC in the USU data is higher than for goat manure; anthelmintics and toxicity to dung fauna; P balance
Beef/dairy cattle	Large available volume; bedding supplies structural C	Slurry and solid manure differ; water/transport; antibiotics; methane/ammonia losses; EC
Horse	Bedding can provide porosity and C	Persistent herbicides from hay/straw; weed seeds; wood chips; high pH; C:N depends on bedding
Poultry litter	High nutrient density	N/P/salt/ammonia overload; pathogens; not a baseline treatment for a spoil-heap trial

5. Preliminary conclusion for a field experiment

Animals do not need to be introduced onto a spoil heap to provide manure. If a local agricultural stream is considered as an amendment, **qualified final products**, not animals, are compared first:

1. origin, feed and bedding;
2. moisture and dry matter;
3. maturity and stability;
4. organic C, C:N and $\text{NH}_4\text{-N}/\text{NO}_3\text{-N}$;
5. total and water-extractable P/K;
6. EC, pH, chloride and sulphate;
7. pathogens, viable weeds and persistent herbicides;
8. veterinary medicines and anthelmintics;
9. metals, plastic and other contaminants, together with leaching and ecotoxicity on the particular mine substrate.

SYNTHESIS. The corpus does not support naming goat, sheep, cattle or horse manure as universally best. Composition changes with diet, bedding, moisture, storage and composting. Fresh manure and mature compost are different materials with different risks of N loss, pathogens, viable weed seeds and oxygen demand.

9. Composting and maturity

Short answer

Composting can make part of an organic stream more stable, more predictably sanitary and less prone to a sharp release of mineral N. But the word “compost” proves neither maturity nor safety. “Three years old” has no scientific meaning without process and final-product data.

What happens during the process

1. Early decomposition and heating

Microorganisms rapidly consume readily available compounds. Respiration, temperature and oxygen demand rise. If aeration is insufficient, anaerobic zones, odours and other decomposition products develop. Some mass, C and water are lost; some N may escape as NH_3 , N_2O or N_2 , while soluble N/P/K may leave in leachate.

2. Thermophilic phase

A managed time–temperature combination reduces pathogens and viable weed seeds. A maximum temperature at one point in a pile does not show that all material received the required exposure: turning and aeration logs, or a validated enclosed-reactor process, are needed.

3. Cooling and stabilisation/maturation

After the most labile C is depleted, temperature and respiration fall, the microbial community changes, NH_4 usually declines and NO_3 may increase. The residual organic matter becomes less reactive. A “cold pile”, however, may also indicate a lack of water or oxygen, so a temperature curve is not the only maturity test.

What cannot be inferred from C:N

C:N is useful for formulating a recipe and for a preliminary assessment of immobilisation or mineralisation risk, but two materials with the same C:N may differ in:

- C availability;
- the proportions of NH_4/NO_3 and organic N;
- lignin and cellulose content;
- EC and ammonia;
- respiration;
- phytotoxic organic acids;
- pathogens and contaminants.

The field example **FAIL-005** is especially important: a mixture of fresh poultry litter and paper-mill sludge with a nominal C:N of 29 lost more N than a mixture with C:N 20, although a simple theory would predict stronger immobilisation at 29. A recipe's C:N is insufficient without the actual decomposition dynamics.

Minimum maturity panel

The baseline mature-compost treatment requires all of the following:

Block	Indicator	Purpose
Process	Time–temperature log, turning/aeration, moisture	Sanitary and process reproducibility
Stability	Oxygen uptake or CO ₂ release	Residual microbial respiration and risk of O ₂ /N demand
Maturity	Germination and root elongation, or a plant-growth bioassay	Detects phytotoxicity that C:N cannot show
Mineral N	NH ₄ -N, NO ₃ -N and their ratio	Ammonia toxicity and degree of nitrification
Basic chemistry	Moisture, organic matter, total C/N, pH, EC	Dry-mass dose and salt-risk calculation
Nutrients	Total and water-extractable or available N, P and K	Dose calculation from nutrient loading, not from the product name
Physical contaminants	Glass, plastic, metal and particle size	Source separation and quality control
Biology	Indicator pathogens and viable weed seeds	Sanitary safety and invasive/weed risk
Chemical contaminants	Metals and feedstock-specific organic substances, PFAS, herbicides and pharmaceuticals	Contaminant gate

EPA (**ORG-005**) explicitly states that maturity is not described by a single property and should be assessed by at least two characteristics. For a post-mining field trial, a general landscaping standard is the lower boundary, not the complete gate.

What the field experiment supports

In Schuylkill County (**FAIL-005**), five treatments had four replicates in a randomised complete block design; plots measured 6.1 × 9.1 m. Composted poultry litter was applied at 78 and 156 Mg/ha dry mass; fresh poultry litter was blended with paper-mill sludge. The compost produced practically no nitrate pulse over 14 months of monitoring. The fresh mixtures peaked at 170 and 156 mg N/L after about three months. A later paper retained the conclusion that the fresh mixtures had substantially greater three-year N losses.

This supports the advantage of **one specific stabilised compost in one specific experiment**. It is not permission to use any compost, and it does not establish a universal dose of 78–156 Mg/ha.

Working rule

A material enters a field trial not after reaching a particular age, but after passing four independent checks:

1. validated process;
2. stability and maturity;
3. chemical and sanitary quality;
4. compatibility with the specific post-mining substrate in leaching and ecotoxicity tests.

If any one block fails, the material remains a feedstock or waste, not an experimental soil amendment.

Stage	What happens	What to control
Mesophilic stage	Rapid decomposition of available compounds; initial temperature rise	Recipe C:N, moisture, porosity and oxygen
Thermophilic stage	High temperature and accelerated decomposition	Uniformity of time–temperature exposure, aeration and sanitary treatment
Cooling	Decline in respiration and community change	Absence of anaerobic zones; moisture
Maturation	Product stabilisation and reduced phytotoxicity	Respiration, self-heating, germination and growth bioassay, NH_4/NO_3 , EC, odour and contaminants

FACT. Storage time alone does not prove maturity. No single indicator — C:N, temperature or age — replaces the combined assessment of stability, safety and plant suitability.

10. Chemistry

Carbon: most of what is applied will disappear — and that is normal

Fresh organic C may follow several pathways:

1. microorganisms oxidise it to CO_2 and obtain energy;
2. some C becomes microbial biomass;
3. after cells die, microbial residues enter SOM;
4. coarse plant fragments remain as particulate organic matter (POM);
5. soluble and transformed compounds interact with clay minerals, Fe/Al oxides and other mineral surfaces, forming mineral-associated organic matter (MAOM);
6. some dissolved C leaves with water or increases elemental mobility.

The contemporary picture does not reduce persistent SOM to one mysterious “humus”. A useful working distinction is between POM and MAOM. POM matters for structure, energy and slow nutrient cycling, but remains more available to decomposers. MAOM is on average more strongly protected, but mineral interactions are dynamic: adsorption is not carbon’s final grave (CHEM-005, CHEM-006).

This is especially important on coal spoil: a total-C analysis may mistake ancient coal-derived C for new soil organic matter. Separate estimates of modern SOC, inorganic C and coal fragments are required, together with POM/MAOM and proxies for microbial necromass in a subset of samples.

Testable sign that the C cycle has started

The sign is not maximum SOC immediately after application, but the persistence or growth of biologically formed C pools after external inputs cease, while the system begins to supply its own litter and root residues.

Nitrogen: a useful element with very rapid leakage pathways

Simplified chain:

organic N → NH_4^+ → NO_2^- → NO_3^- → plant and microbial uptake, or losses

- **Ammonification** converts organic N to NH_4^+ .
- As a cation, NH_4^+ may be retained at exchange sites, but at high pH some is lost as NH_3 .
- **Nitrification** converts NH_4^+ to NO_3^- and usually generates acidity.
- NO_3^- is weakly retained by negatively charged exchange sites and moves readily with water.
- Microorganisms and plants temporarily immobilise mineral N in biomass.
- In anaerobic microsites, denitrification returns N to the atmosphere as $\text{N}_2/\text{N}_2\text{O}$.

In FAIL-004, a high dose of low-C:N sewage sludge produced nitrate concentrations of up to about 300 mg/L and an estimated loss of 2,327 kg inorganic N/ha over two years. This is not a minor side effect: rapid green growth can coexist with failure in water quality.

What must be measured

Total N is insufficient. Measurements must include $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, potentially mineralisable N, N in microbial biomass, plants and litter, gaseous losses at least in an intensive module, and N in runoff and leachate. The material dose should be limited both by the target C input and by maximum permissible N/P loading.

Phosphorus: deficiency and pollutant at the same time

Organic P is mineralised to phosphate, but its availability is regulated by the mineral matrix:

- at low pH, P interacts strongly with Fe/Al phases;
- at high pH, it interacts with Ca phases;

- organic ligands may compete for surfaces and alter sorption;
- erosion carries particulate P, while surface runoff carries dissolved P;
- sandy, highly organic or P-saturated materials may retain it poorly.

In soils at the As Pontes coal site, Fe/Al, pH and organic C explained 79% of the variation in the logarithm of the phosphorus sorption index (CHEM-004). The same compost dose will therefore result in different plant availability and different water risks on different spoil heaps.

What must be measured

Total P, water-extractable and dissolved reactive P, an appropriate agronomic extractant, P sorption and desorption, Fe/Al/Ca phases, and P in plants, litter and runoff sediment. “P was added” is not the same as “plants received P”.

pH: a switch for several processes at once

pH affects:

- metal toxicity and mobility;
- P sorption and precipitation;
- microbial activity and community composition;
- nitrification;
- charge on mineral and organic surfaces;
- selection of plant species.

A material therefore cannot be selected on the assumption that “organic matter usually buffers”. It may raise or lower pH, while DOC can alter metal and metalloid mobility independently of bulk pH. Incubation and leaching tests are needed for the pair specific material × specific substrate.

CEC: not a general sponge, but a set of charged sites

Cation exchange capacity (CEC) helps temporarily retain NH_4^+ , K^+ , Ca^{2+} , Mg^{2+} and some metal cations. It is provided by clay minerals and the pH-dependent charges of organic matter. However:

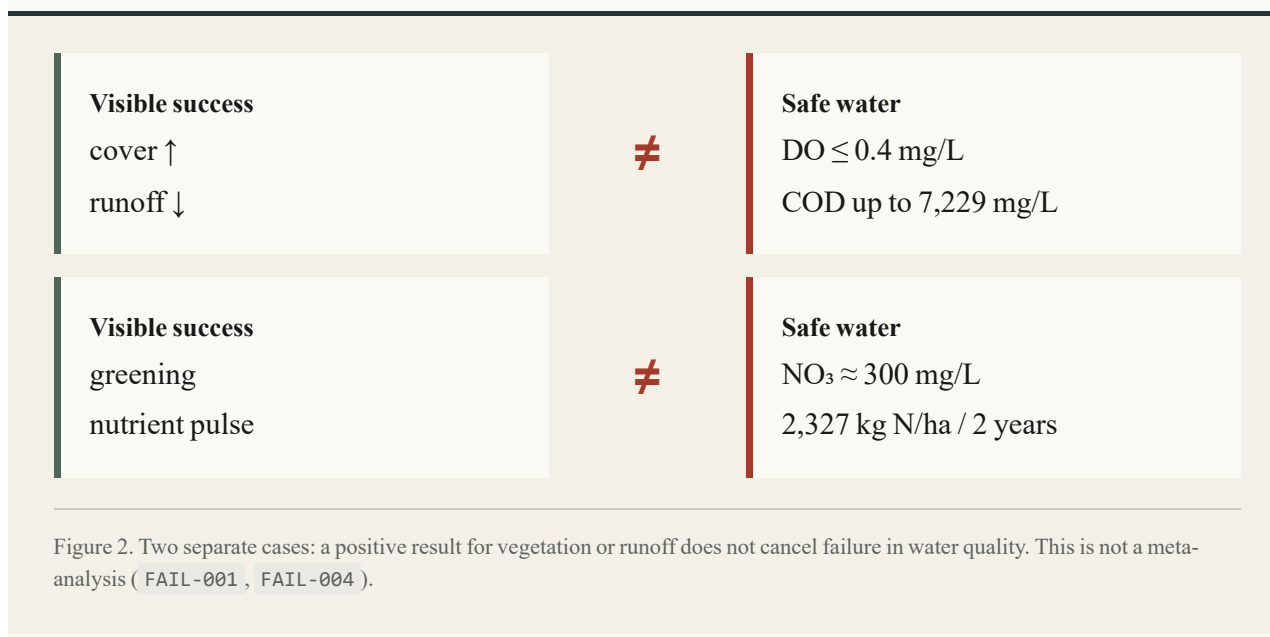
- CEC does not retain NO_3^- in the same way;
- high CEC does not guarantee that a cation is available to plants;
- a stony substrate containing only 5–30% fine earth has few reactive surfaces;
- compost can raise CEC, but without a mineral matrix some dissolved products may be lost.

This explains the important role of loam in KUZ-006: it is not merely “soil for roots”, but a source of surfaces, water and buffering with which the organic cycle can interact.

Block	Mechanism and possible benefit	Possible failure	What to measure
Carbon	Energy for organisms, POM, microbial residues, aggregates and mineral-associated organic matter	Rapid mineralisation to CO ₂ ; fossil carbon distorts SOC	TOC corrected for geogenic C, POM/MAOM, respiration, aggregate-associated C
Nitrogen	Starts plant growth and microbial biomass	Nitrate leaching, NH ₃ /N ₂ O loss, immobilisation, salinisation	Total N, NH ₄ -N, NO ₃ -N, mineralisation, leachate, plant uptake
Phosphorus	Roots, energy and biomass	Fe/Al sorption or runoff and eutrophication	Available and total P, sorption, P in runoff and leachate
pH	Governs nutrient availability and toxicity	Pyrite can sustain acidity for decades	pH, acidity/alkalinity, sulphate, Fe, acid–base accounting
EC / salts	Diagnoses dissolved salts	Osmotic stress, sodicity, saline leachate	EC, major ions, SAR/ESP where required
CEC	Capacity to retain some positively charged nutrients	High CEC does not cancel poor structure or toxicants	CEC/ECEC together with pH, particle-size distribution and organic matter
Metals	Immobilisation is possible at suitable pH and with suitable organic matter and mineralogy	Mobilisation through DOC or changing acidity/redox conditions	Total, bioavailable and dissolved forms; pore water
Aggregation	Roots, fungi, fauna and organic matter bind particles	Compaction, sodicity, mechanical disruption	Bulk density, penetration resistance, water-stable aggregates, pore connectivity

11. Water

Water has its own section because a good plant response can coexist with poor water quality.



Indicator	What it shows	Risk of false success
Nitrate	Loss of available N and downstream pollution risk	Biomass increases, but the nutrient pulse leaves the system
DOC	Mobile organic carbon and complexation	Increased DOC can transport Cu and other metals
COD / dissolved oxygen	Oxygen demand and receiving-water condition	Less surface runoff does not mean safe water when COD is high and DO is low
Metals	Transport of dissolved and suspended forms	pH and DOC alter mobility after application
Runoff / infiltration	Water pathway and erosion	Lower runoff may increase infiltration and leachate formation
Salinity	Mass of dissolved salts	Greening does not cancel salt accumulation or export

FACT. FAIL-001 : a high dose of pulp-and-paper sludge reduced surface runoff and erosion, but was accompanied by $\text{DO} \leq 0.4 \text{ mg/L}$ and COD of up to 7,229 mg/L. FAIL-004 : recovery of plant cover after application of low-C:N sewage sludge was accompanied by nitrate concentrations of up to about 300 mg/L and a loss of 2,327 kg inorganic N/ha over two years. These cases do not show that every organic material is dangerous; they show that water endpoints are mandatory.

12. Biology

Biology: who actually builds the system

Bacteria and archaea

They mineralise organic matter, carry out nitrification and denitrification, and participate in Fe/S redox chemistry. Specialised communities may form on burning or acidic spoil, but their presence does not mean that restoration is safe.

Fungi and mycorrhiza

Fungal hyphae connect pores, contribute to aggregation and help plants obtain P and water. Arbuscular mycorrhizal fungal (AMF) inoculation often improves early growth in studies on mined land, but review BIO-003 emphasises the shortage of long-term field outcomes. Compatibility among fungus, plant and substrate matters more than the label on a commercial product.

In a 29-year chronosequence on iron-ore tailings (BIO-004), AMF colonisation increased after perennial vegetation appeared, and different genera appeared at different times. This also permits passive accumulation of symbionts; a separate inoculation treatment must demonstrate an added benefit over natural colonisation.

Roots and plants

Roots create biopores, rhizodeposits and new C inputs. But rapid cover by non-native grasses may stabilise the surface while delaying the target succession. Measurements must include not only cover, but reproduction, recruitment, litter and the trajectories of native and non-native species.

Soil fauna

Fauna fragment litter, mix material and influence pores and aggregates. Earthworms can accelerate processes, but introducing non-native species may alter local ecosystems. The baseline design does not introduce earthworms; it first tracks natural colonisation and uses fauna indicators.

Is “real soil” needed?

Three different operations must not be conflated:

1. **Topsoil application** — a large volume of material used as a physical layer and nutrient carrier.
2. **Whole-soil and seed-bank transfer** — moving plants, seeds, fauna and biota together with the soil horizon.
3. **Small-volume inoculation** — a small dose intended to provide a living community, not layer thickness.

KUZ-007 shows a pronounced two-year response of the plant community after 20–60 cm of fresh soil–vegetation layer was placed over 40 cm of loam. But the donor soil was removed from licensed land that was itself destined for mining. This is salvage, not a justification for destroying an intact donor meadow.

BIO-001 shows that small inocula on former arable land can direct different community trajectories for six years. BIO-002 shows an early benefit of small doses of forest topsoil on mine substrates in a greenhouse experiment. Neither yet demonstrates that a small dose will restore toxic coal-spoil material.

Preferred hierarchy of donor materials

1. fresh material salvaged from land that will unavoidably be disturbed;
2. material from a local authorised clearance or construction operation;
3. minimal soil crumbs or inoculum, with a damage cap and monitoring of the donor site;
4. cultured native microbial consortia only after identity and function have been tested;
5. a generic commercial inoculum — not by default.

How to test declining dependence on external intervention

The proposed **autonomy index** is not reduced to one number before data exist. It tests all of the following at the same time:

- no further soil amendment is applied;
- irrigation and fertilisation stop after a predefined, limited establishment period;
- plant cover, survival and community recruitment do not fall below a specified threshold;
- annual litter and root inputs replace part of the early external C input;
- mineral N/P availability is not sustained only by the residual pulse;
- microbial biomass and functions, and mycorrhiza, persist;
- aggregate stability and infiltration do not deteriorate;
- runoff and leachate remain safe;
- the community does not shift towards domination by undesirable species.

Only when these conditions are jointly met is there reason to say that the system has begun to support itself. Even then, it will be a young Technosol and a young ecosystem, not restored ancient soil.

Preliminary answer to the article's question

The former soil probably cannot be recreated over a historically short period. Initiating the formation of a new living soil system on some safe technogenic substrates is scientifically plausible and has in places already been shown in part. But organic wastes become resources only after source separation, processing, analysis and testing of the `material-substrate` pair. Without that, a city does not give life back to the land; it merely transfers another risk stream onto the spoil heap.

SYNTHESIS. Biological success is not the maximum number of taxa and not a single enzyme assay. Functions, links to plants and water, persistence and environmental fit matter. An early signal may disappear; an inoculum may fail to establish; a more complex mixture may perform worse than a simple one.

13. Global studies and cases

Functionally different cases are included in the main synthesis. They are not combined in a meta-analysis: sites, materials, doses and outcomes are not comparable.



Open-pit mine benches in Kuzbass, 22 January 2019. Photograph: Natalia Zubkova. The image shows the scale and geometry of surface mining; it is not a study site in the global case matrix and does not prove any restoration outcome.



Patilla pit, Cerrejón, Colombia, 2013. Photograph: Hour.poinç, CC BY-SA 3.0. The image shows the mine and overburden behind it, but not the CASE-018/019 chronosequence sites; it does not demonstrate the 63–89% values or ecological restoration.

Key global cases for the final synthesis

Status: closed selected matrix, 26 September 2026. This is neither a ranking of countries nor a complete registry. Cases were selected because they change the answer to the research question, provide long durations, direct comparisons or important limitations.

Evidence	Where and what	Why it is key	What it does not permit us to claim
CASE-009/010	Virginia coal mine soil; randomised treatments; 16 and 27 years	A rare long-term causal comparison: the control caught up with treatments on some aggregate indicators, while C/N fractions and microbial biomass retained treatment legacies	No treatment was shown to constitute full restoration of a reference ecosystem
CASE-020	Sokolov, Czech Republic; alder on lignite spoil; 4–65 years	Shows accumulation of C/N/P, litter and organic horizons over decades	Chronosequence; the mineral profile remains incomplete and sites differ
CASE-023	Spontaneous succession at Sokolov; 16–56 years plus resurvey	Shows that safe spoil can develop an internal plants–litter–soil trajectory without continual organic applications	Does not transfer to burning, acidic or saline spoil; fossil C complicates stock estimates
CASE-018/019	Cerrejón, Colombia; topsoil transfer plus dry-forest restoration; up to 21 years	Links vegetation, litter, fauna and biogenic aggregates	One programme and chronosequences; restoration remained partial
CASE-021	Garzweiler, Germany; 24 years	Separates the roles of mineral foundation, an N-fixing pioneer crop and compost in structure/SOC	A favourable loess agricultural Technosol is not raw coal spoil
CASE-022	Lusatia, Germany; acidic sulphurous lignite spoil; up to 37 years	Shows that pyrite oxidation can govern chemistry for decades despite forest cover	Greening does not demonstrate removal of the geochemical source
BIO-009	West Virginia coal-land reclamation; 2–32 years	Microbial succession occurs, but convergence with the reference is not guaranteed; pH, texture and SOM matter more than calendar age	Four sites, not a longitudinal experiment; amendments were not tested
CASE-001/004/033	Acid coal spoils in Ohio/Scotland; 10–16 years	Liming, mineral correction and source control cannot be replaced by organic matter; maintenance matters	Older materials/doses and incomplete water panels
CASE-002	Wales, green-waste compost around trees; 11 years	A null/species-specific result breaks the claim that “compost always accelerates trees”	Small spot dose, not reconstruction of soil across a whole site
CASE-015/016	Minnesota taconite tailings; 2–9 years	Combines vegetation, water, cost and logistics; maximum cover was not the safest or cheapest outcome	Not coal; early durations and specific waste streams
CASE-012	Cu/Mo tailings in British Columbia; 13 years	A one-time biosolids application left a C/biomass legacy; the lower dose was more efficient per unit mass	Different metals/water context; high dose raised concern over Zn

Evidence	Where and what	Why it is key	What it does not permit us to claim
CASE-034	Saline Cu tailings in Chile; 3 years	Dose/material produced opposing outcomes for biomass and DOC/Cu mobilisation; olive residue failed	Irrigated non-coal system; autonomy was not tested
CASE-025/026	Subsided coal land in Shanxi; 5–7 years	Organic materials create different C pools and microbial trajectories; manure did not make the system reference-like	Agricultural systems with repeated inputs; water/fungi incompletely assessed
KUZ-006	Kuzbass factorial trial, loam/topsoil × local seed hay ; 4–9 years	Local evidence that a physical root zone and a biological trajectory are different levers	Compost was not tested; green cover is not autonomy
HYP-001/011	South Africa/Poland; manufactured or inoculated materials	Closest analogues of material biologically engineered before planting or field application	No factorial B/C/D/E and B-time comparison of mature compost, direct inoculation and pre-colonised material
MIC-001	Pilbara post-mining soil; native bacteria cultured from 1 g of soil and delivered in pellets	Directly shows the technical scalability of small donor → culture → carrier → post-mining soil , with treatment-dependent function	Not the whole microbiome, not a compost carrier, not a long duration

Selection conclusion

Together, these cases are sufficient to show six different truths: organic materials sometimes help; dose and material change the outcome; water can deteriorate despite good cover; geology can dominate for decades; plants can build an internal cycle; and an inoculum can change selected functions without guaranteeing the emergence of new soil.

13.1. Full case matrix

The table below preserves substrate, amendment, dose, calculation basis, study design, duration, outcomes, positive and negative results, limitations and Source IDs to the extent recorded in the closed corpus.

Long-term and negative field cases

Table note: “positive” means only the reported measured effect, not full ecosystem restoration.

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
CASE-001	10 years	Acidic pyritic coal spoil, Ohio	Digested sewage sludge, fly ash, composted pulp-and-paper sludge, topsoil	pH, plants and other indicators	Long-term differences among materials persisted	Older sludge standards were used; contaminant and water data and the full text are needed
CASE-002	11 years	Former coal mine, Wales	0.75 kg municipal green-waste compost per tree	Survival, height and diameter at breast height (DBH), by species	No overall height or DBH gain; survival depended on species and was worse for alder	Small spot dose; not restoration of soil cycling across the whole site
CASE-003	7 years	Lignite basin, Czech Republic	One-time sewage sludge, paper waste and bark	C, microbial biomass and respiration	Biological and chemical responses persisted	Complex mixture; the active component cannot be identified
CASE-004	16 years	Acidic coal-mined land, Ohio	280 Mg/ha flue-gas-desulphurisation (FGD) material $\pm$ 112 Mg/ha yard-waste compost; 20 cm new soil layer with lime	Vegetation and soil condition	Long-term response differed from the early response	FGD is not an organic material; water data and dose comparison are required
CASE-005	12 years	Pb/Zn-bearing tailings, Missouri	Biosolids with lime/compost versus salvaged topsoil	Plant yield, metal uptake, mammals and soil	Residual-based treatment remained functional	Not coal spoil; attracting animals and metal results do not equal full ecosystem autonomy
CASE-006	9 years	Boreal open-pit gold mine	Eight strategies using peat, biosolids and combinations	Soil–plant–microorganism system	Peat combinations outperformed treatments without peat; year five was more informative than early cover	Not coal; peat harvesting damages a donor site; full text is required for the recent paper

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
FAIL-001	Early runoff	Coal mine	Pulp-and-paper sludge at 224/672 Mg/ha dry mass	Runoff, erosion, DO, COD	Runoff was 4–6 times lower and erosion fell from 47 to <1 Mg/ha	Before plants established, the high dose produced DO ≤ 0.4 mg/L and COD of 7,229 mg/L versus 880 mg/L
FAIL-003	2 years	Pyritic and non-pyritic lignite spoil	Fertiliser, sewage sludge, compost	Soil solution at 20/130 cm and elemental fluxes	Responses differed sharply by substrate	At the pyritic site, up to 6 t Fe/ha/year and 14 t sulphate S/ha/year; organic materials did not provide source control
FAIL-004	3 years	Reclaimed coal site, Pennsylvania	134 Mg/ha low-C:N sewage sludge	Lysimeter water at 1 m	Recovery of plant cover was accompanied by a nitrate and metal pulse	Peak NO ₃ about 300 mg/L; 2,327 kg inorganic N/ha over two years; high dose endangered water
FAIL-005	3 years	Abandoned coal site, Pennsylvania	Composted poultry litter at 78/156 Mg/ha; fresh litter plus paper-mill sludge at C:N 20/29	Nutrient leaching and soil retention	<1% of N leached from compost; litter/sludge lost 393 kg N/ha at C:N 29 and 107 kg N/ha at C:N 20	C:N is not the sole maturity indicator; the conclusion applies to the particular poultry-litter and sludge materials
KUZ-006	4–9 years	Overburden, Kuzbass	Bare spoil / 10 cm loam / 10 cm topsoil $\times$ 0–3 rates of local seed hay	Chemistry, flora, cover and biomass	Loam with local seed hay produced a pronounced near-natural trajectory; topsoil added a weed reserve	Compost and manure were not tested; cover does not demonstrate water or microbial autonomy
KUZ-006-P	4 years	3 ha coal spoil heap, Kuzbass	≥ 20 cm loess-like loam + 5 t local seed hay	Cover, flora and height	80–90% cover; 77 vascular plant species	Operational trial without full factorial replication; cover is not soil restoration
CASE-009/010	16 and 27 years	Sandstone/siltstone coal mine soil, Virginia	Control; 30 cm topsoil; 112 Mg/ha sawdust; biosolids at 22–224 Mg/ha, n=4, randomised complete block design (RCBD)	SOM, N, mineralisation, aggregation, C/N fractions, microbial biomass and vegetation	Amendments had strong effects at five years; by 16 years the control approached them in bulk SOM/N; by 27 years overall aggregate distribution largely converged, while biosolids retained C/N legacies and higher MBC	One outcome shows convergence and others legacy; the result cannot honestly be reduced to the word “worked”

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
CASE-011	35 years	Surface-mined land, Illinois	Cumulative 801–1,815 Mg/ha biosolids dry mass versus mineral-fertilised fields	Trace metals in groundwater	Most regulated metals below limits; Fe/Mn higher; early Zn signal declined after biosolids quality and regulation changed	Nitrate, PFAS, pharmaceuticals, pathogens and ecosystem trajectory were not tested
CASE-012	13 years	Cu/Mo tailings, British Columbia	One-time biosolids at 0/150/250 Mg/ha dry mass	C pools, biomass and selected chemistry	Advantage in C and biomass persisted; lower dose stored more C per unit mass; Zn exceeded a guideline at 250 Mg/ha	Tailings are not coal spoil; water and ecological endpoints were incomplete
CASE-013	21 years	Metal-contaminated alluvial tailings	224 Mg/ha lime + 224 Mg/ha biosolids	Physical, chemical and biological soil condition, plants and metals	Many soil functions improved; plant metal concentrations declined	Bioavailable Cd/Zn remained a problem; non-randomised and not a coal site
CASE-016	5–9 years for early plots; 2 years of full-scale work at publication	Coarse taconite tailings, Minnesota	10–90 Mg/ha peat, yard/municipal compost or paper residues; some treatments with fertiliser	Cover, biomass, early cost and logistics	Some 10 Mg/ha plots reached 90% cover by year five; high paper-residue dose required extra N; a source within 100 km was economically decisive	Not coal; paper stream was not composted; partly overlaps CASE-015; ecosystem and soil autonomy were not measured
CASE-015	2–3 growing seasons	Coarse taconite tailings, Minnesota	Biosolids rates corresponding to 100/200/400 lb available N/acre, with or without paper residue; standard control	Infiltration-water chemistry, nitrate mass, metals, cover and cost	Organic materials increased cover; authors selected 200N as a compromise	Almost every treatment had nitrate >10 mg/L; 400N had about 3× the nitrate of 200N; 400N plus paper residue had greatest cover but cost ≥6× 200N and released small amounts of Hg/Co; short duration
CASE-017	2–19 years, age gradient	Revegetated coal spoil, Singrauli, India	Mixed grasses and trees; no separate organic amendment	Biomass, litter, roots, pH, bulk density, water-holding capacity, N/P, Walkley–Black C and microbial C	Plant biomass, measured organic C and MBC increased with age; by 19 years substantial litter and root inputs had formed	Different sites, not repeat measurements; initial differences and species composition confounded with age; coal C may distort SOC; calculated balance is not measured flux

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
BI0-009	2–32 years, chronosequence	Reclaimed contour coal mines, West Virginia	Backfilled spoil + about 20 cm topsoil, compaction, grass–legume mixture	Chemistry, texture, moisture, microbial biomass/richness, bacterial and fungal composition	Microbial communities changed gradually; pH, SOM and texture were important factors	The 32-year site showed no clear convergence with the reference in biomass, richness or composition; four sites are not a longitudinal study; amendments were not tested
CASE-018/019	1–21 years, two chronosequences	Technosols at a dry-forest coal site, Cerrejón, Colombia	Topsoil transfer and revegetation	Microstructure, biogenic aggregates, macrofaunal traces, physicochemical indicators, litter, SOM	Formed biogenic aggregates appeared by 20 years; SOM reached 63–89% of reference; litter links vegetation to soil	One restoration programme; not repeat observations of the same plots and not an amendment comparison; restoration remained partial
CASE-020	4–65 years, chronosequence	Lignite spoil, Sokolov, Czech Republic	Alder afforestation	C/N/P stocks and profile distribution, litter/organic horizons, microbial links	C/N accumulated rapidly in the first 15–20 years; upper organic layers approached reference after 30–40 years	Mineral layers and the whole profile lagged; parent materials and sites differed with time
CASE-021	0–24 years, replicated chronosequence	Agriculturally reclaimed loess over lignite mine, Garzweiler, Germany	Lucerne pioneer phase, crop rotation, compost and ploughing	SOC, aggregates, macroporosity, pore connectivity and microbial biomass	Foundation mineralogy, N-fixing crop and compost performed different functions; plant residues alone did not maintain high SOC	Transferable mechanism, but loess agricultural soil is not raw coal spoil; chronosequence
CASE-022	Up to 35–37 years	Acidic sulphurous lignite-mine soil, Lusatia, Germany	Amelioration and pine/oak afforestation	Organisms, roots/mycorrhiza, chemistry and seepage-water ion balance	Some biological properties approached unmined sites; leaching declined	Pyrite oxidation governed chemistry for decades; external forest recovery did not remove the geochemical source
CASE-023	16–56 years plus resurvey about 15 years later	Unreclaimed coal spoil heaps at Sokolov, Czech Republic	Spontaneous deciduous succession	Repeat measurements of C stocks by depth and microtopography	Mean observed soil-C accumulation about 0.50 t C/ha/year	Site trajectories differed; parent material contains fossil C; transfer is possible only after engineering clearance
CASE-024	Assessment base spanning 24 years	48 coal mines, South Africa	Conventional rehabilitation with varying subsequent maintenance	299 multi-criteria assessments	Land capability and soil loss often met thresholds; soil fertility, landform and species composition remained weak	Industry observational benchmark, not a soil-amendment trial; shows maintenance demand may persist

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
CASE-025	5 years	Reclaimed agricultural land over coal-mining subsidence, Shanxi, China	Equal 2.7 t C/ha as biochar, compost, biogas residue, cattle manure or maize straw	Total, stable, labile and readily oxidisable C fractions	Materials produced different C-pool profiles: biochar led in total C and management index, compost in readily oxidisable C, manure in labile C	Only C assessed; nutrient inputs not equalised; water, vegetation and autonomy not measured
CASE-026	7 years	Reclaimed maize land over coal-mining subsidence, Shanxi, China	Control / mineral fertiliser / decomposed poultry manure, RCBD, n=3	SOM/nutrients and bacterial richness/composition	Manure improved SOM/N and changed the microbial community	Community still differed from farmland; continued inputs required; metals, antibiotics, water and fungi incompletely assessed
CASE-028	2–21 years, chronosequence	Afforested coal spoil, Raniganj, India	Natural and managed revegetation	Physicochemical indicators, MBC/enzymes and vegetation	Many soil and plant indicators increased with age	Site and history differences confounded with time; not an amendment experiment; fossil-C caveat
CASE-030	About 20–25 years, cross-sectional comparison	Hard-coal spoil heap, Upper Silesia, Poland	Spontaneous succession on bare spoil / succession over topsoil / planting over topsoil	Structure, water, nutrients and light/occluded/mineral C fractions	Planted/topsoiled treatment retained more water and more stable C fractions; total SOC did not differ	No historical randomisation; mechanical compaction damaged topsoiled soil; no biological endpoints
CASE-031	6 years	Constructed topsoil over coal mine, Candiota, Brazil	Four perennial grasses; all planted plots limed, fertilised and supplied with N annually	TOC at 0–3 cm, chemical C fractions and organic-matter spectroscopy	Cover crops partly increased C pools versus bare constructed soil; some species favoured humic-acid C	Natural and bare treatments were not randomised; surface layer only; annual inputs; total C remained well below natural soil
CASE-032	15 months	Acidic sandy cassiterite tailings, Jamari, Brazil	Six covers × compost/NPK/lime, six replicates	Chemistry, organic matter and physical properties	Lime, organic material and fertiliser treatments improved chemistry	Organic matter and physical properties did not differ; short non-coal mixed-treatment experiment limits causal interpretation
CASE-033	About 10 years after 1978 application	Pyritic coal spoil, Baads, Scotland	0/10/25/50 t lime/ha with peat, sewage sludge, weathered poultry litter or Alginure	pH, available metals and vegetation; adjacent long-term water/metal comparison	Most plots with 50 t lime/ha still had pH ≥5.12; organic-only treatments usually remained bare	Surviving plots sparse and unbalanced; slope and inflow confounded; sludge not analysed before use; repeated organic input was required

ID	Duration	Site and initial substrate	Treatment	What was measured	Result	Why this is insufficient / risk
CASE-034	3 years	Saline Cu tailings, La Cocinera, Chile	Goat manure / biosolids / grape or olive residues / mixtures, 13 treatments × 3 replicates	CEC/SOC/NPK, microbial indicators, DOC/Cu in pore water, plant biomass and Cu	Biosolids B1 and some grape-residue/manure systems produced high late biomass; treatment advantages persisted over control	Three years of irrigation; many fertility measures declined; very large early DOC/Cu pulses; olive residue almost eliminated production; autonomy untested
CASE-035	12 months	Reconstructed coal-site profile in outdoor containers, Mpumalanga, South Africa	Nine organic/fly-ash treatments and control, n=4	pH, bulk density, two crops, roots, nutrients and C	Lucerne with composted manure and wood chips performed best across the combined indicators	Mini-lysimeter; one winter and summer; high doses and mixed components; no water-quality or field-persistence data

Preliminary synthesis

1. Early greening systematically overstates success: responses at 9–16 years may differ from those at 1–3 years.
2. The most dangerous false success is good plant cover combined with nitrate, DOC or metal losses in water.
3. A high dose of organic material is not inherently a strong treatment; it is often a strong pulse of nutrients and oxygen demand.
4. A single C:N ratio does not guarantee stability: material provenance, process history, maturity, N forms and field hydrology remain necessary.
5. The physical rootable layer and the biological trajectory should be tested separately from added organic C.
6. The longest controlled coal-site case shows something causally important: over decades, vegetation alone can catch up with early amendment in some functions, while particular inherited C/N fractions remain different. Success must therefore be evaluated using several outcomes and the cost of acceleration, not only the final difference.

14. Negative results

A negative result here is not necessarily a complete project failure. It is a result that disproves the simple promise “organic material was applied, therefore things improved”.

Negative and limiting cases

Status: final synthesis list, 26 September 2026. “Negative” here means a result that disproves a simple promise, not necessarily complete failure of the project.

Evidence	Positive outward sign	What went wrong or was not supported	Lesson
FAIL -001	Reduced runoff and erosion at a coal site	DO ≤ 0.4 mg/L and COD up to 7,229 mg/L at a high paper-sludge dose	Less runoff does not mean safer water
FAIL -004	Greening after sewage-sludge application	Nitrate up to ~ 300 mg/L and 2,327 kg inorganic N/ha over two years	The largest nutrient pulse may become a pollution event
FAIL -005	Manure blended to nominal C:N 20/29	N losses remained 107/393 kg/ha, while compost lost $< 1\%$ N	C:N does not replace maturity and process history
FAIL -003	Fertiliser/sludge/compost were applied	Pyritic spoil produced massive Fe/sulphate fluxes irrespective of organic material	Active acid generation requires source control
CASE -002	Green-waste compost around trees	No overall height or DBH gain; survival was species-dependent and worse for alder	Compost effects cannot be generalised across plant species
CASE -015	Maximum early cover	The highest-rate treatment had more nitrate export and cost $\geq 6\times$	Maximum biomass is a poor selection rule
CASE -033	Organic materials on coal spoil	Organic-only plots mostly remained bare; effects did not persist without sufficient liming	Organic material does not replace pH correction
CASE -034	Some treatments produced high late biomass	Early DOC/Cu pulses; olive residue nearly stopped production; nutrient indicators declined	Waste identity and water chemistry matter more than the word “organic”
CASE -032	Chemistry improved after treatment	OM and physical properties did not differ after 15 months	Fertility correction is not soil formation

Evidence	Positive outward sign	What went wrong or was not supported	Lesson
CASE-029	Early enzyme/plant response	Biological gain did not persist; pH/EC/sodicity/water remained controlling	An early microbial signal may be temporary
BIO-006	Reclaimed pasture could be grazed	Grazing/trampling increased compaction; the enclosure retained more water	Animals belong after stabilisation, not before it
BIO-009	32 years of conventional reclamation	Microbial biomass, richness and composition showed no clear convergence with the reference	Age plus cover does not guarantee microbiome restoration
MIC-001	Cultured native bacteria improved N/SIR	The bacteria-plus-cyanobacteria mixture improved no measured soil property; diversity did not change	More organisms or complexity is not necessarily better
MIC-003	Microbiome addition can restore function	A low-diversity inoculum did not restore nitrification	Culturing that loses diversity may remove necessary guilds
MIC-006	AMF inoculation increased root colonisation	Enzymes and glomalin did not improve	A colonisation marker is not ecosystem function
HYP-001	Some inocula improved early plant indicators	Tea made from native mine soil did not help; later biomass differences narrowed	“Native living soil” alone does not demonstrate benefit

How to use this list

Every future treatment must have a paired safety endpoint and a predefined failure condition. No positive plant result cancels the assessment of water, contaminants, persistence or donor-site impacts.

SYNTHESIS. A green slope may be a stage of restoration. It may also be a well-concealed problem.

15. Long-term studies

Weeks–5 years	7–16 years	20–40 years	56–65 years
vegetation · enzymes · mineral N · phytotoxicity · water failures	persistence · convergence · amendment legacies	organic horizons · aggregates · litter/root cycles · fauna · persistent C pools	continuing soil-forming trajectory
experiments / repeated field observations	longitudinal and repeat observations	experiments + chronosequences	chronosequence; not one 65-year experiment

Figure 3. Evidence horizon and processes visible at different times. Block length denotes the time window, not effect size.

FACT. Time windows in the corpus show different processes: weeks to 5 years — early plant response, enzymes, mineral N, phytotoxicity and water problems; 7–16 years — persistence, convergence among treatments and amendment legacies; 20–40 years — organic horizons, aggregates, fauna, and litter and root cycles; 56–65 years — an ongoing soil-forming trajectory.

Virginia provides a rare long-term randomised comparison: by 16 and 27 years, the control converged with amendment treatments in some aggregate indicators, while particular C/N fractions and microbial biomass retained treatment legacies. Sokolov at 4–65 years shows C/N/P accumulation and horizon formation, but it is a chronosequence. Cerrejón at up to 21 years links vegetation, litter, fauna and biogenic structure, but is not a randomised amendment experiment. Lusatia shows pyritic geochemistry remaining dominant for many years even under vegetation.



Smolnická spoil heap, Sokolov lignite basin, Czechia, 2023. Photograph: Lubor Ferenc, CC BY-SA 4.0. This is a contemporary post-mining landscape in the same basin, not the specific CASE-020/023 age-sequence sites; the photograph does not demonstrate measured changes in C, N, P or the soil profile.

Mandatory boundary: a chronosequence compares sites of different ages; a longitudinal study repeatedly measures the same experiment. A single “65-year curve” must not be drawn from different sites.



Bundesarchiv, Bild 183-1987-0212-305
Foto: Link, Hubert | 22. Januar 1987

Forest island on the former Lohsa III mine, Lusatia, 1987. Photograph: Hubert Link; Bundesarchiv, Bild 183-1987-0212-305 / CC BY-SA 3.0 DE. The image shows a reclaimed site in the region, but does not measure acidity, element export or the condition of the specific CASE-022 site.

16. Technosols

SYNTHESIS. A Technosol is not a promise to return the historical soil that existed before mining. It is a constructed or profoundly transformed soil system in which a mineral root zone, amendments, plants and biological processes can form functions over time.

A functional Technosol requires safe parent material; a sufficient fine-earth fraction; loose placement without destructive compaction; manageable water; compatible pH/EC; qualified organic material; plants; and monitoring. The Garzweiler case shows that the mineral foundation, a pioneer N-fixing crop and compost perform different functions. The Kuzbass factorial experiment shows the distinction between a physical root zone and a biological trajectory.



Garzweiler opencast lignite mine, Germany, 2023. Photograph: Stephan Sprinz, CC BY 4.0. The photograph shows the scale of the mining operation, but not the studied soil profile or the result of 24 years of reclamation in [CASE-021](#).

17. Pre-living-material hypothesis

Link in the hypothesis	Direct evidence	Close analogue	Not tested
Safe organic streams → mature compost	Yes: standards, field trials and maturity data	Municipal and agricultural composting systems	No universal recipe exists for all streams
Small biological inoculum → multiplication of some organisms	Yes: cultured native bacteria from 1 g of donor soil	Carriers, synthetic communities (SynComs), trap cultures	No universal donor-material dose
Secondary maturation → functionally different material	Mechanistically plausible	Polish constructed compost and pre-growth analogues	No direct field comparison of B/C/D/E
Pre-colonised material → persistent field advantage	No	Early analogues in plant and microbial response	The central promise of the hypothesis
Reduced external inputs	Partial evidence from long-term trajectories	Spontaneous succession and persistent vegetation	Not demonstrated for system E

UNKNOWN. No direct experiment was found that demonstrates an advantage of pre-colonised mature compost over ordinary mature compost or direct inoculation. This is not a claim of worldwide novelty; it is the boundary of the closed search.

1. Natalia's original idea

The testable sequence is not the direct application of waste or ordinary compost to a spoil heap. It proposes:

1. collect traceable and safe organic streams;
2. carry out controlled composting with a sanitary thermophilic phase of sufficient duration;
3. confirm maturity and the absence of unacceptable contaminants;
4. after the thermophilic phase, add a small amount of compatible living soil or another biological inoculum;
5. allow the mixture to undergo a separate secondary maturation phase;
6. apply the resulting material only to an engineered, safe and prepared technogenic substrate;
7. test whether a more persistent cycle develops: plants → roots and litter → microorganisms and fauna → available elements → new plants .

The key distinction from the ordinary question “does compost help?” is the proposed additional effect of **inoculation before application followed by community development in the organic carrier**.

2. Were direct analogues found?

Within the global search conducted, **no published experiment was found that fully matches the entire sequence**:

finished, sanitary and mature compost → small amount of compatible inoculum from natural soil → controlled secondary maturation → prepared coal spoil → plants → long-term field test of safety and reduced dependence on external inputs.

This is not proof of novelty and does not claim that no such experiment has ever existed. It is the boundary of the literature found.

The final targeted search identified **two different closest analogues, each covering only part of the sequence**.

HYP-011 (Poland, 2026) is closest in product purpose and field application. A 20:60:20 mixture of poultry feathers, wheat straw and lignite was inoculated with three cultured strains **at the beginning** of the process, composted for 41 days in a dynamic reactor, and the finished product applied to post-mining sandy soil at Konin. There was no late inoculation after the sanitary phase; the field work had only one treated and one untreated plot, without a treatment using the same mature uninoculated compost. The article therefore shows that a pre-microbially enriched waste compost can be manufactured and applied on post-mining land, but not that it behaves differently from ordinary mature compost.

HYP-001, Coaltech/University of Cape Town, is closest in the sequence **inoculum** → **separate pre-plant incubation** → **coal-derived mineral substrate**. A mixture of 95% ultrafine coal-processing tailings and 5% spent malt grain was inoculated with compost or vermicompost “tea”, brewery-digester liquid, a commercial consortium, or “tea” from native mine soil, activated and incubated for seven days before *Eragrostis tef* was planted. The system differs from the original hypothesis: the organic component was not mature compost, the inoculum was liquid, the secondary phase was short, and the experiment was conducted in pots.

It nevertheless provides a causally important result. Compost “tea” and the commercial consortium improved early plant indicators, while the inoculum from native mine soil did not. By the second cycle, differences in microbial biomass had become small and did not explain plant productivity. Simply adding living native soil therefore does not guarantee a useful result; donor origin, community function, carrier and the inoculum’s fate after planting matter.

3. Closest technologies worldwide

Source	Sequence	Category	What it adds to the hypothesis	Main boundary
HYP-001 Coaltech 2023	Coal-processing tailings + 5% spent malt grain → liquid microbial inoculum → 7-day incubation → pots	Close analogue of E, not a direct match	Pre-incubation of a biologically enhanced Technosol; direct comparison of several inocula	Not mature compost; short duration; native-soil “tea” did not help
HYP-011 Poland 2026	Feathers + straw + lignite → cultured inoculum on day 0 → 41 days of composting → 18.3 t/ha on post-mining sand → maize	Engineered inoculated compost	Complete route from waste mixture through inoculated composting to field application; process control present	Inoculum was not added late; field did not compare inoculated with ordinary compost; one plot per treatment; one season
HYP-002 Asemaninejad et al. 2018	Mine residues + pulp-mill sludge + <0.02% forest humus	Close analogue of C	A very small donor-soil input sometimes substantially changed biomass and microbiome	Secondary maturation not established; Cu/Ni sometimes became more soluble
HYP-003 Romero-Estonillo et al. 2023	Mine soil + compost, 15-day stabilisation → PGPR/AMF at planting	Close analogue of D, not a direct match	PGPR produced an effect; AMF results, alone and combined, were not universal	Inoculum added at planting, not before separate maturation
HYP-004 Li et al. 2026	Cattle manure + rice straw → stage-specific inocula on days 0/5/14/22	Compost-process analogue	Inoculation timing changed succession, TN, humification, GI and pot response	Not donor soil and not a mine substrate
HYP-005/006 compost-succession studies	Thermophilic phase → cooling → prolonged maturation	Mechanism	Mature compost is not biologically static; community and N/C continue to change	No B/C/D/E field outcome
HYP-007 Ngo and Cavagnaro 2018	Compost × 40-day pre-plant wetting × AMF/plant	Analogue of B-time and direct inoculation D	Pre-plant history changes mineral N; compost may increase growth and reduce AMF colonisation	Agricultural pot system, not E

Source	Sequence	Category	What it adds to the hypothesis	Main boundary
HYP-008 Tkacz et al. 2015	Sterile sand or compost + 10% natural soil → plants and serial dilution	C	Recipient medium and plant filter the community; pathogens may be transferred	No secondary maturation and no mine substrate
HYP-009 Han et al. 2022	1/3/5 cm donor-soil layer → three-year field restoration	Soil-transfer dose response	Donor origin and quantity jointly direct the trajectory	10/30/50 L/m ² , not a small inoculum
HYP-010 SARE ONE22-422	Finished compost + 10/25/50% spent mushroom substrate → 14 days	Closest procedure	Fungal biomass and F:B changed with dose before application	Field work cancelled; no plant/soil/water outcomes

4. What has already been demonstrated

Directly demonstrated

- The thermophilic phase radically restructures a compost microbiome; cooling and maturation bring a new succession. Adding a sensitive natural-soil community before the sanitary thermophilic phase is illogical if the objective is to retain its living components.
- Even mature compost suitable for commercial use continues to change during prolonged maturation: respiration and soluble labile C decline, the bacterial community changes and nitrification increases (HYP-006).
- Timing the addition of targeted microbial consortia can change the composting process and final product indicators (HYP-004). This demonstrates the importance of inoculation timing, not the superiority of natural soil.
- On mined-land materials, some inocula improve plant establishment while others, with the same carrier, have no effect (HYP-001 , HYP-003).
- A very small input of forest humus can alter plant and microbial responses in a constructed Technosol, but the effect depends on the mine residue and organic carrier, and metal mobility can worsen (HYP-002).
- Donor origin and dose matter; greater soil transfer often directs the community more strongly, but increases the ecological cost (HYP-009).
- Inoculum can transfer undesirable organisms, and nutrient-rich compost can reduce AMF colonisation (HYP-007 , HYP-008).

Supported by close mechanisms

- Secondary maturation may reduce readily decomposable C and NH₄-dominated instability; this must be checked through respiration, DOC, the NH₄:NO₃ ratio and phytotoxicity, not the calendar.
- Adding a mineral fraction creates surfaces for sorption and potential organo-mineral associations. Their extent is determined by clay content, mineralogy, Fe/Al oxides, Ca, pH and dissolved organic matter; the mere presence of soil inoculum does not demonstrate stabilisation.

- Pre-incubation can alter the initial nutrient pulse, but the direction is not universal: nitrification may reduce NH_4 while accumulating mobile NO_3 .

5. What has not been demonstrated

- System E has not been shown to be better on average than ordinary mature compost (B), direct addition of whole donor soil (C), or cultured inoculum applied at the time of placement (D).
- Natural soil has not been shown to be the best inoculum compared with the compost microbiome, cultured native consortia, AMF/PGPR or spontaneous plant-mediated colonisation.
- No universal minimum effective dose of donor soil has been established.
- Additional microbial diversity has not been shown to persist after contact with the mine substrate, climate and plant.
- A reduction in the need for repeat application after 5–20 years has not been demonstrated.
- Safety has not been demonstrated for runoff/leachate, metals, nitrate, P, pathogens or invasive propagules.
- A constructed community has not been shown to move towards the local reference ecosystem rather than towards a persistent but different anthropogenic state.

6. Chemical basis

Carbon

During the first phase, readily available compounds are mineralised to CO_2 , water and microbial products. Some C enters microbial biomass and necromass; some remains as particulate organic matter. Secondary maturation after mineral soil has been added may provide new mineral surfaces for sorption and aggregation, but protection depends on mineralogy and surface saturation. The opposite effect is also possible: inoculation may accelerate decomposition, increase CO_2 loss and leave less organic C at the time of application.

Nitrogen

Organic N passes through ammonification to NH_4^+ , microbial immobilisation, nitrification to NO_3^- , gaseous losses and, in anaerobic microsites, denitrification. More mature material usually produces less labile-N shock, but secondary maturation does not guarantee lower field risk: conversion of NH_4^+ to NO_3^- may increase N mobility. The required tests therefore extend beyond total N or C:N to $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, potentially mineralisable N, respiration and N in leachate.

Phosphorus

P is released by mineralisation, incorporated into microbial biomass, sorbed by Fe/Al oxides, precipitated with Ca or left in solution. The mineral fraction of donor soil may reduce dissolved P where sorption capacity is suitable, or instead add P and organic ligands and increase mobility. Sorption tests and water-extractable P measurements are required for the particular mixture.

pH and CEC

Compost and donor soil may increase buffering and CEC through charged organic/mineral surfaces. But mixture pH cannot be reliably obtained by mass averaging. In pyritic spoil, acid generation may exceed amendment buffering many times over; in saline/sodic material, an organic amendment does not replace correction of salinity/sodicity.

Salts and water

Secondary maturation does not automatically remove soluble salts. EC, chloride, sulphate and sodium must be measured before application. Improved aggregation and water retention are useful only if DOC/COD, nitrate, P and metals in water do not rise at the same time.

7. Biological basis

A small portion of compatible donor soil could theoretically introduce bacteria, fungi, AMF propagules, decomposers, protozoa, nematodes, microarthropods, spores and seeds. It also adds mineral surfaces and nutrients; without a sterilised donor-material control, a biological effect cannot be separated from a physicochemical one.

Why an effect might persist:

- the organic carrier gives the inoculum a protected medium and substrate before contact with the adverse mine-waste matrix;
- the secondary phase allows the carrier to be colonised and interactions to form;
- after planting, roots provide a new niche and carbon source;
- compatible donor material may accelerate the arrival of rare functional groups.

Why an effect might disappear:

- mature compost already carries a large community of its own;
- recipient pH, salts, metals and moisture, and plant identity, will filter most introduced taxa;
- the inoculum may be quantitatively too small or functionally incompatible;
- nutrient-rich compost may reduce plant dependence on AMF;
- an early community difference may disappear after labile C is depleted.

8. Risks

1. Pathogens, parasites, weed seeds, invasive organisms and undesirable fungi from donor soil.
2. Damage to the donor ecosystem when soil is removed.
3. A pulse of nitrate, P and salts after secondary maturation.
4. Mobilisation of metals and metalloids by organic ligands or altered pH.
5. Anaerobic zones, odour, methane/N₂O and high oxygen demand from an unstable product.

6. Multiplication of a community that grows well in the carrier but functions poorly in the mine substrate.
7. Falsely attributing an effect to “microbes” when it was caused by minerals or nutrients in donor soil.
8. Cost and reproducibility: a microbiome may be unstable from batch to batch.

9. The donor-soil problem

The doses found span orders of magnitude, but do not form a universal dose–response curve:

- **HYP-002** : forest humus at less than 0.02% of the organic carrier’s dry mass — an extremely small signal;
- **BIO-002** : 5% and 25% fresh forest soil in a greenhouse mixture with post-mining substrate — already a substantial share;
- **HYP-008** : 10% v/v natural soil followed by serial dilution in a controlled microcosm;
- **HYP-009** : transfer of soil layers 1, 3 and 5 cm thick — about 10, 30 and 50 L/m², an ecologically costly transfer;
- **HYP-010** : 10–50% fungus-rich spent mushroom substrate — a carrier amendment, not a small soil inoculum.

These values cannot be combined into one “optimal percentage”. They differ in purpose, dose unit, donor material and recipient medium. A new experiment requires a logarithmic pilot dose series with live- and sterilised-material controls. The preferred donor-source hierarchy is:

1. material that will in any event be lawfully removed or destroyed;
2. a small rhizosphere or forest-litter sample multiplied without repeated removal;
3. a compatible locally cultured consortium of known biosafety;
4. commercial inoculum only after taxa and functions have been confirmed;
5. exclude intact valuable donor habitat.

10. Comparison of systems A/B/C/D/E and B-time

System	Treatment	Expected distinction	What could produce a false conclusion
A	Mine substrate without organic amendment	Baseline natural succession and geochemical constraint	Different initial patches, seed rain and hydrology
B	Qualified mature compost	C/nutrients/structure plus compost’s own microbiome	Mistaking an early nutrient pulse for soil formation
C	B + a small amount of whole living donor soil, mixed at application	Transfer of whole donor soil without prior development in compost	Donor minerals/nutrients; harsh substrate immediately filters the inoculum
D	B + cultured native bacterial/fungal inoculum, mixed at application	Transfer of the culturable fraction without prior development in compost	Carrier effect; cultivation bias; harsh substrate immediately filters the inoculum

System	Treatment	Expected distinction	What could produce a false conclusion
E	Pre-colonised mature compost + controlled secondary maturation	Possible carrier colonisation, altered C/N forms and community before field use	Effect of additional time/moisture/aeration rather than living inoculum; pathogen transfer; C/N losses; nitrate accumulation
B-time	The same mature compost given the same secondary holding time as E, but without living inoculum	Separates time/moisture/aeration from pre-colonisation	Does not control the carrier unless it is added separately

There is a scientific basis for expecting E to differ from B/C/D and B-time because maturation and inoculation timing can change chemistry and community. There is no scientific basis for assuming in advance that E will be better.

11. Theoretical calculation

11.1 Purpose

This is a **MODEL / HYPOTHESIS, NOT AN EXPERIMENTAL FACT**. The calculation shows the scale of loading and helps exclude dangerous treatments; it does not predict plant growth or soil formation.

11.2 One observed material profile

For transparency, the example does not use an invented “average compost”. It uses an empirical mean for goat-manure compost from [ORG-007](#) (Utah State University analytical-laboratory samples, 2005–2019): moisture 54%; as received, N 1.0%, P₂O₅ 0.9%, K₂O 1.9%; pH 8.4; EC 5 dS/m; C:N 10. Conversion to dry matter gives approximately N 2.17%, elemental P 0.85% and elemental K 3.43%; indicative C derived from the stated C:N × N is about 21.7% of dry mass. The last value is suitable only for a preliminary mass estimate and does not replace direct total organic carbon (TOC) analysis.

Dry-compost dose	Wet mass at 54% moisture	Approximate C	Total N	Elemental P	Elemental K
20 Mg dry matter/ha	43.5 Mg/ha	4.35 Mg/ha	435 kg/ha	171 kg/ha	685 kg/ha
50 Mg dry matter/ha	108.7 Mg/ha	10.87 Mg/ha	1,087 kg/ha	427 kg/ha	1,713 kg/ha
100 Mg dry matter/ha	217.4 Mg/ha	21.74 Mg/ha	2,174 kg/ha	853 kg/ha	3,426 kg/ha

Formula for each nutrient: $\text{loading, kg/ha} = \text{dry-mass dose, Mg/ha} \times \text{concentration, \% dry matter} \times 10$.

This table neither recommends goat-manure compost nor says that all total N/P/K will become available. It shows why even a “moderate” dry-mass dose can apply hundreds of kilograms of nutrients per hectare, and why dose should be limited by water risk rather than desired layer thickness.

11.3 Inoculum mass

Applying the HYP-002 proportion (<0.02% dry mass) to 20 Mg dry carrier gives less than 4 kg dry humus per hectare. Five per cent donor soil gives 1 Mg/ha; 25% gives 5 Mg/ha. These treatments differ by hundreds or thousands of times and are not equivalent interventions.

11.4 What the model cannot calculate in principle

- pH and EC cannot honestly be derived by linear averaging;
- potentially mineralisable N requires incubation of the specific mixture;
- P availability requires sorption/desorption data for the specific post-mining substrate;
- C persistence requires separation of compost C, new plant C and fossil coal C;
- water response requires a column or lysimeter experiment.

12. Can E actually differ from ordinary compost?

Yes, it can differ measurably. The literature shows that community succession, maturation duration, moisture history and inoculum composition alter microbial biomass/composition, C transformations, N forms, humification indicators and sometimes plant condition.

But an additional advantage of E has not been demonstrated. The effect may equal B if mature compost already carries a functionally sufficient community; equal C or D if colonisation proceeds just as rapidly after direct application; equal B-time if the difference is created only by additional holding; or be worse than B/C/D because of nutrient loss, nitrate accumulation, pathogen transfer, donor mismatch, AMF suppression or added cost.

The critical unproven transition is:

change in microbiome and maturity indicators during the secondary phase → safer water and a more self-sustaining post-mining soil system years later.

That is the transition the experiment must test.

13. How to test it experimentally

Stage 1 — controlled mesocosm

On one thoroughly characterised safe post-mining substrate:

- **A**: prepared post-mining substrate without compost;
- **B**: ordinary qualified mature compost;
- **C**: B + a small amount of whole living donor soil, mixed at application;
- **D**: B + cultured native bacterial/fungal inoculum, mixed at application;
- **E**: pre-colonised mature compost + defined secondary maturation before application;

- **B-time** : the same mature compost given the same secondary holding time as E, but without living inoculum;
- **C-killed** : the same mass of donor mineral material after sterilisation;
- **D-killed/carrier** : inactivated cultured product + identical carrier;
- **E-killed/carrier-time** : the same carrier and secondary phase with inactivated inoculum.

Mandatory rules:

1. Equalise dry compost mass, target C/N/P/K, donor-mineral mass, water, mixing and incubation temperature.
2. Do not fix calendar time in advance: define transition by temperature stability, oxygen, respiration, $\text{NH}_4\text{:NO}_3$, EC, germination/phytotoxicity and sanitary criteria.
3. Block donor batches and mesocosm position; randomise treatments.
4. Determine sample size from pilot variance and a preregistered power calculation, not an attractive number.
5. Planted and unplanted subplots must distinguish plant filtering from processes caused only by the applied material.
6. Use several native plant functional groups; do not combine AMF-dependent and less-dependent plants into one measure.

Co-primary outcomes:

- **safety**: nitrate, ammonium, dissolved/suspended P, DOC/COD, DO, EC, pH, salts and site-relevant metals in leachate;
- **autonomy trajectory**: plant survival/recruitment, litter/root inputs, microbial biomass/function, fungal community/AMF, aggregation, infiltration and water retention after external inputs cease.

Stopping rules: unacceptable leachate, inadequate pathogen/weed control, anaerobic instability, plant toxicity or metal mobilisation. Only safe treatments that are not inferior on water endpoints advance.

Stage 2 — replicated field experiment

Take forward not the treatment with the greatest biomass, but Pareto-safe treatments. Use randomised blocks, a baseline season, runoff/leachate measurement, no reapplication after establishment, and surveys at 1, 2, 3, 5, 7 and 10+ years. Success requires declining dependence on intervention, not one green season.



HYP-011 field study on post-mining land at Konin/Kleczew. Figure 1 from Choińska-Pulit et al. (2026), CC BY 4.0. The diagram shows the control area, treatment area and separating strip. Each treatment had one large area; many measured plants do not replace independent plot replication.

18. The Polish experiment of 2026

FACT • CLOSE ANALOGUE • field experiment (HYP-011). The closest technological analogue used a feather/straw/lignite mixture at 20:60:20, microbial inoculation, 41 days of processing and application to post-mining soil at a field rate of 18.3 t/ha of product; an early positive plant response was observed in the maize experiment. It has not been conclusively established whether the field rate was calculated on a wet- or dry-mass basis.

Card field	Recorded
Feedstocks	Feather : straw : lignite = 20:60:20
Inoculation	Microbial strains and timing are given in bibliographic record HYP-011
Processing	41 days; reactor conditions, C:N and NH ₄ -N are retained in the evidence record
Field rate	18.3 t/ha; the calculation basis should be checked against the original publication
Crop / outcome	Maize; early plant response
Strength of evidence	Study of a constructed material and its field application; close analogue, not a direct test of system E

THERE WAS NO FIELD CONTROL USING THE SAME MATURE UNINOCULATED COMPOST. The experiment therefore does not isolate the effect of inoculation and does not demonstrate an advantage of our sequence.



HYP-011 field test: control without compost on the left, compost area on the right. Figure 6 from Choińska-Pulit et al. (2026), CC BY 4.0. The visible difference concerns one season and the complete compost material; it does not isolate the effect of inoculation or demonstrate long-term soil restoration.

G. The Polish experiment of 2026

Publication: Anna Choińska-Pulit, Justyna Sobolczyk-Bednarek, Dominika Kufka, Amelia Zielińska. “Development and Field Evaluation of a Microbially-Inoculated Feather–Straw–Lignite Compost Material for the Reclamation of Post-Mining Soils.” *Materials* 2026, 19(14), 3035; published 14 July 2026; DOI 10.3390/ma19143035 (HYP-011).

Field	Verified record
Feedstocks	Poultry feathers 20%, wheat straw 60%, lignite 20%
Inoculum	Multi-strain complex: <i>Bacillus altitudinis</i> 33, <i>Bacillus methylotrophicus</i> Alk, <i>Streptomyces fulvissimus</i> K59
Inoculation time	At the beginning of the process, not after the thermophilic phase
Process	Scale-up from laboratory to a 200 dm ³ dynamic reactor; 41 days
Product	C:N 12.09; NH ₄ -N 0.03%; application at 18.3 t/ha
Field	Sandy post-mining soil near Konin; maize (<i>Zea mays</i>); field assessment in 2025, one season
Study design	One treated plot and one unamended plot; many measured plants within one plot do not replace independent plot replication

Field	Verified record
Result	Soil urease 3.91 UU; P ₂ O ₅ 3.4 g/kg; mean shoot height 30.23 versus 25.88 cm, a 15% difference, t(645)=6.63, p<0.001
Limitations	Early-spring moisture and temperature constrained absolute enzyme activity; no water/leachate, microbiome persistence or autonomy endpoints

Critical boundary: **there was no ordinary mature uninoculated compost field control.** Inoculated and uninoculated batches were compared during composting, but the field comparison does not answer the question of ordinary compost B versus pre-inoculated material D/E. This is a close analogue, not a direct test of the hypothesis (HYP-011).

19. Culturable native microbiome

FACT • DIRECT EVIDENCE FOR THE CULTURABLE FRACTION • controlled 28-week experiment (MIC-001). In the Pilbara experiment, a culturable bacterial fraction was obtained from 1 g of donor soil, multiplied, placed on a carrier and applied to post-mining soil. After 28 weeks, the bacteria-only treatment produced +75% total N relative to control and +147% substrate-induced respiration relative to control; bacteria plus cyanobacteria did not produce a better result in the measured properties.

THE CULTURABLE FRACTION IS NOT A COPY OF THE WHOLE SOIL MICROBIOME. The culturable part of the community was scaled, not whole soil and not its full set of functions.

Critical boundary: this is a culturable fraction, not an enlarged copy of soil. Culturing selects organisms able to grow in the chosen medium; rare taxa, obligate symbionts and some interactions are lost, and community drift continues during scale-up.

H. Culturable native microbiome

What can actually be grown

- Culturable native bacteria and some free-living fungi can be multiplied in a controlled medium and delivered through a carrier (MIC-001/002).
- AMF can be increased through trap cultures with a host plant; they are obligate biotrophs and therefore require compatible living plants (MIC-004/005).
- Defined consortia/SynComs are easier to standardise, but reproduce only a narrow part of the food web (MIC-007/008).

Direct fact about a small donor sample

MIC-001 : 1 g native natural soil → 25 mL broth for 7 days → serial transfer of 1 mL for another 7 days → 1 mL culture onto an extruded pellet → degraded post-mining soil in the Pilbara. After 28 weeks, the bacterial treatment increased total N by 75% and substrate-induced respiration by 147%; the bacteria-plus-cyanobacteria mixture improved none of the measured soil properties. This is cultivation of the culturable fraction, not multiplication of whole soil.

MIC-005 : 50 g field material → a 1,000 mL pot containing autoclaved sand and host plants → four months. This confirms host-assisted multiplication of AMF, but does not establish a per-hectare dose.

Whole soil, cultured inoculum and SynCom

Approach	Benefit	Loss/risk	Evidential boundary
Whole soil	Best retention of unknown bacteria, fungi, propagules, fauna and interactions	Donor damage, pathogens/seeds, low scalability	Direction of trajectory demonstrated; no universal minimum dose; effect may remain within the inoculated layer (HYP-009 , MIC-009)
Cultured/enriched inoculum	Large volume from a small sample; quality control and carrier delivery possible	Selection of fast-growing culturable fraction, community drift, loss of guilds/interactions	Individual post-mining soil functions improved; ecological equivalence not demonstrated (MIC-001/002/003)
Defined consortium / SynCom	Reproducible composition and target functions	Narrow food web; unpredictable competition/facilitation	Establishment and benefit are context-dependent (MIC-007/008 , HYP-001/011)

Cultivation bias selects organisms according to medium, C source, oxygen, temperature and serial transfers; rare guilds, trophic/spatial interactions and obligate symbionts without a host are lost (MIC-002/003). Carrier delivery is possible through pellets, compost-based media for AMF, and engineered organic/mineral matrices, but the carrier itself changes pH, water and nutrients, so an uninoculated carrier control is required (MIC-001/004).

Pre-colonising mature compost is technically possible as a carrier concept, but it has not been demonstrated that, after secondary maturation, it outperforms applying the same inoculum directly at the site. $E > D/C$ is a testable hypothesis, not an established fact.

20. Whole soil, cultured inoculum and synthetic community (SynCom)

Approach	What is transferred	Advantage	Loss	Scale	Risk	Evidence
Whole soil	Living community, mineral particles, organic matter, propagules and unknown relationships	Maximum completeness of transferred material	Variability; biota cannot be separated from medium	Limited by donor-material availability	Donor-site impact, pathogens, weeds, ecological mismatch	Field soil-transfer literature; close analogues
Cultured native inoculum	Culturable fraction of selected bacteria and fungi	Scale-up of a small sample; controlled carrier	Cultivation bias; rare taxa and obligate symbionts	Laboratory to mesocosm and field is possible	Drift, contamination, low persistence	MIC-001 and related work
Synthetic community (SynCom)	Defined strains with known functions	Repeatability and causal testing	Simplified network; missing unknown functional groups	Technically scalable	Ecological mismatch, community collapse, missing functions	Laboratory and greenhouse evidence stronger than field evidence
Direct inoculation	Living material applied directly to substrate or planting zone	Simple; no secondary maturation	Weak protection and short establishment window	Potentially field-scalable	Desiccation, predation and dilution	Many disparate field analogues
Pre-colonised mature compost	Inoculum receives time in the carrier before field use	Possible protection and accumulation of biomass/metabolites	Community may change before field use	NOT YET CALCULABLE	Contamination, shelf life, loss of target taxa	Central hypothesis; no direct comparative evidence

21. Mycorrhiza

FACT. Arbuscular mycorrhizal fungi are obligate biotrophs: they cannot be scaled in the same way as free-living bacteria. Multiplication requires a living host plant; trap cultures, spores and colonised root fragments are used.

Limitations: host-plant choice alters the community; greenhouse multiplication does not guarantee field establishment; high colonisation is not equivalent to improved enzyme activity, glomalin, water condition or growth; donor-site impact and pathogen risk remain. In A–E, AMF require a separate host-plant multiplication module and the corresponding controls.

7. Mycorrhiza

AMF are obligate biotrophs: normal multiplication requires a compatible living host. Demonstrated schemes use trap plants, spores, colonised root fragments and hyphal substrate. MIC-004 shows on-farm multiplication in a diluted compost-based medium; MIC-005 uses 50 g of mine/reference material in a 1 L trap pot with three host-plant groups for four months.

This is the strongest example showing that a small donor sample can be increased without removing topsoil on a massive scale. But the result is not universal:

- the host plant selects part of the AMF community;
- high P availability can reduce symbiosis and sporulation;
- locally sourced inoculum may be better adapted, but “local” does not guarantee compatibility or safety;
- commercial inoculum is more reproducible, but may fit local plants and the local environment poorly;
- root colonisation does not guarantee plant growth, restored enzyme activity or field persistence (MIC-006).

22. Experiment A–E

A prepared substrate without compost	B ordinary mature compost	C B + whole donor soil / direct inoculation
D B + cultured native inoculum	E pre-colonised mature compost + secondary maturation	B-time same holding period without live inoculum

Figure 4. Main systems A–E and time control. Inactivated-material, carrier and AMF controls are added to the causal design; E is not presumed to be the winner.

HYPOTHESIS. The experiment must identify separately the effects of mature compost, whole donor soil, cultured inoculum, pre-colonisation time and carrier. E is not presumed to win.

HYPOTHESIS. The design below is intended to test the hypothesis; it is not permission for field application.

1. Testable hypothesis

Can a single application of qualified organic material, alone or together with biological inoculation, accelerate the transition of a safe post-mining substrate towards a system that, after establishment, increasingly supports plants, soil structure and nutrient cycling through its own roots, litter and microbiome — without unacceptable effects on water?

Nested question: does cultured inoculum from a small local donor sample differ from direct donor-soil application, and does pre-colonisation of mature compost produce an additional effect?

2. Zero-stage engineering safety: the site

A biological experiment is prohibited where there is active combustion, geotechnical instability, uncontrolled acid generation/drainage or unacceptable mobility of salts and toxicants. Before randomisation, mineralogy, acid–base balance, pH, EC/SAR where applicable, total and leachable contaminants, particle-size distribution, bulk density, hydrology, slope and thermal condition must be characterised.

3. Stage 1: controlled mesocosm

One homogenised, safe and characterised post-mining substrate; one batch of qualified mature compost; one compatible donor ecosystem; identical mineral and plant inputs.

Main treatments

- **A**: post-mining substrate without amendment;
- **B**: post-mining substrate + mature compost;
- **C**: mature compost + a small amount of living donor soil, mixed at application;
- **D**: mature compost + cultured bacterial/fungal inoculum from the same donor sample, mixed at application;
- **E**: mature compost pre-colonised with the same cultured inoculum and given defined secondary maturation before application.

Mandatory causal controls

- **B-time**: compost receives the same secondary holding period as E, but without living inoculum;
- inactivated-material control for C (**C-killed**): the same mass of donor mineral material after sterilisation;
- inactivated-material and carrier control for D (**D-killed/carrier**): inactivated cultured product with an identical carrier;
- inactivated-material, carrier and holding-time control for E (**E-killed/carrier-time**): the same carrier and secondary phase with inactivated inoculum;
- AMF subfactor only with compatible host plants and a paired no-AMF control.

Dry compost mass, water, carrier, mixing, temperature and measurable C/N/P/K/salt inputs must be equalised across treatments. Equal liquid volume is not an equal inoculum dose: viable cells/propagules, biomass, community composition and functional markers must be recorded.

Replication and randomisation

- independent donor batches and compost batches are random effects, not pseudoreplicates;
- a pilot first estimates variance, followed by a power calculation for the co-primary safety and autonomy outcomes;
- block randomisation is used for chamber/bench position;
- planted and unplanted sub-treatments separate plant filtering from the material's own dynamics;
- the protocol and exclusion rules are preregistered before outcomes are known.

Duration and sampling

Baseline; a time series through secondary maturation; after application — 1, 2, 4 and 8 weeks, then 3, 6, 12, 18 and 24 months. Progression to the field stage requires at least one complete growing cycle and a safe leachate profile.

4. Measurements

Co-primary safety outcomes

Leachate/runoff volume; pH; EC; alkalinity/acidity; NO₃; NH₄; dissolved/suspended P; DOC; COD/DO where applicable; sulphate; site-specific metals/metalloids; feedstock-related PFAS and organic contaminants; pathogens and weed propagules.

Co-primary function and autonomy outcomes

Plant survival, growth, reproduction and recruitment; root/litter inputs; microbial biomass; respiration and enzyme activity; N transformations; P mobilisation; bacterial/fungal composition; functional genes where possible; AMF colonisation; aggregate stability; bulk density/porosity; infiltration/water retention; erosion; condition after irrigation, fertilisation and material inputs cease.

Inoculum persistence

The donor/cultured community is tracked with strain-appropriate markers and community sequencing. Both presence and function are measured: DNA detection alone is not establishment, and establishment alone is not benefit.

5. Stopping rules

A treatment stops or does not advance if it produces unacceptable contaminant export in leachate, inadequate pathogen/weed control, anaerobic instability, plant toxicity, salt damage, metal mobilisation, erosion or evident ecological mismatch. Selection follows a Pareto rule: no treatment advances solely because it produces maximum biomass.

6. Stage 2: replicated field experiment

Only safe mesocosm treatments that are not inferior to controls under predefined criteria enter the field. Minimum structure:

- two independent sites within one broad substrate class, preferably three;
- randomised blocks within each site by slope, aspect, moisture and baseline chemistry;
- final replicate count determined by a power calculation; six blocks per site is only an illustrative value, not a fixed requirement;
- plots approximately 10 × 10 m or larger, with buffer zones and permanent observation cores;
- machinery lanes isolated so that compaction does not become a hidden treatment;
- replicated runoff plots and/or lysimeters within blocks;
- adjacent reference ecosystem and the best old local Technosol recorded as trajectory benchmarks, not experimental treatments.

A–E should be retained where possible in the field comparison. If cost requires fewer treatments, C, D and E must not be combined while the cultured-microbiome hypothesis remains the main question.

7. Time horizon

Where possible, a full hydrological and biological baseline is collected before treatment. After treatment: event-based sampling, then 1, 2, 4 and 8 weeks; 3, 6 and 12 months; annually from year 2 through year 5; mandatory resurveys at 7, 10, 15 and 20 years. No result before year five is called persistent soil formation.

8. Success criterion

Success is declining dependence on intervention, not merely green cover. After a predefined establishment period, repeat material application, regular irrigation and “rescue” fertilisation cease. A treatment succeeds only if, without repeated external loading, it maintains safe water, plant recruitment, internal root/litter inputs, biological cycles, physical structure and an acceptable community trajectory.

9. Animal module

Goats, sheep and cattle are excluded from stages 1–2. A separate late grazing trial is permissible only after thresholds for cover, roots, erosion, water and contaminants have been met. It requires ungrazed exclosures, replicated paddocks, a soil-moisture stopping rule, protection for young woody plants and monitoring of animal exposure. Angora goats are one possible treatment, not the preferred answer in advance.

10. What the experiment can establish

The design separates the effects of organic material (B versus A), direct whole donor soil (C versus B and C-killed), cultured native inoculum (D versus B and D-killed/carrier), and pre-colonisation with secondary maturation (E versus D, B-time and E-killed/carrier-time). It also tests whether a microbial-community change leads to useful plant, process and water outcomes, and whether an effect persists after external inputs cease. A causal conclusion will apply only to the stated substrate, material, donor, climate and restoration objective; it will not demonstrate universal applicability.

23. Kuzbass: transferability

SYNTHESIS. Kuzbass is used to test transferability, not as the basis for a global conclusion. One recipe cannot be applied alike to burning, acid-generating, saline/sodic, unstable, coarse, compacted, young-Technosol and old revegetated spoil heaps.

Transferability of the global evidence to Kuzbass

The matrix does not recommend a particular site; it defines gates for testing whether global evidence transfers to a specific site.

Spoil type/condition	What to check first	What may transfer	What not to transfer automatically	Decision
Burning/heating	Thermal survey, gases, internal combustion, stability	Engineered extinguishing/isolation and monitoring	Compost, manure, inoculum, animals	BIOLOGICAL EXPERIMENT PROHIBITED until the source is controlled
Actively acid-generating / pyritic	Acid–base accounting, sulphate/Fe, drainage	Source control, covers, alkaline/mineral correction	Success of organic material alone on neutral spoil	ENGINEERING FIRST
Saline/sodic	EC, SAR/ESP, salts, drainage	Salt-tolerant treatment selection; justified gypsum/mineral correction	High-EC compost/digestate; irrigation-dependent case as evidence of autonomy	Limited mesocosm after correction
Geotechnically unstable / eroding steep slope	Slope, movement, settlement, runoff paths	Grading, drainage, erosion control, root-zone stabilisation	Large wet-mass application before stabilisation	ENGINEERING FIRST
Coarse/stony, little fine earth, chemically acceptable	Particle-size distribution, fine earth, bulk density, water retention	Loose mineral root zone, loam/fine earth, qualified compost at a limited dose, local seed hay	Compost as a substitute for the mineral skeleton	Most promising after a material × substrate test
Compacted reconstructed layer	Penetration resistance, pore network, machinery traffic	Traffic control, ripping/loose placement, roots, low-risk organic material	Inferring benefit from chemistry alone	Physical correction precedes biological interpretation
Existing young revegetated Technosol	Community, roots/litter, water, baseline microbes	Factorial compost × inoculum trial; autonomy without repeated inputs	Animals at an early stage	Possible experimental site

Spoil type/condition	What to check first	What may transfer	What not to transfer automatically	Decision
Old spontaneously revegetated spoil heap	Safety/geochemistry, reference history	Reference trajectory, chronosequence/resurvey, small non-destructive sampling	Treating age as an intervention, or unnecessary organic amendment	Reference/control; usually not an amendment site

Local evidence that changes the design

KUZ-003/005/006/007 show that moisture, relief, fine earth, root-zone material and local propagules may matter more than age. Loess-like material and local seed hay served different functions; topsoil also introduced a weed seed reserve. Global compost results therefore cannot be transferred without a common mineral foundation and control of plant inputs.

KUZ-008 excludes burning spoil heaps from biological treatment. KUZ-009/010 show why a regional name is not a substrate specification and why site-specific data must precede a recipe.

Transferable global conclusions

1. Dose is limited by water and contaminant risk, not by desired layer thickness.
2. Qualified mature compost differs from fresh manure, mixed municipal solid waste and untreated sewage sludge.
3. Root-zone physics and hydrology are independent intervention measurements.
4. Fossil coal carbon must be separated from new biological carbon.
5. A successful first season means establishment, not restoration.
6. Pre-inoculated living material and Angora goats remain experimental modules, not default practice.



On a waste-rock dump near Apanas, 2020. Natalia Zubkova archive. The photograph establishes the author's presence and the visible scale of the industrially altered landform; it does not measure temperature, gas composition or the boundaries of an internal combustion source.

24. Angora goats and the Maiminskaya solar power plant

24.1. Angora goats

Short answer

For the first field experiment — **no**. Manure can be studied as a processed and qualified external material without introducing goats, sheep or cattle onto a young site. Animals would add effects that are difficult to disentangle: selective feeding, trampling, compaction, local urine and dung hotspots, and transport of seeds and parasites. This would make the causal answer worse, not better.

What is supported

- On a reclaimed Spanish coal pasture (BIO-006), water-holding capacity and available water were greater in an exclosure; ungulate trampling increased compaction. Nurse shrubs partly protected soil from trampling while accumulating organic matter.
- Grazing may be an acceptable **final land use** if the restored land can already withstand it. The BIO-007 risk-assessment system links safety to stocking density, productivity, manager behaviour and the enforceability of restrictions.
- At the Navajo coal site (BIO-008), carefully planned cattle grazing with fencing, daily supervision, feed and water control, and animal-health testing was preliminarily feasible. But it was an experiment in post-mining land use, not evidence that cattle created soil. An

episode involving sulphate-rich pit water showed that forage alone does not guarantee site safety.

Goats versus sheep

No reliable comparative mined-land restoration experiment using goats and sheep was found in the corpus. Sheep therefore cannot be declared “better” merely because they graze grass more often while goats browse shrubs more strongly, nor can goats be declared beneficial because of their manure.

Biologically plausible differences require separate testing:

- goats may damage woody regeneration and nurse shrubs more strongly where they can reach them;
- sheep may concentrate more on the sward and can also compact a wet or weakly structured surface;
- for both species, stocking density, duration, season, moisture, slope, forage and protection of young plants determine the outcome more strongly than the animal’s name.

These are working mechanisms for risk assessment, not an established species ranking.

What the global search added

Evidence	System	What was actually measured	What cannot be transferred
BIO-010	Angora goats / Merino sheep / mixed grazing; 7.5–12.5 animals/ha; southern Australia, 1981–1984	Pasture composition, sward, bare ground and interaction with stocking rate in a replicated trial	Mature improved pasture, not a young spoil heap; a favourable goat result on one pasture does not establish general goat priority
BIO-011	Angora goats under short-duration grazing in Texas	Seasonal diet of grass, forbs and browse, and intake	Shrub selection does not demonstrate a benefit to nutrient cycling; it also implies risk to shrubs and young trees
BIO-012	Angora goats versus leafy spurge, North Dakota	Four-year response in target-weed density	Invasive-species control is a land-management service, not evidence of pedogenesis
Solar-site grazing literature	Mainly sheep on established agricultural/solar swards	Early soil-health, pasture and biodiversity responses	Construction, shade and previous farming are confounded with grazing; these sites are not spoil heaps

The first comparative field experiment with Angora goats and Merino sheep usefully inoculates us against the simple conclusion “sheep are always safer”. On one established annual pasture, high stocking density increased bare ground more strongly under sheep, while Angora goats maintained more clover and fewer weeds. But accompanying animal-response data indicated higher Angora-goat mortality under high stocking pressure and cold stress. Species and breed therefore do not replace the management frame: climate, stocking density, season, shelter and target vegetation remain decisive.

Angora goats — preliminary profile, not the final answer

- **Size:** extension sources confirm that Angora goats are smaller than many common breeds; adult bucks weigh about 180–225 lb (approximately 82–102 kg). A breeding-condition threshold of ≥ 75 lb (~ 34 kg) was found for does, but this is not a reliable average weight for adult females, so no mean female weight is fixed here.
- **Diet:** this is a mixed grazer–browser, not a pure “shrub eater”. In the Texas diet study, browse varied from about 10% to 38% seasonally; the mean was about 21%, and grass predominated at times.
- **Vegetation management:** direct evidence exists for leafy-spurge control and changes in improved-pasture composition.
- **Ecological risk:** shrub preference makes young trees, nurse shrubs and woody regeneration vulnerable. Animals can transport seeds; hoof pressure and urine/dung patches remain spatially uneven.
- **Animal welfare:** the mohair breed is nutritionally demanding and vulnerable to cold/wet conditions, especially after shearing; unsuitable climate or shelter may make the idea unacceptable even if vegetation responds favourably.
- **Nutrient return:** faecal output was measured in the Texas diet study, but universal kilograms of N/P per Angora goat per year cannot be inferred without a scenario for diet, intake, retention, urine and live mass. General goat-manure tables are not breed-specific evidence.

For now, only a conditional answer is defensible: Angora goats **may** be a tool for targeted vegetation management on an already stable, well-established site with protected woody regeneration. There is no evidence yet that they create a soil system or provide a net benefit on a former coal spoil heap.

Design decision

1. Livestock are excluded from phases 1–3 of the field experiment.
2. Manure compost is tested as a separate material of known dose and composition.
3. If the future land-use objective includes grazing, a separate late-stage trial begins only after thresholds for plant cover, root anchoring, erosion, compaction, water condition and contaminants in forage have been met.
4. A grazing treatment requires an ungrazed enclosure, replicated paddocks, a defined stocking rate, a soil-moisture stopping rule, and monitoring of bulk density, infiltration, erosion, plant community and animal exposure.

Conclusion

Animals may form part of the future management of a sustainable pasture. There is currently no basis for making them part of the mechanism that initiates soil formation. They are unnecessary for the original question and, at an early stage, are more likely to obstruct a clean and safe experiment.

Sources

- BIO-006 : DOI 10.1016/j.agee.2023.108483.
- BIO-007 : DOI 10.1016/j.agry.2012.03.002.
- BIO-008 : DOI 10.21000/JASMR97010255.
- BIO-010 : DOI 10.1071/AN09128.
- BIO-011 : DOI 10.2307/3899028.
- BIO-012 : Lym, Sedivec & Kirby (1997), Montana State University Range Science archive.

Main conclusion: Angora goats are not needed to initiate soil formation. Their possible role is vegetation management at a late stage, after a stable plant and soil layer exists. Grazing and browsing can change botanical composition and control some shrubs, but stocking density, season, trampling, compaction, bare ground, water-holding capacity and animal welfare determine the direction of the effect. Angora goats are sensitive to cold and wet conditions after shearing; they require shelter and proper management.

24.2. Maiminskaya solar power plant: provenance boundaries

Status	What can be claimed
DOCUMENTED	Natalia was at the Maiminskaya solar power plant in the winter of 2019 (AUTH-002).
AUTHOR’S RECOLLECTION	Natalia recalls proposing the use of sheep.
POSSIBLE WITNESS	Denis Shakin is named as a possible witness to the conversation; no independent confirmation is present in the corpus.
EXTERNAL REPORT	On 29 June 2020, <i>Kommersant Krasnoyarsk</i> , citing Hevel’s press service, reported 50 sheep at the Ust-Kanskaya solar power plant and possible extension of the practice, including to Maiminskaya (AUTH-003).
NOT DEMONSTRATED	It has not been demonstrated that Natalia’s proposal caused the Hevel experiment.

25. Economic model

SCENARIO MODEL. NOT AN ESTIMATE FOR APANAS. The model describes a hypothetical, complex, 100 ha coal spoil heap of the Apanas type. It is not a standard, average reclamation cost, commercial estimate, or reconstruction of expenditure at an existing site.

MODEL OF A COMPLEX 100 HA APANAS-TYPE SPOIL HEAP — NOT AN ESTIMATE FOR THE APANAS SPOIL HEAP. Apanas defines the type of complexity and the scale of reasoning; the model does not reconstruct its actual works, volumes or expenditure.

25.1. Three levels of outcome

Scenario	100 ha	Per hectare	Status
Lower-complexity scenario	\$4.7–5.9 million	\$47,000–59,000/ha	Scenario range
Central	\$9.5 million	\$95,000/ha	Rounded central scenario
High complexity	\$15.4–21.3 million	\$154,000–213,000/ha	Scenario range

Conversion rate: 84.3414 RUB/USD on 26 September 2026, official Bank of Russia series (ECO-004).

25.2. Central scenario

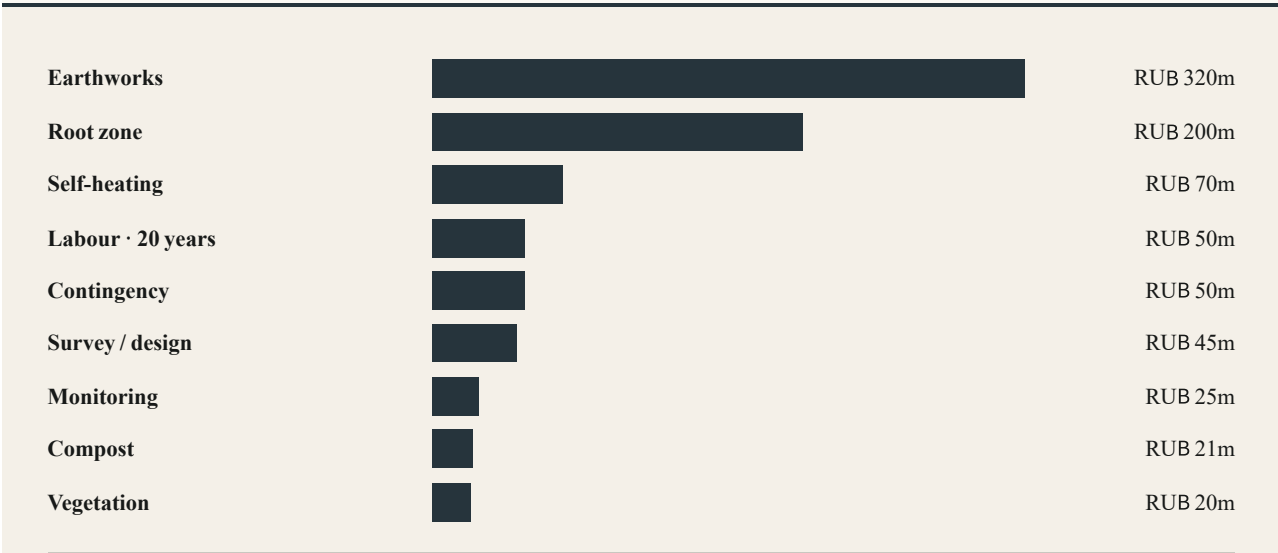


Figure 5. Structure of the central scenario; rows are rounded and the model total is rounded to RUB 800 million. These are not observed site expenditures.

Line item	RUB million	Evidence status	Comment
Control / elimination of self-heating	~70	SCENARIO ASSUMPTION + external benchmark	Actual area of the active zone is unknown

Line item	RUB million	Evidence status	Comment
Surveys, design and supervision	~45	EXTERNAL BENCHMARK + SCENARIO ASSUMPTION	Not a proposal for a particular site
Partial reshaping of the mass	~320	CALCULATED from volume and rate	Principal cost driver; operator is not counted twice where included in the contractor rate
Reconstruction of the mineral root zone	~200	CALCULATED + SCENARIO ASSUMPTION	Depends on thickness and local material
Compost / organic material	~21	CALCULATED from a benchmark	Does not include the unknown cost of system E
Vegetation	~20	EXTERNAL BENCHMARK + SCENARIO ASSUMPTION	Establishment, not an ecosystem guarantee
Additional human labour, 20 years	~50	SCENARIO ASSUMPTION	Long-term support beyond contractor rates
Environmental monitoring, 20 years	~25	SCENARIO ASSUMPTION	Sampling, surveys, equipment maintenance and data
Contingency / repeat interventions	~50	SCENARIO ASSUMPTION	Repeat work without false precision
Rounded total	800	CALCULATED, rounded	\$9.5 million / 100 ha

Unexpected result of the model: in the central scenario, the main cost drivers are earthworks and reconstruction of the root zone, not compost. This is not a universal law. The original question began with manure, but the economics led it to rock.

25.3. Human labour

The separate labour line concerns long-term support: field workers, technicians, environmental specialists, agronomists, soil scientists, sampling and vegetation-survey personnel, monitoring maintenance and data collection. Operators and drivers are not added a second time where they are already included in machinery/transport contractor rates.

25.4. Stripping ratio: evidential boundary

Source / site	Period	Stripping ratio	Unit	Context	Limitation
Kuzbass Fuel Company (ECO-005)	Q4 2010	6.1	m ³ /t coal	Actual aggregated quarterly indicator for the company's open-pit production	Not one mine and not Apanas; 2010
KFC (ECO-005)	2010 / 2009	7.3 / 7.1	m ³ /t coal	Annual production indicators	Group-average context

Source / site	Period	Stripping ratio	Unit	Context	Limitation
Central Kuzbass, gently dipping seams (ECO-006)	Data/design practice to 2017	9.3–12.3; calculated 11.5	m ³ /t coal	Current actual range and limiting design parameter for a combined system	11.5 is not a universal mean
Quintette, Canada (ECO-007)	Published 2016	3.5–6.4	m ³ /t coal	Comparable open-pit context	Different geology and system
Cerrejón, Colombia (ECO-007)	Published 2016	5–6	m ³ /t coal	Large open-pit operation	Not Kuzbass

The range 6.1–11.5 m³/t coal is used only as a **scenario-comparison parameter** for a complex open-pit operation. It does not transfer to underground mining, is not called universal for Kuzbass, and is not attributed to Apanas.

25.5. Modelled coal volume and restoration cost per tonne

SCENARIO MODEL. Hypothetical spoil volume: 32.3 million m³ / 100 ha .

associated coal production = spoil volume / stripping ratio

- 32.3 / 11.5 = 2.8087 million t ;
- 32.3 / 6.1 = 5.2951 million t ;
- published range: 2.8–5.3 million t coal .

THIS IS NOT A RECONSTRUCTION OF PRODUCTION AT THE APANAS SITE.

It is a mathematical relationship between a hypothetical spoil volume and associated coal production.

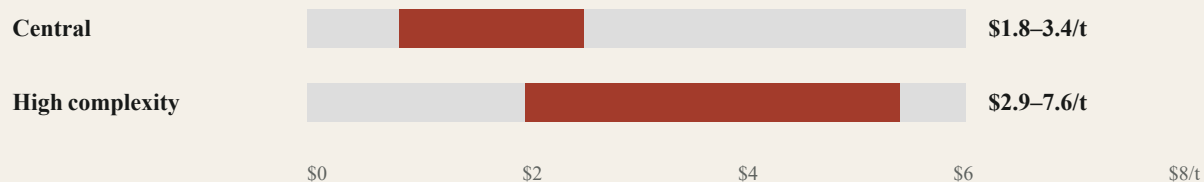


Figure 6. Scenario restoration cost per tonne of associated modelled coal production. Not the total environmental cost of coal.

scenario restoration burden = scenario restoration cost / associated modelled coal production

- Central scenario, \$9.485 million : $\$9.485 / 5.295 = \$1.79/\text{t}$; $\$9.485 / 2.809 = \$3.38/\text{t}$ → **\$1.8–3.4/t.**

- High complexity, \$15.4–21.3 million, independent combination of extremes: $\$15.4 / 5.295 = \$2.91/\text{t}$; $\$21.3 / 2.809 = \$7.58/\text{t} \rightarrow \text{\$2.9–7.6/t}$.

SCENARIO RESTORATION COST IS NOT THE TOTAL ENVIRONMENTAL COST OF COAL. The ranges \$1.8–3.4/t and \$2.9–7.6/t are the scenario cost of restoring disturbed land per tonne of associated modelled coal production. They are not a “true cost”, a total environmental cost, or the full cost per tonne.

25.6. Included and excluded

Included in the model	Excluded from the model
Safety and control of self-heating; engineering surveys; earthworks; root zone; organic material; vegetation; additional labour; monitoring; contingency for repeat intervention	Climate damage; combustion CO ₂ ; health damage; air-pollution externalities; monetary valuation of biodiversity; historical water damage; agricultural losses; resettlement; social/cultural consequences; full legal liability and other externalities

25.7. Sensitivity without false statistics

Very strong influence	earthwork volume × rate per m ³	root-zone volume × source/transport
Strong	area of active self-heating	share of mass requiring reshaping
	contingency for repeat intervention	
Moderate in the central structure	transport distance	compost dose
	labour and monitoring intensity	

Figure 7. Transparent ranked sensitivity analysis: three to five leading parameters without invented probability distributions. Ranking applies to the central model structure.

A transparent one-parameter-at-a-time scenario comparison shows that the total is driven most strongly by: (1) the proportion/volume of earthworks and the rate per m³ moved; (2) the volume and source of mineral root-zone material; (3) the area of the active self-heating zone;

followed by transport distance and the contingency for repeat intervention. Compost dose, labour and monitoring matter, but have smaller absolute weight in the central structure. This is not Monte Carlo modelling: distributions for probabilistic inference have not been established.

Preserving suitable topsoil, loam or fine earth during mining may reduce the future cost of root-zone reconstruction. This is an economic implication of the scenario model that requires site-specific calculation, not a ready quantitative promise.

25.8. System E

UNKNOWN. System E is **NOT YET CALCULABLE**. For pre-colonised mature compost plus secondary maturation, the following are unknown: inoculum dose per hectare; viable-inoculum yield; **donor-product** scale-up; shelf life; carrier; duration and conditions of maturation; area and equipment requirements; contamination control; and field persistence. Cost cannot be calculated before the experiment.

1. Summary parameter table

Parameter	Min.	Typical/reference	Max.	Unit	Conditions	Source	Confidence
Municipal, yard and other compost in post-mining field trials	10	—	112	Mg/ha; dose basis varies by case	10–90 in Minnesota; 112 yard-waste compost in combined Ohio treatment; not a universal recommended range	CASE-004/016	Medium: values known, moisture often unreported
Green-waste compost around trees	0.75	—	0.75	kg/tree, actual applied mass	Local application, not blanket per-hectare spreading	CASE-002	High
Engineered inoculated compost	18.3	—	18.3	t/ha; product-mass basis not fully defined	Polish post-mining sand; feather:straw:1 ignite 20:60:20; 41-day process	HYP-011	Medium
Weathered poultry litter	1	—	4	t/ha; dose basis not reported	Factorial trial with peat, sludge, Alginure and lime on pyritic coal spoil	CASE-033	High for stated dose; low for moisture
Cattle manure in equal-C-input experiment	8.0	—	8.0	t/ha; as reported	Supplied 2.7 t C/ha in five-year Shanxi experiment	CASE-025	High for dose; moisture unavailable

Parameter	Min.	Typical/reference	Max.	Unit	Conditions	Source	Confidence
Decomposed poultry manure	12	—	12	t/ha per application; dose basis not reported	Seven-year reclaimed maize system; repeated pre-sowing fertilisation	CASE-026	High for dose; frequency must be confirmed from full table before cost calculation
Organic ameliorant mixtures	40	—	132	t/ha; as reported for thesis treatments	One-year container experiment with reconstructed coal profile; component effects mixed	CASE-035	Medium
Biosolids in long-term one-time field trials	22	—	250	Dry mass, Mg/ha	Virginia 22/56/112/224 ; British Columbia 150/250; other field cases 224	CASE-009/010/012/013	High
Biosolids in short Minnesota trial	7.17	—	28.69	Dry mass, Mg/ha	Originally 3.2/6.4/12.8 dry short tons/acre	CASE-015	High
Biosolids under repeated cumulative application	801	—	1,815	Cumulative dry mass, Mg/ha	35-year Illinois fields; several applications, not one dose	CASE-011	High for cumulative total; application schedule absent from current extraction
Sewage sludge in old Scottish trial	5	—	20	t/ha, partly dried; exact dry-matter fraction unavailable	Combined with 0/10/25/50 t lime/ha	CASE-033	High for dose; low for dry matter
Paper-mill residue in Minnesota trial	62.77	—	125.54	Dry mass, Mg/ha	Originally 28/56 dry short tons/acre; incorporated to 15.2 cm	CASE-015	High
Peat, paper and compost residues in Minnesota programme	10	—	90	Mg/ha; basis varies by material and study	Early multi-site experiments	CASE-016	Medium
Biochar in equal-C-input experiment	8.3	—	8.3	t/ha; as reported	Supplied 2.7 t C/ha	CASE-025	High for dose; moisture absent
Compost in equal-C-input experiment	11.0	—	11.0	t/ha; as reported	Supplied 2.7 t C/ha	CASE-025	High for dose; moisture absent

Parameter	Min.	Typical/reference	Max.	Unit	Conditions	Source	Confidence
Biogas-plant residue in equal-C-input experiment	7.7	—	7.7	t/ha; as reported	Supplied 2.7 t C/ha	CASE-025	High for dose; moisture absent
Maize straw in equal-C-input experiment	6.7	—	6.7	t/ha; as reported	Supplied 2.7 t C/ha	CASE-025	High for dose; moisture absent
Lime in ordinary mine and field experiments	2	—	224	Mg/ha or t/ha	Jamari 2; Candiota 10.4; Scotland 10/25/50; metal tailings 224	CASE-013/031/032/033	High; substrate-dependent, not a general range
Additional lime under an old pyrite rule	40	—	40	t CaCO ₃ /ha per 1% FeS ₂	Historical design rule from Scottish thesis; not a modern site prescription	CASE-033	Low; historical benchmark only
FGD mineral amendment	280	—	280	Mg/ha	Acid coal land in Ohio; sometimes +112 Mg/ha yard-waste compost and 20 cm reconstructed layer	CASE-004	High for case; not transferable without chemistry
Fertile-soil/root-zone layer	0.10	—	0.50	Thickness, m	Kuzbass: 10 cm in trial / ≥20 cm in operational work; Virginia 30 cm; Candiota 30–40 cm; Poland about 50 cm	KUZ-006 , CASE-009/030/031	High
Spent malt grain in constructed coal Technosol	5	—	5	% w/w	95% coal-flotation tailings; preliminary optimum about 5–10%, final design 5%	HYP-001	High for pot experiment
Activated microbial inoculum in constructed Technosol	2.5×10 ⁷	—	2.5×10 ⁷	Cells/g Technosol	After “tea” preparation and activation; 7-day incubation after mixing	HYP-001	High

Parameter	Min.	Typical/reference	Max.	Unit	Conditions	Source	Confidence
Extraction ratio for soil/compost “tea”	1:4	—	1:4	Solid:water, mass to volume	22 °C, darkness, daily manual shaking, 7 days, then coarse filtration	HYP-001	High
Starting sample for culturing native bacteria	1	—	1	g donor soil per 25 mL broth	7 days at 30 °C, serial transfer of 1 mL, another 7 days; 1 mL culture per pellet	MIC-001	High
Starting sample for AMF trap culture	50	—	50	g field material per 1,000 mL pot	Autoclaved sand + three host-plant groups; four months	MIC-005	High
Whole-soil inoculum dose	—	—	—	—	No universal minimum; studies use incomparable volumetric, layered and suspension doses	BIO-001/002/005, HYP-009	High confidence that no universal value is established
Initial compost-mixture moisture	50	60	70	% wet mass	USDA process-management range, not shipped-product moisture	ORG-010	High as engineering guidance
Initial compost-mixture C:N	20:1	—	40:1	Mass ratio	Range for rapid composting; not proof of maturity	ORG-010	High
Process to Further Reduce Pathogens (PFRP), in-vessel or aerated static pile	3	—	3	Days at ≥55 °C	Sanitary time–temperature regime, not total composting duration	ORG-010	High
PFRP, windrow	15	—	15	Days at ≥55 °C	At least five turnings; sanitary stage only, followed by maturation	ORG-010	High

Parameter	Min.	Typical/reference	Max.	Unit	Conditions	Source	Confidence
Upper loose bulk density of compost mix for aeration	—	—	641	Approx. kg/m ³	Original threshold 1,080 lb/yd ³ ; above it, airflow may be inadequate	ORG-010	Medium after unit conversion; process, not transport, benchmark
Bulk density of clean wood chips	264	—	368	Approx. kg/m ³	Originally 445–620 lb/yd ³ ; feedstock estimate only	ORG-010	Medium; actual chip size and moisture required

2. Application, repetition and effect duration in individual cases

Case	Material	Dose	Application / preparation	Repetition	Observation, years	Did the effect persist?	Source
Virginia CASE-009/010	Biosolids; sawdust; topsoil	Biosolids 22/56/112/224 dry Mg/ha; sawdust 112 Mg/ha; 30 cm soil layer	Reclaimed coal site; randomised, n=4; exact incorporation depth absent from current extraction	One initial application	16 and 27	Some early bulk differences converged; C/N-fraction and MBC legacies persisted	CASE-009/010
Ohio CASE-004	FGD ± yard-waste compost; reconstructed layer/lime	280 Mg/ha FGD; 112 Mg/ha compost; 20 cm reconstructed layer	Combined mineral, organic and profile intervention	One initial application	16	Vegetation legacy persisted; water and autonomy data incomplete	CASE-004
Wales CASE-002	Municipal green-waste compost	0.75 kg/tree	Local application around planted trees	One	11	No universal height/DBH benefit; survival depended on species	CASE-002
Illinois CASE-011	Biosolids	801–1,815 dry Mg/ha cumulative	Repeated field applications	Repeated; detailed schedule not extracted	35	Narrow groundwater-metal record persisted; ecological effect not evaluated	CASE-011
British Columbia CASE-012	Biosolids	150/250 dry Mg/ha	One-time addition to tailings	One	13	C/biomass advantage persisted; lower dose more efficient per unit mass; Zn risk at 250	CASE-012

Case	Material	Dose	Application / preparation	Repetition	Observation, years	Did the effect persist?	Source
Metal tailings CASE-013	Lime + biosolids	224 + 224 Mg/ha	Co-application; exact mixing depth not extracted	One	21	Many soil functions persisted; Cd/Zn risk remained	CASE-013
Minnesota CASE-015	Biosolids ± paper-mill residue	7.17/14.35/28.69 dry Mg/ha biosolids; 62.77/125.54 dry Mg/ha paper residue	Surface application and incorporation to about 15.2 cm; slopes graded beforehand; seed and 4.48 Mg/ha straw mulch	One	2–3 growing seasons	Cover increased, but nitrate and cost penalties rose with dose; later persistence unknown	CASE-015
Minnesota CASE-016	Peat, yard compost or municipal solid-waste (MSW) compost, paper residues	10–90 Mg/ha	Field plots and full-scale slopes; sources within 100 km noted	One reported application	5–9 for plots; 2 for early full scale	Some 10 Mg/ha treatments reached 90% cover by year 5; 44.8 Mg/ha reached the standard in 3–5 years	CASE-016
Shanxi CASE-025	Biochar/compost/digestate/manure/straw	8.3/11.0/7.7/8.0/6.7 t/ha; 2.7 t C/ha each	Incorporated into 0–30 cm; baseline and application in 2011; 0–20 cm sampled in 2011 and 2016	One initial equal-C application	5	C-pool differences persisted to 2016	CASE-025
Shanxi CASE-026	Decomposed poultry manure	12 t/ha plus defined nutrient equivalent	Compacted, levelled/backfilled agricultural land; fertilisation before maize sowing	Repeated in seven-year system; number of applications requires verification before costing	7	SOM/N and bacteria changed; community remained different from adjacent farmland	CASE-026
Poland CASE-027	Sludge or compost + lake chalk	Sludge 33; compost 45 Mg/ha in maximum treatments	Field phytoremediation; depth not extracted	Not reported	Exact duration requires verification from full table	SOC/plant response, but pine phytotoxicity in sludge treatment	CASE-027
Scotland CASE-033	Peat/sludge/poultry litter/Alginure + lime	Peat/sludge 5/10/20; litter 1/2/4; Alginure 2.4/5.2/10.4; lime 0/10/25/50 t/ha	Pyritic spoil; also 300 kg/ha NPK and sowing	Authors judged old additions needed renewal; no documented repeat dose	About 10	Effect of 50 t lime often persisted; organic-only treatments mostly remained unvegetated	CASE-033

Case	Material	Dose	Application / preparation	Repetition	Observation, years	Did the effect persist?	Source
Chile CASE-034	Goat manure/biosolids/grape and olive residues/mixtures	Exact treatment doses retained in primary article; no safe normalisation completed in registry	Incorporated to 20 cm; 13 treatments ×3; irrigated for three establishment seasons	No repeat organic application; irrigation repeated	3	Late biomass in some treatments; fertility declined, early DOC/Cu pulse, olive-residue treatments failed	CASE-034
South Africa CASE-035	Manure/chip/grass/lucerne/fly-ash mixtures	40 or 132 t/ha by treatment	Reconstructed rock-subsoil-soil profile in 1×1×1.2 m containers	One	1	Positive multi-indicator mixture within experiment; field persistence unknown	CASE-035
Kuzbass KUZ-006	Loess-like loam or topsoil + local seed hay	10 cm layer in factorial trial; operationally ≥20 cm + 5 t seed hay over 3 ha	Grading, root-zone placement, mechanical seed-hay distribution	One material/seed-hay application	4–9	Strong cover/community trajectory; soil/water autonomy not demonstrated	KUZ-006
Poland HYP-011	Inoculated feather:straw:ignite compost	18.3 t/ha	Feedstocks 20:60:20, inoculation day 0, 41 days reactor composting, application to post-mining sand	One field application	One season	Plant/soil response reported; no same-uninoculated-compost field treatment and no long-term test	HYP-011
Coaltech HYP-001	5% spent malt grain + cultured/“tea” inocula	Carrier 5% by mass; 2.5×10^7 cells/g	7-day extraction, 7-day activation, mixing at 50% field capacity, 7-day incubation at 30 °C with daily gas exchange	Prepared for each pot cycle; not repeated field application	Two plant cycles of about 90 days	Early benefit of compost “tea”/EM; native-soil “tea” did not help; later differences narrowed	HYP-001
Pilbara MIC-001	Cultured native bacteria/cyano bacteria in pellets	1 g donor soil → culture; 1 mL culture per pellet	Two 7-day culture stages; carrier was an extruded seed pellet	One	28 weeks	Bacteria improved N/SIR; mixture with cyanobacteria did not; long-term persistence unknown	MIC-001

3. Substrate preparation before organic material is applied

The economic model must contain separate modules; organic-material application is not the first cost line:

Condition	Mandatory work before the biological stage	Evidence base
Burning/heated spoil	Thermal survey, extinguishing/isolation, gas and stability control	SUB-003 , KUZ-008
Actively acid-generating material	Acid-base accounting; segregation/encapsulation/cover/drainage and calculated alkaline correction	SUB-001/003 , FAIL-003 , CASE-022/033
Geotechnical instability/erosion	Grading, landform and drainage design, stabilisation	SUB-003 , KUZ-006 , CASE-024
Compacted root zone	Controlled machinery traffic, ripping/decompaction or loose placement	KUZ-005/006 , CASE-021/030
Coarse material/little fine earth	Mineral fine earth or root-zone layer where required; compost does not replace a mineral skeleton	KUZ-005/006 , CASE-016
Saline/sodic material	Drainage and material-specific salinity/sodicity correction before high-EC amendments	CASE-008/029/034
Toxic/mobile material	Isolation/removal/stabilisation and leaching tests	SUB-001 – SUB-006 , CASE-005/013/034

4. Composting: process inputs, not a fixed recipe

Stage/parameter	Documented value	Process requirement	Source
Feedstock mix	Initial C:N 20:1–40:1 ; moisture 50–70% , target around 60%	Sorting, shredding, recipe/material balance	ORG-010
Active aerobic phase	Oxygen, moisture and temperature control	Windrow turner/loader or forced aeration/reactor equipment	ORG-010
Sanitary treatment, static/in-vessel	≥55 °C for at least 3 days	Confirm heating of the whole mass, not one point	ORG-010
Sanitary treatment, windrow	≥55 °C for at least 15 days and at least five turnings	Documented turning and temperature log	ORG-010
Maturation	No universal calendar duration	Slower decomposition until stability/maturity indicators pass	ORG-005/010
Product release	Dewar/self-heating test, respiration, NH ₄ :NO ₃ where used, germination/phytotoxicity, EC/pH, pathogens/weeds/contaminants	Representative sampling and batch quality control	ORG-005/008/010
Demonstrated engineered process	41 days total	Dynamic reactor for feather/straw/lignite product; inoculum on day 0	HYP-011

No justified universal finished-product yield was found in the selected corpus. ^{ORG-006} documents substantial mass, C and nutrient losses during composting, but source-specific factors cannot be used as a general yield. A future economic calculation must use the material balance of the particular batch and facility.

5. Secondary maturation and inoculum inputs

Technology	Quantity	Carrier / conditions	Additional phase	Equipment requirements	Evidential boundary
Coaltech: native-soil/compost tea	1:4 solid:water; final 2.5×10^7 cells/g Technosol	Liquid; activation on malt residue; 95:5 coal tailings:malt	7 days extraction + 7 days activation + 7 days incubation after mixing	Dark vessels, shaker/mixer, filtration, cell count, incubation at 30 °C	Greenhouse, not mature compost and not field (HYP-001)
Cultured native bacteria	1 g soil/25 mL broth; serial 1 mL transfer; 1 mL culture per pellet	Nutrient broth, then extruded pellet	7 + 7 days culture	Sterile vessels/incubator, culture QC, pellet production/drying	Culturable fraction only; 28 weeks (MIC-001)
AMF trap culture	50 g field material per 1,000 mL pot	Autoclaved sand, <i>Brachiaria</i> /sunflower/soybean host plants	4 months	Greenhouse, irrigation, host plants, stress/cutting, spore/root analysis	Multiplication experiment, not field dose (MIC-005)
Direct whole-soil inoculum	No universal dose	Donor soil/suspension/crumb	Varies	Sampling, biosafety, donor-site damage control	Context-dependent (BIO-001/002/005 , HYP-009)
System E	Not reported: no direct experiment	Mature compost pre-colonised with cultured native inoculum	Duration, temperature and moisture not established	Unknown before mesocosm	Hypothesis; process cost cannot yet be calculated

6. Transport mass and volume

Documented examples:

- The ^{CASE-015} design assumed biosolids at about 28% dry matter: 11 wet short tons/acre yielded about 3.1 dry short tons/acre. Transported wet mass was therefore about 3.6 times dry mass. The report also contains a description of batch moisture that appears inconsistent in the extracted text; the original table must be checked visually before economic use.
- In ^{CASE-015}, paper residue is described as about 40% moisture in the design and 25.9% in a later description of the analysed batch; the value for the specific batch, not an average across fragments, must be used.
- In ^{ORG-007}, mean laboratory moisture of received compost ranged from 28% for beef-cattle compost to 54% for goat compost; these are preliminary examples, not project inputs.
- In ^{ORG-010}, clean wood-chip bulk density was $445\text{--}620 \text{ lb/yd}^3 \approx 264\text{--}368 \text{ kg/m}^3$; a compost mixture above about $1,080 \text{ lb/yd}^3 \approx 641 \text{ kg/m}^3$ may lack air space. Neither range replaces measured density of the delivered batch.

Required fields for a future project:

wet mass = dry mass / dry-matter fraction

loose volume = wet mass / measured loose bulk density

equivalent applied layer = volume / 10,000 m²

All three formulas must use the same batch and compaction state. A nominal 20 cm treated layer does not mean 2,000 m³ compost per hectare where compost is mixed with mineral material.

7. Monitoring schedules actually observed

Evidence family	Actual sampling/observation structure	Economic implication
CASE-015	Ten infiltration-water samplings from June 2002 to September 2003 plus runoff events; vegetation tracked for three seasons	Early event-based water monitoring is labour-intensive
CASE-009/010	One randomised experiment assessed after about 5, 16 and 27 years	Long-term resurveys show convergence and residual legacies invisible in year one
CASE-011	35-year groundwater record under repeated biosolids application	Repeated application requires life-cycle water monitoring, not one closure sample
CASE-012/013	Resurvey 13 and 21 years after a one-time high dose	One-time application still creates long-term benefits and monitoring obligations
CASE-025	0–20 cm samples in 2011 and 2016	Two points reveal persistent C change, but not seasonal losses
CASE-026	Seven-year fertilisation experiment; final soil chemistry and bacterial sequencing	Microbial analysis need not be monthly, but an end point alone misses transitions
CASE-034	Three-year multi-season monitoring of pore water, chemistry, microbes and biomass	Water and biomass may move in opposite directions; both blocks are needed
KUZ-006	Baseline soil in 2014, repeat in 2018; vegetation in 2015–2023 with annual focal-plant measurements	Soil chemistry may be measured less often than vegetation, but baseline is mandatory
BIO-009 / long chronosequences	Age intervals from 2 to 32+ years	Reference/chronosequence reduces repeat-sampling cost but does not replace longitudinal causality

Synthesis-supported monitoring schedule: baseline + early event-based sampling + annually in years 1–5 + years 7, 10, 15 and 20. This is a proposed design inferred from gaps among cases, not a schedule copied from one source; monitoring is a separate line in the scenario model.

8. Life-cycle interpretation

- First measurable plant effects: weeks to one growing season in pot/field experiments.
- Early chemistry/water harm: first runoff/leachate events and the first 1–2 years (FAIL-001/004/005, CASE-015/034).

- Physical/biological soil effects: often 3–10 years before persistent treatment separation.
- Persistent amendment legacy: shown at 10–27 years for some treatments.
- Spontaneous/vegetation-driven profile development: 20–65 years in chronosequences.
- Repeat intervention: explicit in Illinois biosolids and agricultural fertilisation systems; old Scottish organic treatments were judged to require renewal. Many one-time experiments did not demonstrate that future intervention would be unnecessary.

9. Missing economic-model inputs

These values must not be filled by assumption:

- facility-specific compost yield from wet feedstock;
- delivered-product moisture and loose/compacted bulk density;
- rejection fraction due to contamination;
- secondary-maturation duration and system E vessel/area requirements;
- viable-inoculum yield and shelf life per donor sample;
- exact C/D/E field dose;
- site earthwork volume, drainage and engineering-clearance cost;
- local laboratory panel and monitoring frequency;
- probability and cost of failure/rework.

These parameters require measurements for the particular site and facility; the evidence corpus does not provide them.

26. Time as part of restoration

SYNTHESIS. Money for restoration can be planned and spent; lost decades cannot be bought back. This is the author’s interpretation of the factual timeline, not a monetary coefficient. The corpus does not permit a price to be assigned to one “lost year”.

Long-term evidence shows persistence and convergence at the same time: some aggregate amendment effects disappear, while some legacies remain; horizons, aggregates, fauna and persistent C pools develop over decades; in chronosequences extending to 65 years, the soil-forming trajectory continues. This does not mean that every site will require exactly 65 years.

56–65 YEARS: SOME OF THE EVIDENCE IS A CHRONOSEQUENCE, NOT CONTINUOUS OBSERVATION OF ONE SITE. The longest trajectories in the corpus must not be retold as one 65-year longitudinal experiment.

27. What remains unknown

1. There is no universal amendment recipe for coal spoil: mineralogy, pH, salts, texture, hydrology and climate alter the outcome.
2. No direct factorial B/C/D/E and B-time experiment was found on mined land comparing mature compost, direct whole donor soil, cultured native inoculum and pre-colonised material after secondary maturation.
3. No direct factorial C/D/E experiment was found comparing a small amount of donor soil, cultured inoculum and pre-colonised compost.
4. There is no universal minimum effective donor-soil dose or coefficient $1 \text{ kg donor} \rightarrow X \text{ tonnes equivalent living substrate}$.
5. It has not been demonstrated that a cultured community retains the functions of whole soil; enrichment inevitably selects taxa.
6. It is unknown whether a possible pre-colonisation advantage persists years after transfer to coal spoil.
7. Most field studies do not measure water, chemistry, physics, microbiome, fauna and plant reproduction at the same time.
8. Chronosequences separate time from site differences less reliably than longitudinal randomised experiments.
9. Total carbon in coal waste does not always separate fossil C from new biogenic C.
10. The long-term fate of PFAS, pharmaceuticals, microplastics and mixed contaminants in some organic streams is insufficiently understood.
11. There is no direct comparison of goats and sheep on mined land, still less an experiment using Angora goats as a soil-forming technology.
12. There is no basis for naming one manure type universally best.
13. Actual cost per hectare and the carbon/logistics footprint cannot be calculated without a particular facility, wet mass, distance, dose and site.
14. Kuzbass lacks sufficient paired long-term monitoring of water, microbiology and soil physics in one experimental network.
15. Science offers no general promise of returning historical soil; an achievable objective may be a safe, self-sustaining Technosol or ecosystem.

These gaps do not require endless searching. Points 2–6 are answered by a new causal experiment; 7–9 by design and measurement; 10 by feedstock qualification; 11–12 by optional late-stage experiments; 13–14 by a future site-specific feasibility assessment; and 15 by selecting the restoration objective in advance.

Additional site-specific uncertainties remain concerning contaminants, the absence of a direct mined-land restoration experiment with Angora goats, the absence of a universal “best” manure, the unknown cost of system E, and the lack of any guarantee that historical soil can be

restored.

28. Conclusion and programme for a new experiment

Category	Conclusion
SUPPORTED	A safe mineral root-zone substrate, plants and soil biota can initiate the restoration of individual functions; organic materials sometimes accelerate or alter the trajectory.
CONDITIONALLY SUPPORTED	Controlled mature compost and selected inocula may be useful after the zero-stage engineering safety gate; it is technically possible to scale a culturable fraction from a small donor sample.
NOT SUPPORTED	A universal recipe; equivalence of green cover and restored soil; the ability of organic materials to replace engineering work; cultured inoculum as a copy of soil; goats as a soil-forming technology.
UNKNOWN	Persistent advantage of system E over B/C/D; optimal dose and composition; field persistence; long-term water condition; cost of scale-up.

The new experiment should compare A/B/C/D/E and B-time using the same mature material, with controls for inactivated material, carrier and AMF, randomisation and sufficient replication; first in a mesocosm, then in a replicated field stage. Co-primary outcomes are water safety and functionality/autonomy. Stopping rules must activate for nitrate, DOC, metals, salinity, phytotoxicity or site-stability problems. E can win only by a measured persistent advantage, not as a preselected narrative.

People probably cannot recreate an exact copy of the soil lost through mining. But after engineering clearance, they can create initial conditions in which soil-forming processes begin to work again, measure them and gradually reduce their own intervention.

28.1. What this investigation does not demonstrate

Not demonstrated	Precise boundary
System E is better than B/C/D	No direct comparative experiment was found in the closed corpus; this does not prove that no such study exists anywhere in the world literature.
A cultured microbiome is equivalent to whole soil	MIC-001 shows scale-up of the culturable fraction, not copying the full community, rare taxa, obligate symbionts and all functions.
There is one universally best manure	Composition depends on species, diet, bedding, moisture, storage and processing.

Not demonstrated	Precise boundary
There is a universal dose of organic soil amendment	Dose depends on material, calculation basis, substrate, climate, water, objective and contaminants.
Angora goats restore soil on mined land	No direct mined-land restoration experiment with Angora goats is present in the corpus; only a possible late vegetation-management role remains.
56–65 years guarantees return of historical soil	Some long-duration evidence consists of chronosequences; even a long trajectory does not promise a copy of pre-mining soil.
The economic model is an estimate for Apanas	It is a scenario for a complex 100 ha Apanas-type spoil heap, not a calculation for an existing site.
\$1.8–3.4/t is the total environmental cost of coal	It is only a scenario restoration cost; climate, health, biodiversity, historical water damage and social externalities are excluded.

This limitations map is brief navigation. Full grounds and Source IDs are in sections 3, 15, 17–20 and 24–27, and in the source registry.



Open-pit mine in Kuzbass, 2 January 2019. Photograph: Natalia Zubkova. The image records the visible scale of landform disturbance; it does not establish substrate chemistry, ownership, closure status, soil recovery or ecological restoration.

29. Source registry

The complete frozen registry appears below. Verification path: claim → Source ID → bibliographic record → DOI/URL or local copy → limitation.

Source registry for Evidence Investigation V1.0

Version: 26 September 2026. This file is the frozen registry for the English edition of Evidence Investigation V1.0. A source record means inclusion in the evidence corpus, not automatic acceptance of every conclusion in the publication. Publications belonging to one evidence group are not treated as independent confirmations.

Evidence boundary: a source's presence in the registry does not mean that its conclusions were accepted without verification.

Fields

SUB-001 · Li et al. (2019), <i>Effects of surface coal mining and land reclamation on soil properties: A review</i>			
Type	peer-reviewed review	Subject / geography	coal-mining land, global
What it supports	Disturbance and reconstruction affect physical, chemical and biological properties; at minimum, landform, soil, hydrology, vegetation and landscape must be addressed	What it does not support / limitation	The review does not demonstrate the effectiveness of any specific organic amendment
URL/DOI	https://doi.org/10.1016/j.earscirev.2019.02.015	Local copy	—
Status	Accepted for field map		
SUB-002 · OSMRE / ARRI, Forestry Reclamation Approach			
Type	federal programme and technical guidance	Subject / geography	Appalachia, USA
What it supports	Suitable rooting material, loose placement, compatible ground cover, native trees and correct planting are required; compaction is an independent constraint	What it does not support / limitation	Greening or tree planting does not demonstrate restoration of the original ecosystem
URL/DOI	https://www.osmre.gov/programs/arri	Local copy	—
Status	Accepted		

SUB-003 · INAP, Global Acid Rock Drainage Guide			
Type	international technical guidance	Subject / geography	mining waste
What it supports	Sulphides, oxygen and water can sustain contaminated drainage for decades or centuries; prediction and prevention at source take priority	What it does not support / limitation	Biological amendments do not replace source control
URL/DOI	https://www.inap.com.au/acid-drainage/	Local copy	papers/SUB-003_GARD_2024_Sustainable_Mine_Closure.pdf
Status	Accepted		
SUB-004 · Tibbett (2024), <i>Post-mining ecosystem reconstruction</i>			
Type	peer-reviewed primer	Subject / geography	post-mining landscapes
What it supports	Hazardous and profoundly altered materials often require reconstruction of a safe, stable ecosystem rather than literal return to a past state	What it does not support / limitation	Not a trial of a specific technology
URL/DOI	https://doi.org/10.1016/j.cub.2024.03.065	Local copy	—
Status	Accepted		
SUB-005 · Ren et al. (2022), monitoring spontaneous combustion after reclamation			
Type	primary field study	Subject / geography	Shanxi, China
What it supports	Spontaneous combustion can resume after reclamation and damage vegetation again	What it does not support / limitation	A vegetation indicator does not replace engineering diagnosis of the combustion source
URL/DOI	https://doi.org/10.1002/ldr.4297	Local copy	—
Status	Accepted		
SUB-006 · Querol et al. (2011), soil cover and spontaneous combustion			
Type	review and field data	Subject / geography	coal spoil heaps, China
What it supports	Combustion is associated with gases, condensates and leaching; soil cover requires a separate engineering assessment	What it does not support / limitation	The problem cannot be reduced to “apply soil and plant”
URL/DOI	https://doi.org/10.1016/j.coal.2010.09.002	Local copy	—
Status	Accepted		

CHEM-001 · **Angst et al. (2021), plant- vs microbial-derived stabilised SOM**

Type	peer-reviewed review	Subject / geography	soils
What it supports	Persistent SOM forms from plant and microbial compounds in aggregates and MAOM; contributions depend on the soil and environment	What it does not support / limitation	Does not provide a universal stable-carbon fraction for spoil heaps
URL/DOI	https://doi.org/10.1016/j.soilbio.2021.108189	Local copy	—
Status	Accepted		

CHEM-002 · **Witzgall et al. (2021), particulate OM**

Type	primary isotope experiment	Subject / geography	mineral soils
What it supports	Aggregates and organo-mineral associations form simultaneously on the surface of decomposing litter	What it does not support / limitation	A laboratory mechanism cannot automatically be extrapolated to field scale on a spoil heap
URL/DOI	https://doi.org/10.1038/s41467-021-24192-8	Local copy	—
Status	Accepted		

CHEM-003 · **Müller et al. (2024), roots, aggregation and OM formation**

Type	primary incubation study	Subject / geography	arid topsoil and subsoil
What it supports	Roots and fungi enhance aggregation; root legacies differ between upper and lower horizons	What it does not support / limitation	Not a mine-site trial; some effects in subsoil did not persist after root death
URL/DOI	https://doi.org/10.1016/j.soilbio.2024.109503	Local copy	—
Status	Accepted with limitation		

CHEM-004 · **Álvarez et al. (1996), P adsorption in coal mine soils**

Type	primary study	Subject / geography	As Pontes, Spain
What it supports	Fe/Al, pH and organic C explained a substantial share of variation in P sorption	What it does not support / limitation	Does not demonstrate P availability to every plant or runoff risk
URL/DOI	https://doi.org/10.1016/0048-9697(95)04934-7	Local copy	—
Status	Accepted		

CHEM-005 · Kleber et al. (2021), mineral–organic interfaces			
Type	peer-reviewed synthesis	Subject / geography	soils and sediments
What it supports	Mineral–OM interactions are dynamic: adsorption may lead to protection, reaction or further oxidation; “attached to a mineral” does not mean “stabilised forever”	What it does not support / limitation	Not a mine-site field trial and does not supply a simple C-storage coefficient
URL/DOI	https://doi.org/10.1038/s43017-021-00162-y	Local copy	—
Status	Accepted		
CHEM-006 · Lavallee et al. / Cotrufo framework (2022 chapter), SOM formation and persistence			
Type	peer-reviewed synthesis	Subject / geography	soils
What it supports	Provides a working distinction among DOM, POM and MAOM; persistence depends on microbial processing, access and mineralogy rather than a mythical single “humus”	What it does not support / limitation	The conceptual framework does not replace fractionation on a specific spoil heap
URL/DOI	https://doi.org/10.1016/bs.agron.2021.11.002	Local copy	—
Status	Accepted		
ORG-001 · US EPA, <i>Composting Yard Trimmings and Municipal Solid Waste</i>			
Type	official technical guidance	Subject / geography	municipal compost
What it supports	Describes mesophilic and thermophilic phases, aeration and temperature control of pathogens	What it does not support / limitation	Heating of a pile alone does not demonstrate maturity of the whole product
URL/DOI	https://archive.epa.gov/composting/web/pdf/cytmsw.pdf	Local copy	—
Status	Accepted		
ORG-002 · Ontario Compost Quality Standards			
Type	official standard	Subject / geography	Canada
What it supports	Maturity is assessed through a combination of indicators; respiration and germination/growth tests are permitted	What it does not support / limitation	Time in storage alone is not a sufficient criterion
URL/DOI	https://www.ontario.ca/page/ontario-compost-quality-standards	Local copy	—
Status	Accepted		

ORG-003 · **USDA ARS, fresh poultry manure vs compost in reclaimed coal mine soil**

Type	official report of primary research	Subject / geography	USA
What it supports	Fresh low-C:N manure creates a high N-loss risk; composting with C-rich material reduced dissolved organic C export	What it does not support / limitation	Poultry manure does not substitute for a comparison of goat, sheep, cattle and horse manure
URL/DOI	https://www.ars.usda.gov/research/publications/publication/?seqNo115=333125	Local copy	—
Status	Accepted		

ORG-004 · **FAO manure composition tables**

Type	intergovernmental reference database	Subject / geography	agriculture
What it supports	Manure composition depends on species and moisture; values must be compared on a common basis	What it does not support / limitation	Reference averages do not replace analysis of a specific batch
URL/DOI	https://www.fao.org/4/w6928e/w6928e22.htm	Local copy	—
Status	Accepted as ranges		

ORG-005 · **US EPA, *Compost Use on State Highway Applications***

Type	official technical specification	Subject / geography	roadside and landscape soil incorporation
What it supports	Maturity cannot be established by one indicator; bioassay and stability/respirometry are needed, with control of inert material, metals, pathogens and weed seeds	What it does not support / limitation	An older, non-mine-specific document; compliance does not resolve PFAS or other modern contaminants
URL/DOI	https://archive.epa.gov/composting/web/pdf/highwy4.pdf	Local copy	papers/ORG-005_EPA_compost_specification.pdf
Status	Accepted		

ORG-006 · **Faverial et al. (2016), manure-based compost quality**

Type	controlled composting experiment	Subject / geography	cattle, horse, goat and poultry manure plus green waste, Guadeloupe
What it supports	Initial manure type substantially altered C:N, nutrients and NH ₄ ; thermophilic treatment and stabilisation reduced NH ₄ to similarly low values but entailed C/N/P/K losses	What it does not support / limitation	A small tropical process does not determine the composition of other batches and is not a mine-field trial
URL/DOI	https://doi.org/10.1371/journal.pone.0157884	Local copy	—
Status	Accepted		

ORG-007 · **Utah State University Analytical Laboratory, manure/compost averages 2005–2019**

Type	official laboratory summary	Subject / geography	solid manure and compost, Utah
What it supports	Provides comparable wet/as-received averages for N, P ₂ O ₅ , K ₂ O, pH, EC, moisture and C:N for goat, sheep, beef, dairy and horse manure and compost	What it does not support / limitation	Not a peer-reviewed trial; batch bases and conditions differ; the raw-goat sample count is not shown as large; screening guidance only
URL/DOI	https://extension.usu.edu/yardandgarden/research/sustainable-manure-and-compost-application	Local copy	—
Status	Accepted for empirical screening		

ORG-008 · **European Commission JRC (2014), *End-of-waste criteria for biodegradable waste subjected to biological treatment***

Type	official technical proposal and analytical campaign	Subject / geography	compost and digestate, EU
What it supports	Separately defines compost and digestate and specifies source separation, stability, pathogens, weed propagules, physical impurities and metal/organic-pollutant limits	What it does not support / limitation	Not a universal current authorisation; predates current PFAS and microplastic evidence; product compliance does not demonstrate suitability for a particular mine substrate
URL/DOI	https://publications.jrc.ec.europa.eu/repository/handle/JRC87124	Local copy	papers/ORG-008_JRC_end_of_waste_compost_digestate.pdf
Status	Accepted as qualification framework		

ORG-009 · **Zhang / UC Davis / US EPA workshop (2017), *Digestate Alone and With Compost***

Type	technical presentation with pilot and field product data	Subject / geography	food-waste and dairy-manure digestate
What it supports	Shows that whole, liquid, concentrated and pelleted digestate are different products; one food-waste pellet contained 8.98% moisture, 4.99% N, 37.76% C, 1.75% P and 2.67% K on a wet basis	What it does not support / limitation	One engineered product and agronomic trial; not a mine-land study, regulation or “typical digestate”
URL/DOI	https://www.epa.gov/sites/production/files/2017-11/documents/cba2017-digestate_alone_and_with_compost.pdf	Local copy	papers/ORG-009_EPA_food_waste_digestate_case.pdf
Status	Accepted only as a concrete example of variability		

ORG-010 · USDA NRCS (2010), *National Engineering Handbook, Part 637, Chapter 2: Composting*

Type	official engineering guidance and reference tables	Subject / geography	farm and municipal compost feedstocks
What it supports	Provides comparable indicative N, C:N, moisture and bulk-density values for food waste, manure, leaves, grass, paper/cardboard and wood streams; describes process control and several independent maturity/stability tests	What it does not support / limitation	An older reference compiled from different materials; ranges do not replace batch analysis; does not cover PFAS and is not a mine-land trial
URL/DOI	https://directives.nrcs.usda.gov/sites/default/files2/1712930995/Chapter%20%20-%20Composting.pdf	Local copy	papers/ORG-010_USDA_NRCS_composting_handbook.pdf
Status	Accepted as screening reference		

BIO-001 · Wubs et al. (2016), *Soil inoculation steers restoration*

Type	six-year field experiment	Subject / geography	former arable land, Netherlands
What it supports	Small inoculum doses can steer plant and soil communities towards different trajectories	What it does not support / limitation	Not a mine site; transferability to a toxic or lifeless substrate has not been established
URL/DOI	https://doi.org/10.1038/nplants.2016.107	Local copy	—
Status	Accepted with limitation		

BIO-002 · Small-volume forest topsoil additions (2022)

Type	primary greenhouse experiments	Subject / geography	Mount Polley Mine, Canada
What it supports	Small volumes of forest soil improved symbiont colonisation and growth of some seedlings; donor–plant compatibility matters	What it does not support / limitation	Greenhouse conditions and early growth do not demonstrate long-term field persistence
URL/DOI	https://doi.org/10.1016/j.apsoil.2022.104622	Local copy	—
Status	Accepted with limitation		

BIO-003 · Mycorrhizal fungi in mine restoration (2022)

Type	peer-reviewed review	Subject / geography	mined land, global
What it supports	AMF effects depend on mineral substrate and conditions; long-term field data are insufficient	What it does not support / limitation	Does not justify a universal commercial inoculum
URL/DOI	https://doi.org/10.1016/j.ecoleng.2022.106580	Local copy	—
Status	Accepted		

BIO-004 · Torres-Arias et al. (2021), 29-year revegetation and AMF			
Type	long-term chronosequence / field study	Subject / geography	iron-mine tailings, Quebec/Labrador
What it supports	Over 29 years, seeded species were replaced and mycorrhisation increased after perennial colonisation; different AMF genera appeared at different times	What it does not support / limitation	Not coal; a chronosequence across different tailings is not one repeated experiment
URL/DOI	https://doi.org/10.1016/j.apsoil.2021.104145	Local copy	—
Status	Accepted with limitation		
BIO-005 · Gerrits et al. (2023), soil translocation synthesis			
Type	systematic review of field trials	Subject / geography	restoration sites
What it supports	Effects of whole-soil transfer are context-dependent; where biota are the target, small crumbs rather than wholesale donor-topsoil removal may suffice	What it does not support / limitation	Reviews plant-community outcomes; does not demonstrate mine-soil chemistry or safety
URL/DOI	https://doi.org/10.1111/1365-2664.14364	Local copy	—
Status	Accepted		
BIO-006 · Guignabert et al. (2023), <i>Soil amelioration induced by nurse shrubs in coal mines reclaimed to pastures and their synergistic effects with grazing</i>			
Type	primary field comparison, exclosure × shrub	Subject / geography	reclaimed opencast coal-mine pasture, northern Spain
What it supports	Water-holding and available water were higher without grazing; ungulate trampling increased compaction; nurse shrubs added organic matter/fertility and partly shielded soil from trampling	What it does not support / limitation	Does not compare goats, sheep and cattle; grazing history and wild/domestic ungulate effects are mixed; does not show that livestock are required for soil formation
URL/DOI	https://doi.org/10.1016/j.agee.2023.108483	Local copy	—
Status	Key argument against animals in the early experiment		
BIO-007 · Maczkowiack et al. (2012), <i>Grazing as a post-mining land use: A conceptual model of the risk factors</i>			
Type	peer-reviewed risk framework and stakeholder survey	Subject / geography	six open-cut mines, Bowen Basin, Australia
What it supports	Grazing risk depends not only on soil but also on productivity, stocking decisions, commercial viability and compliance with management caveats	What it does not support / limitation	A conceptual/risk model, not a treatment trial; concerns cattle grazing mainly as an end land use, not soil creation
URL/DOI	https://doi.org/10.1016/j.agsy.2012.03.002	Local copy	—
Status	Accepted as post-restoration decision framework		

BIO-008 · Gamble, Gadzia & Raisbeck (1997), *Livestock Grazing for Management of Reclaimed Land at Navajo Mine: Animal Response*

Type	conference field report	Subject / geography	reclaimed surface-coal mine, New Mexico
What it supports	With carefully managed cattle grazing, fencing, water/forage planning and health monitoring, the first two years showed no adverse animal-health signal; operational hazards and a water-quality episode were identified	What it does not support / limitation	Short duration, company-linked programme and focus on animal response rather than soil recovery; not a goat/sheep comparison and not evidence of a soil-building benefit
URL/DOI	https://doi.org/10.21000/JASMR97010255	Local copy	papers/BIO-008_Navajo_Mine_grazing_animal_response.pdf
Status	Accepted with strong limitation		

BIO-009 · Kane et al. (2020), *Soil microbial succession following surface mining is governed primarily by deterministic factors*

Type	peer-reviewed coal-mine chronosequence	Subject / geography	contour-mined coal land, West Virginia, USA; 2, 10, 15 and 32 years after reclamation
What it supports	Bacterial and fungal communities changed with age; effects of measured deterministic factors on bacterial assembly were about seven times stronger than the stochastic component, while fungal variation was explained only by environmental factors; SOM, texture and pH were especially important	What it does not support / limitation	Four different sites, not repeated observation of one site; biomass, richness and community composition did not clearly approach reference pasture even after 32 years; standard topsoil plus grass/legume reclamation, without organic amendment
URL/DOI	https://doi.org/10.1093/femsec/fiaa114	Local copy	—; full open HTML checked, publisher PDF endpoint returned 403
Status	Accepted as a long-term microbial trajectory with chronosequence limitation		

BIO-010 · McGregor (2010), *Influence of stocking rate and mixed grazing of Angora goats and Merino sheep... 1. Botanical composition...*

Type	four-year replicated grazing experiment	Subject / geography	improved annual temperate pasture, southern Australia; Angora/Merino/mixed grazing at 7.5, 10 and 12.5 animals/ha
What it supports	Species × stocking-rate interaction was strong; on this particular pasture at high stocking rates, goats retained more clover, fewer weeds and caused a smaller increase in bare ground than sheep; diet varied seasonally	What it does not support / limitation	Not post-mining land, young restoration or native-ecosystem recovery; continuous grazing and results are pasture- and climate-specific; companion evidence indicates high Angora-goat mortality under increased stocking and cold stress
URL/DOI	https://doi.org/10.1071/AN09128	Local copy	—
Status	Accepted as a breed comparison, not evidence of spoil-heap transferability		

BIO-011 · Taylor & Kothmann (1990), <i>Diet Composition of Angora Goats in a Short-Duration Grazing System</i>			
Type	primary field study of diet selection	Subject / geography	Edwards Plateau rangeland, Texas
What it supports	Angora-goat diets varied seasonally; shrubs were selected disproportionately when available, while grasses dominated in some warm seasons; intake and faecal output were measured	What it does not support / limitation	Two pastures, a specific 0.19 AU/ha system and climate; dietary preference does not demonstrate restoration benefit or acceptable damage to young woody plants
URL/DOI	https://doi.org/10.2307/3899028	Local copy	—
Status	Accepted for Angora-goat feeding mechanism		
BIO-012 · Lym, Sedivec & Kirby (1997), <i>Leafy spurge control with Angora goats and herbicides</i>			
Type	four-year vegetation-management experiment at two sites	Subject / geography	North Dakota rangeland invaded by leafy spurge
What it supports	Repeated Angora-goat grazing reduced density of the target invasive species; supports targeted vegetation management under a defined regime	What it does not support / limitation	Weed control is not soil restoration; grazing can spread viable seed and alter non-target vegetation; the study does not address compaction, water or contaminants on spoil heaps
URL/DOI	https://arc.lib.montana.edu/range-science/item/739	Local copy	—
Status	Accepted only as evidence of targeted browsing		
CASE-001 · Pichtel et al. (1994), <i>ten-year amendment comparison</i>			
Type	ten-year field experiment	Subject / geography	acidic pyritic coal spoil, USA
What it supports	Compares digested sludge, fly ash, composted paper-mill sludge and topsoil; shows long-term differences in pH and vegetation cover	What it does not support / limitation	High historical sludge doses and standards require modern contaminant assessment
URL/DOI	https://doi.org/10.2134/jeq1994.00472425002300040022x	Local copy	—
Status	Priority case		
CASE-002 · Haigh et al. (2019), <i>municipal green-waste compost</i>			
Type	11-year controlled field experiment	Subject / geography	former opencast coal mine, Wales
What it supports	0.75 kg compost per tree altered survival but produced no general height/DBH gain; response depended on species	What it does not support / limitation	Does not measure the full soil cycle
URL/DOI	https://doi.org/10.1177/1178622119877837	Local copy	—
Status	Priority mixed result		

CASE-003 · Růžek et al. (2012), sludge + paper waste + bark

Type	field experiment, 2001–2008	Subject / geography	lignite basin, Czech Republic
What it supports	A one-off waste mixture and overseeding were accompanied by measurements of C, microbial biomass and respiration	What it does not support / limitation	The complex mixture prevents attribution of the effect to one component
URL/DOI	https://doi.org/10.17221/397/2011-PSE	Local copy	—
Status	Priority case		

CASE-004 · FGD product ± yard-waste compost (2013)

Type	16-year field experiment	Subject / geography	acidic coal-mining land, Ohio
What it supports	Long-term vegetation response differed from early response; combinations of materials may function for more than ten years	What it does not support / limitation	FGD is not organic material; water and whole-ecosystem data are needed
URL/DOI	https://doi.org/10.1016/j.fuel.2012.06.081	Local copy	—
Status	Priority case		

CASE-005 · Tri-State residuals vs topsoil (2014)

Type	12-year field experiment	Subject / geography	Pb/Zn tailings, Missouri
What it supports	Compares biosolids/lime/compost with harvested topsoil; evaluates plants, metals and small mammals	What it does not support / limitation	Metal tailings are not coal spoil
URL/DOI	https://doi.org/10.1016/j.scitotenv.2014.03.029	Local copy	—
Status	Comparable case		

CASE-006 · Detour Lake amendment trial (2026)

Type	nine-year field experiment	Subject / geography	open-pit gold mine, boreal Canada
What it supports	Compares eight strategies including peat, biosolids and combinations; jointly evaluates soil, plant and microbial outcomes	What it does not support / limitation	Not coal; published very recently and requires full-text review
URL/DOI	https://doi.org/10.1016/j.jenvman.2026.130328	Local copy	—
Status	Priority new case		

CASE-007 · Dong et al. (2026), leguminous green manure			
Type	ten-year field experiment	Subject / geography	reclaimed coal mine, Gujiao, Shanxi
What it supports	Natural recovery was compared with continuous alfalfa and hairy vetch; alfalfa increased SOC, TP, wet-stable aggregates, bacterial diversity and biomass	What it does not support / limitation	A managed agricultural system, not return of the zonal ecosystem; plot history/replication and water outcomes require additional verification in the available text
URL/DOI	https://doi.org/10.3389/fpls.2026.1802650	Local copy	—
Status	Priority case of internal C/N input		
CASE-008 · Walmsley et al. (2022), <i>From spoil to soil</i>			
Type	greenhouse and early field trial	Subject / geography	Loy Yang brown-coal mine, Australia
What it supports	Local overburden/subsoil/topsoil, coal, fly ash, paper-mill ESR and green-waste compost were mixed into Technosols; five years of field monitoring were planned	What it does not support / limitation	Only early plant results are available; high EC/sodicity was already a problem; a productive-pasture target is not ecological restoration
URL/DOI	https://doi.org/10.36487/ACG_repo/2215_92	Local copy	—
Status	Promising but incomplete case		
CASE-009 · Bendfeldt et al. (2001), <i>Quality of Amended Mine Soils After Sixteen Years</i>			
Type	16-year randomised field experiment	Subject / geography	surface coal mine, Wise County, Virginia
What it supports	Control, 30 cm topsoil, 112 Mg/ha sawdust and biosolids at 22/56/112/224 Mg/ha, n=4; by year 16 the vegetation-only control approached amended treatments in SOM/N mineralisation	What it does not support / limitation	Short-term advantage did not persist as a general soil-quality advantage; historical biosolids composition and planted fescue/pine context
URL/DOI	https://doi.org/10.2136/sssaj2001.1736	Local copy	—
Status	Key negative long-term case		

CASE-010 · Wick et al. (2010), 27-year Virginia follow-up

Type	27-year continuation of the same randomised experiment	Subject / geography	surface coal mine, Wise County, Virginia
What it supports	Biosolids plots retained more aggregate-associated C/N; 22–56 Mg/ha performed better for some available C/N measures; microbial biomass C was higher under biosolids, while overall aggregate distribution had largely converged	What it does not support / limitation	Does not overturn the 16-year convergence result for other indicators; high inter-replicate variability, one experiment and historical biosolids require caution
URL/DOI	https://doi.org/10.21000/JASMR10011364	Local copy	papers/CASE-010_Wick_27_year_Virginia.pdf
Status	Key mixed long-term case; primary source checked		

CASE-011 · Oladeji et al. (2012), *Effects of long-term application of biosolids for mine land reclamation on groundwater chemistry: trace metals*

Type	35-year groundwater monitoring	Subject / geography	1,790 ha of strip-mined land, Fulton County, Illinois
What it supports	In seven biosolids fields with cumulative loading of 801–1,815 dry Mg/ha and seven fertiliser fields, most groundwater metals remained below regulatory limits; Fe/Mn were consistently higher, while Zn differed mainly before Part 503	What it does not support / limitation	Tests trace metals, not nitrate, PFAS, pharmaceuticals, pathogens, microplastics or ecological restoration; repeated historical applications are not modern single-dose compost
URL/DOI	https://doi.org/10.2134/jeq2011.0472	Local copy	—
Status	Very long water-safety series; accepted within a narrow boundary		

CASE-012 · Antonelli et al. (2018), *Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation*

Type	13-year field follow-up	Subject / geography	Cu/Mo tailings, British Columbia
What it supports	Single applications of 150/250 dry Mg/ha maintained a larger C pool and biomass after 13 years; the lower dose stored more C per unit of biosolids	What it does not support / limitation	Tailings are not coal spoil; high-rate biosolids; Zn at 250 Mg/ha exceeded the federal soil guideline; water, microbial and community autonomy were not fully evaluated
URL/DOI	https://doi.org/10.1016/j.ecoleng.2018.04.001	Local copy	—
Status	Key positive long-term case with dose caveat		

CASE-013 · Ippolito et al. (2024), *Soil health as a proxy for long-term reclamation success of metal-contaminated mine tailings using lime and biosolids*

Type	21-year field follow-up	Subject / geography	alluvial metal-mine tailings
What it supports	After 224 Mg/ha lime plus 224 Mg/ha biosolids, pH, aggregation, SOC, mineralisable N, microbial indicators and vegetation improved relative to the degraded area	What it does not support / limitation	Not a randomised coal-mine trial; bioavailable Cd/Zn in seep/soil remained above ecological screening levels and forage could require management; a green site does not mean absence of food-chain or water risk
URL/DOI	https://doi.org/10.1016/j.seh.2024.100096	Local copy	—
Status	Very long mixed-success case		

CASE-014 · Bogorodskaya (2016), “Microbiological assessment of anthropogenically disturbed forest ecosystems in Central Siberia”

Type	six-year monitoring of a chronosequence up to 30 years, plus review of local trials	Subject / geography	Borodinsky lignite mine, Kansk–Achinsk Basin
What it supports	On the stable level surface of a 30-year spoil heap, qCO ₂ was comparable with the control; on a 23-year eroding slope the microbiocenosis remained pioneering and unbalanced; application of the fertile soil layer accelerated microbial and plant succession	What it does not support / limitation	Not Kuzbass; a chronosequence is not repeated observation of one treatment; the short manure/sawdust/bacterial-preparation trial provides no long-term water-safety or autonomy evidence
URL/DOI	https://doi.org/10.15372/SJFS20160207	Local copy	papers/CASE-014_Bogorodskaya_2016_microbiological_assessment.pdf
Status	Key case: topography may outweigh age		

CASE-015 · Eger & Antonson (2005), *Use of Biosolids to Reclaim Coarse Taconite Tailings*

Type	official final field report	Subject / geography	coarse taconite tailings, Minnesota
What it supports	Combines replicated infiltration bins and a 12-acre slope demonstration; compares biosolids at 100/200/400 lb available N/acre ± paper-mill residue, water chemistry, vegetation and actual project costs	What it does not support / limitation	Not a coal substrate; two to three growing seasons are insufficient for soil autonomy; nitrate exceeded 10 mg/L in most treated plots and the high dose produced about three times more nitrate than 200N; historical biosolids/contaminant standards
URL/DOI	https://www.lrl.mn.gov/docs/2024/other/241364.pdf	Local copy	papers/CASE-015_Eger_2004_taconite_biosolids_cost_water.pdf
Status	Key integrated water–cost–cover case		

CASE-016 · Eger, Melchert & Dewar (1999), *Waste for Wastelands*

Type	conference paper, multi-site programme summary	Subject / geography	coarse taconite tailings, Minnesota
What it supports	Early small plots and full-scale application of 10–90 Mg/ha peat, yard compost, MSW compost and paper residues; shows dose, fertiliser interaction and transport-distance economics	What it does not support / limitation	Part of the same Minnesota programme as later CASE-015, so not independent confirmation; success was defined mainly by a vegetation standard and prices are historical
URL/DOI	https://www.asrs.us/wp-content/uploads/2021/09/0132-Eger.pdf	Local copy	papers/CASE-016_Eger_Waste_for_Wastelands.pdf
Status	Accepted as early-phase and economic case		

CASE-017 · Tripathi, Singh & Hills (2016), *Re-vegetation of coal mine spoil: Carbon budget and carbon sequestration potential*

Type	peer-reviewed age-gradient field study	Subject / geography	revegetated coal-spoil dumps, Singrauli, India; 2, 4, 10, 14, 16 and 19 years
What it supports	Across the age gradient, aboveground biomass rose about 23-fold, belowground biomass 26-fold, measured organic C fourfold and MBC 6.6-fold; indicates a possible litter–root–microbe–C trajectory after planting	What it does not support / limitation	Not repeated monitoring; different sites/ages are compared; species mix and initial conditions may differ; Walkley–Black on coal substrate may include fossil/char-like C; calculated carbon budget is not direct flux measurement and does not demonstrate autonomy
URL/DOI	https://doi.org/10.1016/j.ecoleng.2016.01.019	Local copy	papers/CASE-017_Tripathi_2016_19y_coal_spoil_carbon.pdf
Status	Accepted with strong design and C-method limitations		

CASE-018 · Domínguez-Haydar et al. (2018), *Assessment of soil fauna footprints at a rehabilitated coal mine using micromorphology and NIRS*

Type	peer-reviewed chronosequence	Subject / geography	El Cerrejón open-pit coal mine, Colombia; 1–20 years
What it supports	Between two- and 20-year sites, the matrix changed from virtually unstructured material without visible biogenic activity to consolidated aggregates, more homogeneous microstructure and traces of macrofaunal bioturbation	What it does not support / limitation	A chronosequence, not one repeatedly measured plot; rehabilitation included topsoil translocation and revegetation, so individual mechanisms cannot be separated; not an organic-amendment trial
URL/DOI	https://doi.org/10.1016/j.geoderma.2017.10.032	Local copy	—; full repository PDF checked in browser, automated download protected by anti-bot control
Status	Accepted as direct micromorphological evidence of pedogenesis		

CASE-019 · Castellanos-Barliza & León-Peláez (2023), *Soil recovery in a chronosequence of revegetated coal mine spoils in Colombian drylands*

Type	peer-reviewed chronosequence	Subject / geography	El Cerrejón, Colombia; dry-forest Technosols aged 7, 10 and 21 years
What it supports	Physical, chemical and biological properties improved with age; fine litterfall was identified as a key mechanism; SOM at rehabilitated sites was 63–89% of the mature dry-forest reference	What it does not support / limitation	Three ages/different sites; only partial reversal of disturbance; same rehabilitation programme as CASE-018 , so not an independent project; does not test compost/manure
URL/DOI	https://doi.org/10.1016/j.geodrs.2023.e00652	Local copy	—; open author PDF checked in browser
Status	Accepted as integrated long-term coal case		

CASE-020 · Šourková, Frouz & Šantrůčková (2005), *Accumulation of carbon, nitrogen and phosphorus during soil formation on alder spoil heaps after brown-coal mining*

Type	peer-reviewed 19-site chronosequence	Subject / geography	Sokolov brown-coal district, Czechia; alder stands aged 4–65 years
What it supports	C and N accumulated rapidly during the first 15–20 years; by 30–40 years the upper organic layers approached semi-natural alder forest; N fixation and litter quality were probable drivers	What it does not support / limitation	Mineral layers and whole-profile stocks still lagged; different sites/materials (Tertiary clay or gravel–sand), not a longitudinal trial; alder planting is not a universal target
URL/DOI	https://doi.org/10.1016/j.geoderma.2004.05.001	Local copy	—
Status	Accepted as long-term pedogenesis case		

CASE-021 · Pihlap et al. (2019), *Initial soil formation in an agriculturally reclaimed open-cast mining area*

Type	peer-reviewed replicated chronosequence	Subject / geography	Garzweiler lignite mine, Germany; loess fields aged 0, 1, 3, 6, 12 and 24 years
What it supports	CaCO ₃ parent material strongly shaped aggregation; alfalfa reduced microbial N limitation; macroporosity/pore connectivity increased only after compost plus ploughing; crop residues did not sustain high SOC	What it does not support / limitation	Agriculturally reclaimed loess differs substantially from stony/pyritic coal spoil; compost effect is tied to the management sequence; chronosequence, not repeated plot
URL/DOI	https://doi.org/10.1016/j.still.2019.03.023	Local copy	—
Status	Accepted as physical–biological mechanism case		

CASE-022 · Hüttl & Weber (2001), *Forest ecosystem development in post-mining landscapes: a case study of the Lusatian lignite district; and chronosequence water study*

Type	peer-reviewed synthesis and field chronosequences	Subject / geography	acid-sulphurous lignite mine soils, Lusatia, Germany; up to 35–37 years
What it supports	Soil-organism activity could approach regional non-mine levels in 20–30 years, but pyrite oxidation continued to determine chemistry; in an oak chronosequence, Fe/Al/Mn/Ca/Mg/NH ₄ /SO ₄ leaching declined over decades	What it does not support / limitation	Aboveground resemblance does not mean identical soil; lignitic C can imitate some SOM functions; stands/species and amendment histories differ
URL/DOI	https://doi.org/10.1007/s001140100241 ; https://doi.org/10.1016/S0169-2046(00)00102-X	Local copy	—
Status	Accepted as engineering–geochemistry constraint		

CASE-023 · Mustafa et al. (2023), *Soil carbon storage in unreclaimed post mining sites estimated by a chronosequence approach and comparison with historical data*

Type	peer-reviewed chronosequence and resurvey	Subject / geography	spontaneously developing Sokolov coal heaps, Czechia; 16–56 years, resurvey after about 15 years
What it supports	Mean observed soil-C gain in the resurvey was about 0.50 t C/ha/year; older sites supported broadleaf succession without formal reclamation	What it does not support / limitation	High variability and no simple age trend in individual-site increment; 2–10% fossil C in substrate complicates measurement; does not justify inaction on hazardous spoil
URL/DOI	https://doi.org/10.1016/j.catena.2022.106664	Local copy	—
Status	Accepted as rare chronosequence-plus-resurvey case		

CASE-024 · Haagner, Abraha & van Wyk (2025), *Benchmarking rehabilitation in the South African opencast coal industry*

Type	24-year standardised observational assessment database	Subject / geography	299 assessments, 48 opencast coal collieries, South Africa
What it supports	Land capability/soil loss often met thresholds, but landform, species composition and especially soil fertility constrained performance; inadequate aftercare accompanied weeds/invasives and poorly designed berms accompanied erosion; aftercare could be required for at least five years	What it does not support / limitation	Not a randomised trial or organic-amendment comparison; aggregated industry data and contractor-linked authorship; a management score does not demonstrate soil autonomy
URL/DOI	https://doi.org/10.17159/2411-9717/792/2025	Local copy	papers/CASE-024_South_Africa_2025_benchmarking.pdf
Status	Accepted as operational failure/maintenance evidence		

CASE-025 · Zhang et al. (2020), *Response of soil organic carbon fractions to exogenous carbon input in mine reclamation*

Type	five-year replicated fixed-site field comparison	Subject / geography	coal-subsidence reclaimed farmland, Xiangyuan, Shanxi, China
What it supports	At the same input of 2.7 t C/ha, compared biochar 8.3, compost 11.0, biogas residue 7.7, cattle manure 8.0 and maize straw 6.7 t/ha; biochar most increased total/stable-C indicators, compost easily oxidisable C and manure labile pools	What it does not support / limitation	Only C fractions at 0–20 cm; water, salts, contaminants, vegetation community and intervention dependence were not assessed; equal C input is not equal nutrient/pH dose; agricultural maize target
URL/DOI	https://doi.org/10.13930/j.cnki.cjea.190925	Local copy	papers/CASE-025_Zhang_2020_exogenous_carbon_China.pdf
Status	Key direct material comparison with narrow endpoint		

CASE-026 · Li et al. (2021), *Effects of Seven-Year Fertilization Reclamation on Bacterial Community in a Coal Mining Subsidence Area in Shanxi, China*

Type	seven-year field RCBD experiment	Subject / geography	compacted farmland in a coal-mining subsidence area, Lu'an, Shanxi; maize
What it supports	Control, chemical fertiliser and decomposed chicken manure at 12 t/ha; three replicates, 100 m ² plots; manure increased SOM/available N and altered bacterial richness/composition	What it does not support / limitation	Bacterial community still differed from adjacent farmland; manure could convey metals/antibiotic residues; a crop-fertilisation system, not an autonomous ecosystem; no water, fungi or soil-fauna endpoints
URL/DOI	https://doi.org/10.3390/ijerph182312504	Local copy	papers/CASE-026_Li_2021_7y_manure_China.pdf
Status	Accepted as replicated evidence of manure effects on microbiome		

CASE-027 · Placek-Lapaj et al. (2019), *Post-mining soil as carbon storehouse under Polish conditions*

Type	field trial with materials and phytoremediation	Subject / geography	external overburden dump at Bełchatów lignite mine, Poland
What it supports	Sewage sludge or compost with lake chalk increased reported SOC and plant-C stocks under Scots pine/Miscanthus; highest SOC was reported at 33 Mg/ha sludge and 45 Mg/ha compost	What it does not support / limitation	Focuses on C stock; water, contaminants and autonomy were not established; sludge slowed pine growth, consistent with rapid nutrient release/phytotoxicity; exact duration and replication require full-text table verification
URL/DOI	https://doi.org/10.1016/j.jenvman.2019.03.005	Local copy	—
Status	Provisionally accepted; mixed result and phytotoxicity		

CASE-028 · Mukhopadhyay et al. (2015), *Soil development in 2–21 years old coalmine reclaimed spoil with trees*

Type	chronosequence	Subject / geography	Sonepur Bazari coal mine, Raniganj, India; 2, 5, 9, 15 and 21 years
What it supports	Organic C/N, exchangeable cations/CEC, moisture, microbial activity/MBC and native-species richness rose along the age sequence under artificial/natural recovery	What it does not support / limitation	Different sites and intervention histories are compared; the chronosequence does not isolate age; coal-derived C measurement requires methodological control; no direct comparison of organic materials
URL/DOI	https://doi.org/10.1016/j.ecoleng.2015.09.043	Local copy	—
Status	Accepted as integrated trajectory, not causal experiment		

CASE-029 · ACARP C28035 (2023), *Topsoil Deficits in Site Rehabilitation: Accelerated Transformation of Spoils to Functional Soils*

Type	official project summary; 12-month field and greenhouse trials	Subject / geography	coal overburden, Bowen Basin, Queensland, Australia
What it supports	Compost, vermi-liquid and dried manure increased early enzyme activity relative to gypsum plus mulch, but no persistent improvement was observed within the project; pH, EC, sodicity and low OM remained decisive; plant growth was water-limited	What it does not support / limitation	Only 12 months/seasonal data; project-page summary rather than full report; “long-term” means persistence within a short trial, not years; no treatment with animals
URL/DOI	https://www.acarp.com.au/abstracts.aspx?repId=C28035	Local copy	—
Status	Key short-term counterexample of non-persistence		

CASE-030 · Misebo et al. (2026), *Effects of afforestation on Technosol properties in reclaimed hard coal deep mining spoil heaps*

Type	cross-sectional field comparison at 30 sites	Subject / geography	Sośnica hard-coal spoil heap, Upper Silesia, Poland; about 20–25 years
What it supports	Succession on bare spoil, on about 50 cm of topsoil and on planted soil differed in porosity, water retention, nutrients and C fractions; planted topsoil contained more occluded/mineral-associated C although total SOC did not differ	What it does not support / limitation	Not historically randomised; treatments conflate topsoil, planting and site history; subtraction of geogenic C assumes comparable original overburden; biology and cost were not assessed
URL/DOI	https://doi.org/10.1038/s41598-026-37992-z	Local copy	papers/CASE-030_Misebo_2026_Sosnica_Poland.pdf
Status	Accepted with design caveat		

CASE-031 · Leal et al. (2015), *Organic Matter Fractions and Quality of the Surface Layer of a Constructed and Vegetated Soil After Coal Mining. I — Humic Substances and Chemical Characterization*

Type	six-year randomised-block field experiment	Subject / geography	constructed topsoil above an opencast coal mine, Candiota, Rio Grande do Sul, Brazil
What it supports	Four perennial grasses, four replicates, 20 m ² plots; cover crops partly increased TOC and some fractions relative to bare constructed soil, while Hemarthria/Urochloa produced larger humic-acid C stocks	What it does not support / limitation	All plots received initial lime/NPK and annual 40 kg N/ha ; natural and bare sites lay outside the randomised experiment; only 0–3 cm was sampled; after six years total C remained well below natural soil and grass treatments mostly did not differ in total C
URL/DOI	https://doi.org/10.1590/01000683rbc20140783	Local copy	papers/CASE-031_Leal_2015_Candiota_grasses_carbon.pdf
Status	Accepted as a Brazilian coal-soil trajectory, not evidence for organic material		

CASE-032 · Longo, Ribeiro & de Melo (2011), *Use of green fertilizing in the recovery of soils degraded by mining in the amazon forest*

Type	15-month factorial randomised-block field experiment	Subject / geography	acidic sandy cassiterite tailings, Jamari National Forest, Rondônia, Brazil
What it supports	Six plant-cover treatments × four amendment regimes, six replicates (144 plots, 1.5 ha); compost was sawdust and cattle manure at 3:1 ; lime/organic matter/fertiliser altered chemical fertility	What it does not support / limitation	Not coal tailings; after 15 months there were no significant differences in measured OM or physical properties; intensive inputs did not rapidly create soil structure/biology; short duration and mixed components limit attribution
URL/DOI	https://doi.org/10.1590/S0006-87052011000100020	Local copy	papers/CASE-032_Longo_2011_Jamari_compost.pdf
Status	Accepted as an early replicated non-response counterexample		

CASE-033 · Barrett (1992), *Colliery Spoil Reclamation: An Appraisal of Two Sites in West Lothian*

Type	thesis; long-term resampling and historical amendment plots	Subject / geography	pyritic colliery spoil at Foulshiels and Baads, Scotland; work since the 1970s, resurveyed 1990–1991
What it supports	Baads plots established in 1978 compared peat, sewage sludge, weathered poultry manure, Alginure and 0/10/25/50 t lime/ha; about ten years later 50 t/ha lime still controlled acidity in most plots; Foulshiels also assessed water and metals	What it does not support / limitation	Surviving plots were sparse and unbalanced and exposure/inflow were confounded; sludge was not analysed before use; organic-only treatments usually remained bare and were judged to need reapplication, but exact relative ranking cannot be treated as causal
URL/DOI	https://theses.gla.ac.uk/75629/	Local copy	papers/CASE-033_Barrett_1992_West_Lothian_colliery.pdf
Status	Accepted as rare long-term UK evidence of failure/maintenance need		

CASE-034 · **Santibáñez & Ginocchio (2012), *Potential Use of Organic- and Hard-Rock Mine Wastes on Aided Phytostabilization of Large-Scale Mine Tailings under Semiarid Mediterranean Climatic Conditions***

Type	three-year randomised-block field experiment	Subject / geography	La Cocinera copper tailings, Coquimbo, Chile; 2,400 m ²
What it supports	Thirteen treatments, three replicates, 25 m ² plots; goat manure, biosolids, grape/olive residues and mixtures were incorporated to 20 cm. Biosolids and grape residues produced the most late biomass; chemical/microbial responses and pore-water Cu were measured	What it does not support / limitation	Not coal; irrigated through three establishment seasons; most fertility/SOC indicators declined with time; the early biosolids response included extreme DOC/Cu pulses and almost no first-year biomass, and olive residue failed; authors explicitly state that autonomy was not demonstrated
URL/DOI	https://doi.org/10.1155/2012/895817	Local copy	—
Status	Key Latin American comparison of materials and failures; full HTML checked		

CASE-035 · **Coetzee (2015), *Organic Matter Contribution of Ameliorants to Reclaimed Surface Mined Soil and Carbon Storage***

Type	one-year outdoor mini-lysimeter experiment, MSc thesis	Subject / geography	reconstructed spoil/subsoil/topsoil coal profile at University of Pretoria experimental farm, South Africa
What it supports	Ten treatments × four replicates; 40 containers; combinations of composted cattle manure, wood chips, grass clippings, alfalfa and ash. Alfalfa plus manure plus wood chips improved pH, bulk density, root/shoot biomass and C stock relative to control	What it does not support / limitation	1×1×1.2 m containers, not a trial within a spoil heap; only one winter and one summer crop; doses of 40 or 132 t/ha, with components confounded in mixtures; water quality, contaminants, native community and persistence were not tested
URL/DOI	https://repository.up.ac.za/handle/2263/50925	Local copy	papers/EXP-003_South_Africa_organic_ameliorants.pdf
Status	Accepted as controlled mechanism evidence, not long-term field outcome		

HYP-001 · **Coaltech Research Association / University of Cape Town (2023), *Development of Fabricated Soils from South African Coal Waste***

Type	official final report; controlled Technosol/pot experiment	Subject / geography	ultrafine coal-flotation tailings, South Africa
What it supports	95% tailings plus 5% spent malt grain were inoculated with several microbial consortia, held for seven days and planted; EM and compost tea improved early plant indicators while tea from local mine soil did not; microbial-biomass differences largely converged by the second growth cycle	What it does not support / limitation	Closest operational analogue, but not mature compost, not a small donor-soil addition, only seven days of pre-incubation, greenhouse rather than field, and no long-term autonomy or water endpoints
URL/DOI	https://coaltech.co.za/wp-content/uploads/2023/08/Project-8.4.4-Fabricated-Soils-from-South-African-Coal-Waste-August-2023-1.pdf	Local copy	papers/HYP-001_Coaltech_2023_fabricated_coal_soils.pdf
Status	Key close analogue and counterexample to “any living soil helps”		

HYP-002 · Asemaninejad et al. (2018), *Blended pulp mill, forest humus and mine residual material Technosols for mine reclamation*

Type	controlled growth-chamber experiment	Subject / geography	five acidic and neutral/alkaline hard-rock mine residues, northern Ontario
What it supports	A trace volume of forest litter — less than 0.02% of dry sludge mass — served as microbial inoculum with residual pulp-mill sludge; plant biomass could rise up to fourfold and microbial communities shifted towards heterotrophic soil-like taxa	What it does not support / limitation	Not coal; no full B/C/D/E and B-time comparison; available method does not establish a separate secondary-maturation period; soluble Cu/Ni rose in some treated substrates
URL/DOI	https://doi.org/10.1016/j.jenvman.2018.08.114	Local copy	—
Status	Key small-inoculum analogue with metals caveat		

HYP-003 · Romero-Estonillo et al. (2023), *compost plus PGPR/mycorrhiza on Touro mine soil*

Type	controlled pot experiment	Subject / geography	copper-mine soil/tailings, Spain
What it supports	Compost at 1:10 w/w was stabilised for 15 days before planting; PGPR, commercial mycorrhiza or both were then added. PGPR improved survival/growth; mycorrhiza alone and the combination produced no universal added advantage	What it does not support / limitation	Inoculum was added at planting, without subsequent secondary maturation; compost itself was a strong treatment; pot scale and non-coal substrate
URL/DOI	https://doi.org/10.3389/fmicb.2023.1184070	Local copy	—
Status	Accepted as a close analogue of direct microbial inoculation D, not a direct match, and as a counterexample to universal inoculum effects		

HYP-004 · Li, Zeng, Huang & Tan (2026), *Enhancing cow manure composting via staged inoculation of functional microbial consortia*

Type	controlled 50-litre composting experiment and pot bioassay	Subject / geography	cattle manure and rice straw, China
What it supports	Phase-specific inocula were added during mesophilic, thermophilic, cooling and maturation phases and compared with one-time inoculation and uninoculated control; staged inoculation changed succession, TN, humification and maturity indicators and improved the pak choi bioassay	What it does not support / limitation	Not donor soil, mined material or finished mature compost followed by a second maturation phase; a 30-day process and pot bioassay do not establish field persistence
URL/DOI	https://doi.org/10.3389/fmbi.2026.1855343	Local copy	—
Status	Accepted as direct evidence that inoculation timing can affect composting		

HYP-005 · de Gannes, Eudoxie & Hickey (2013), *Prokaryotic successions and diversity in composts as revealed by 454-pyrosequencing and companion fungal analysis*

Type	primary compost-community time series	Subject / geography	several compost recipes and post-thermophilic processes
What it supports	Bacterial and fungal communities changed between thermophilic, cooling and maturation phases; recipe and post-thermophilic management influenced the final community, supporting late recolonisation as a testable mechanism	What it does not support / limitation	Does not test donor soil, post-mining restoration, plant establishment, or E against B/C/D and B-time
URL/DOI	https://doi.org/10.1371/journal.pone.0079512	Local copy	—
Status	Accepted only for timing mechanism		

HYP-006 · Danon et al. (2008), *Molecular analysis of bacterial community succession during prolonged compost curing*

Type	primary time series of prolonged curing	Subject / geography	commercially mature biosolids compost
What it supports	Microbial community, respiration, DOC and N transformations continued changing after commercial maturity; declining labile C and increasing nitrification showed that curing is not biologically static	What it does not support / limitation	No external donor-soil inoculum, mining substrate, plants or field trial
URL/DOI	https://doi.org/10.1111/j.1574-6941.2008.00537.x	Local copy	—
Status	Accepted for secondary-maturation mechanism		

HYP-007 · Ngo & Cavagnaro (2018), *Interactive effects of compost and pre-planting soil moisture on plant growth and mycorrhizal colonisation*

Type	factorial pot experiment	Subject / geography	agricultural soil with tomato/wheat
What it supports	Compost and 40-day pre-planting moisture regimes altered NH ₄ /NO ₃ and plant response; compost increased nutrients/plant biomass but reduced AMF colonisation	What it does not support / limitation	Not mined land or donor-soil pre-inoculation; shows that added fertility can suppress a desired symbiosis
URL/DOI	https://doi.org/10.1038/s41598-017-18780-2	Local copy	—
Status	Key adverse-mechanism analogue		

HYP-008 · Tkacz et al. (2015), plant-driven selection from natural soil inoculum in sand and compost			
Type	controlled multigenerational microcosm	Subject / geography	autoclaved sand or commercial compost with 10% natural-soil inoculum and serial dilution
What it supports	Recipient medium and plant species strongly selected the community; soil inoculum could transfer the pathogen <i>Olpidium brassicae</i> ; compost did not guarantee mycorrhisation	What it does not support / limitation	Plants were introduced immediately, not after separate maturation; artificial microcosm and no mining substrate
URL/DOI	https://doi.org/10.1038/ismej.2015.41	Local copy	—
Status	Accepted for recipient filtering and biosecurity risk		
HYP-009 · Han et al. (2022), <i>Soil inoculum identity and rate jointly steer restoration</i>			
Type	three-year replicated field dose–response experiment	Subject / geography	degraded grassland
What it supports	Two donor communities and inoculum layers of 1, 3 and 5 cm produced dose- and identity-dependent trajectories; larger amounts moved the system closer to the donor	What it does not support / limitation	Doses of roughly 10, 30 and 50 L/m ² are not a small pulse; not mined grassland; minimum ecologically effective dose was not established
URL/DOI	https://doi.org/10.1038/s43705-022-00144-1	Local copy	—
Status	Key evidence of donor and dose dependence		
HYP-010 · SARE ONE22-422 (2022–2023), finished compost inoculated with spent mushroom substrate			
Type	completed farmer project, laboratory phase only	Subject / geography	mature compost plus fungus-rich spent mushroom substrate, USA
What it supports	Mature compost received 10%, 25% or 50% inoculum for 14 days; fungal biomass and fungal:bacterial ratio rose with dose; compost-only and inoculum-only controls were included	What it does not support / limitation	Planned field phase was not completed; high inoculum fractions, no mining substrate, plant or water outcomes; grey evidence
URL/DOI	https://projects.sare.org/project-reports/one22-422/	Local copy	—
Status	Closest procedural analogue, but insufficient outcome evidence		

HYP-011 · **Choińska-Pulit et al. (2026), *Development and Field Evaluation of a Microbially-Inoculated Feather–Straw–Lignite Compost Material for the Reclamation of Post-Mining Soils*, published 14 July 2026**

Type	peer-reviewed controlled composting study plus one-season field evaluation	Subject / geography	sandy post-mining soil, Konin lignite district, Poland
What it supports	A feather:straw:lignite mixture at 20:60:20 was inoculated at process start with <i>Bacillus altitudinis</i> 33, <i>Bacillus methylotrophicus</i> Alk and <i>Streptomyces fulvissimus</i> K59, then composted for 41 days in a 200 dm ³ dynamic reactor. Product C:N reached 12.09 and NH ₄ -N 0.03%; 18.3 t/ha was applied in a 2025 maize field trial. Relative to the untreated plot, urease reached 3.91 UU, P ₂ O ₅ 3.4 g/kg, and mean shoot height 30.23 versus 25.88 cm (+15%; t(645)=6.63, p<0.001)	What it does not support / limitation	Inoculation occurred at the start, not after thermophilic maturation; the field stage had one treated and one untreated plot, without the same mature uninoculated compost, randomised field replicates, multi-year monitoring, leachate, microbiome persistence or autonomy testing
URL/DOI	https://doi.org/10.3390/ma19143035	Local copy	— (full open HTML checked; local PDF not downloaded because host DNS was unavailable)
Status	Closest field-application analogue, but does not answer the comparison between B and E-like pre-inoculated material and does not distinguish systems B/C/D/E		

FAIL-001 · **Paper mill sludge runoff study (2008)**

Type	primary field experiment	Subject / geography	surface coal mine, USA
What it supports	224/672 dry Mg/ha sharply reduced runoff and erosion	What it does not support / limitation	At the high dose before planting, runoff DO was ≤0.4 mg/L and COD rose sharply: physical benefit is not water safety
URL/DOI	https://doi.org/10.2134/jeq2007.0648	Local copy	—
Status	Key counterexample		

FAIL-002 · **Branzini et al. (2014), compost/biochar and As**

Type	primary pot experiment	Subject / geography	contaminated mine soil
What it supports	Compost reduced the solubility of several metals	What it does not support / limitation	Compost produced the largest increase in inorganic-As solubility; a field test is required
URL/DOI	https://doi.org/10.1016/j.envpol.2013.11.026	Local copy	—
Status	Key counterexample		

FAIL-003 · **Element budgets at two afforested mine sites (2001)**

Type	two-year field solution monitoring	Subject / geography	pyritic and non-pyritic lignite spoil
What it supports	Clearly demonstrates substrate dependence of treatment effects	What it does not support / limitation	At the pyritic site, oxidation produced fluxes up to 6 t Fe/ha/year and 14 t sulphate-S/ha/year: amendments did not cancel geochemistry
URL/DOI	https://doi.org/10.1016/S0925-8574(00)00143-9	Local copy	—
Status	Key counterexample		

FAIL-004 · **Stehouwer et al. (2006), *Nutrient and Trace Element Leaching following Mine Reclamation with Biosolids***

Type	three-year field water monitoring	Subject / geography	coal-mine land, Pennsylvania
What it supports	At 134 Mg/ha of low-C:N biosolids, peak leachate NO ₃ reached about 300 mg/L; estimated inorganic-N loss in the first two years was 2,327 kg N/ha; Al, Mn, Cu, Ni, Pb and Zn were mobilised simultaneously	What it does not support / limitation	One site and a high dose permitted at that time do not establish a universal prohibition, but demonstrate the need for N- and C:N-based dosing and water monitoring
URL/DOI	https://doi.org/10.2134/jeq2005.0134	Local copy	—
Status	Key counterexample		

FAIL-005 · **Dere et al. (2012), *Nutrient leaching and soil retention in mined land reclaimed with stabilized manure***

Type	three-year field experiment	Subject / geography	abandoned coal land, Pennsylvania
What it supports	Compost treatments leached <1% of applied N; a mixture of fresh poultry manure and paper-mill sludge at C:N 29 lost 393 kg N/ha in three years, versus 107 kg N/ha at C:N 20	What it does not support / limitation	Poultry manure and a specific paper-mill mixture; cannot be extrapolated to goat, sheep, cattle or horse manure without analysis
URL/DOI	https://doi.org/10.2134/jeq2012.0036	Local copy	—
Status	Key comparative case		

SAN-001 · US EPA (2025), Draft PFOA/PFOS Risk Assessment for Sewage Sludge

Type	official draft risk assessment	Subject / geography	biosolids, USA
What it supports	In some scenarios, modelled risk exceeded thresholds at only 1 ppb PFOA/PFOS; risk depends on dose, site and exposure pathway	What it does not support / limitation	A draft, not final regulation, and does not cover all PFAS
URL/DOI	https://www.epa.gov/biosolids/draft-sewage-sludge-risk-assessment-perfluorooctanoic-acid-pfoa-and-perfluorooctane	Local copy	—
Status	Mandatory safety source		

SAN-002 · US EPA OIG (2018), unregulated pollutants in biosolids

Type	independent regulator audit	Subject / geography	biosolids, USA
What it supports	EPA identified 352 pollutants but could not assess many of them; these included pharmaceuticals, steroids and flame retardants	What it does not support / limitation	Detection is not proof of harm from every substance
URL/DOI	https://www.epa.gov/office-inspector-general/report-epa-unable-assess-impact-hundreds-unregulated-pollutants-land	Local copy	—
Status	Accepted		

SAN-003 · EU JRC, phosphorus loop

Type	official science-policy material	Subject / geography	EU
What it supports	P can be recovered from wastewater/sludge/ash; purification into a product differs from applying whole sludge	What it does not support / limitation	Technical feasibility does not establish economics for a particular city
URL/DOI	https://joint-research-centre.ec.europa.eu/scientific-activities/circular-resource-management/closing-phosphorus-loop_en	Local copy	—
Status	Accepted		

SAN-004 · Huygens et al. / JRC (2022), sewage sludge risk			
Type	official scientific risk-screening report	Subject / geography	EU
What it supports	Sludge carries nutrients but also persistent organic pollutants, microplastics, AMR genes/pathogens; landspreading and recovery routes require separate assessment	What it does not support / limitation	Screening does not imply equal risk for every batch; detection of an ARG or chemical is not automatically proof of harm
URL/DOI	https://doi.org/10.2760/541579	Local copy	papers/SAN-004_JRC_2022_sewage_sludge_risk.pdf
Status	Mandatory safety source		
REG-001 · EU Regulation 2021/2086 on precipitated phosphate salts			
Type	regulation	Subject / geography	EU
What it supports	Struvite is permitted under restricted feedstocks, processes and quality control; mixed municipal waste is excluded	What it does not support / limitation	Not an authorisation for every sludge or struvite product
URL/DOI	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32021R2086	Local copy	—
Status	Accepted		
PAP-001 · Goossen et al. (2023), PFAS from compostable food serviceware			
Type	primary study	Subject / geography	commercial composting, Maine
What it supports	Compost containing “compostable” serviceware had substantially more PFAS than source-separated food waste plus grass/bedding	What it does not support / limitation	Three compost batches are not a universal assessment of all packaging
URL/DOI	https://doi.org/10.1116/6.0002746	Local copy	—
Status	Key counterexample		
PAP-002 · Li et al. (1997), papermill sludge on coal refuse			
Type	field study	Subject / geography	coal refuse, USA
What it supports	Paper-mill sludge was used in practice as an amendment	What it does not support / limitation	Full composition, doses and long-term water effects still require recovery
URL/DOI	https://www.asrs.us/Publications/Conference-Proceedings/1997/0277-Li.pdf	Local copy	—
Status	Under review		

PAP-003 · Shipitalo & Bonta (2008), paper-mill sludge runoff			
Type	13-month field runoff experiment	Subject / geography	recent surface-coal mine, Ohio
What it supports	Sludge consisted of cellulose fibres, clay and lime; 224/672 dry Mg/ha reduced runoff four- to sixfold and erosion from 47 to <1 Mg/ha	What it does not support / limitation	Before planting, runoff DO was ≤ 0.4 versus 8.2 mg/L and COD 7,229 versus 880 mg/L at the high dose; one mill stream, not all paper
URL/DOI	https://doi.org/10.2134/jeq2007.0648	Local copy	—
Status	Key two-sided case		
PAP-004 · Choi et al. (2019), PFAA in municipal organic solid waste composts			
Type	primary analytical study	Subject / geography	nine commercial OFMSW composts and one backyard compost, USA
What it supports	Composts accepting food packaging had total PFAA loads of 28.7–75.9 $\mu\text{g/kg}$ versus 2.38–7.60 $\mu\text{g/kg}$ without packaging; separation of packaging/feedstock matters	What it does not support / limitation	Small sample; not mine application or a risk assessment for each PFAS
URL/DOI	https://doi.org/10.1021/acs.estlett.9b00280	Local copy	—
Status	Key reason not to mix food scraps with packaging		
PAP-005 · Bugsel, B., Bauer, R., Herrmann, F., Maier, M. E., & Zwiener, C. (2022), <i>LC-HRMS screening of per- and polyfluorinated alkyl substances (PFAS) in impregnated paper samples and contaminated soils, Analytical and Bioanalytical Chemistry</i>, 414, 1217–1225			
Type	primary non-target/target screening	Subject / geography	impregnated paper and contaminated soils
What it supports	PFAS patterns supported a possible link between contaminated soil and PFAS-treated paper waste/sludge	What it does not support / limitation	A historical contamination case, not an assessment of all clean paper/cardboard
URL/DOI	https://doi.org/10.1007/s00216-021-03463-9	Local copy	—
Status	Accepted within a narrow boundary; bibliographic record independently corrected for EN edition		

ECO-001 · **Reclamation of sulphide tailings with MSW compost**

Type	technical economic report	Subject / geography	Elliot Lake, Canada
What it supports	Shows that at a transport distance of about 600 km, transport cost roughly \$30–46/t and generated heavy traffic	What it does not support / limitation	Historical prices cannot be applied to present-day Kuzbass without indexation and local data
URL/DOI	https://mend-nedem.org/wp-content/uploads/2251a.pdf	Local copy	—
Status	Accepted as calculation structure		

ECO-002 · **BIOSALIX**

Type	official demonstration-project result	Subject / geography	coal mine, Alberta
What it supports	CAD 15.8 million project tested biosolids plus woodchips plus willow and reported a 29% reduction in required soil volume	What it does not support / limitation	Proof of concept encountered commercial-scale difficulties; project website does not replace the full report
URL/DOI	https://www.eralberta.ca/projects/details/biosalix-mine-reclamation-using-and-organic-residuals-to-augment-soil-quality-and-underpin-a-cleantech-economy-through-short-rotation-willow-feedstock-production/	Local copy	—
Status	Priority economic case		

ECO-003 · **Sergey Nikolaevich (26 September 2026), scenario model for a complex old 100 ha Apanas-type coal spoil heap**

Type	author-supplied calculation model / not a site estimate	Subject / geography	hypothetical old 100 ha coal spoil heap: hazardous processes, earthworks, mineral root zone, organic/biological stage, vegetation, labour, 20-year monitoring and contingency
What it supports	Defines a rounded central scenario of RUB 800 million, ranges of RUB 400–500 million and RUB 1.3–1.8 billion, cost structure, a hypothetical 32.3 million m ³ waste-rock mass and stripping ratio of 6.1–11.5 m ³ /t; arithmetic conversion at the ECO-004 rate gives \$1.8–3.4/t for the central and \$2.9–7.6/t for the severe scenario	What it does not support / limitation	Not an estimate for Apanas, a market price, the total environmental cost of coal or site-specific engineering design; stripping-ratio range is supported separately by ECO-005 – ECO-007
URL/DOI	—	Local copy	SCENARIO_ECONOMIC_MODEL .md
Status	Accepted as author-supplied scenario; final per-tonne arithmetic appears in the main PDF text		

ECO-004 · Bank of Russia, official US-dollar exchange rate on 26 September 2026

Type	official currency basis	Subject / geography	RUB/USD conversion for scenario model ECO-003
What it supports	Fixes 1 USD = 84.3414 RUB on the model date and makes the conversion of rouble scenarios reproducible	What it does not support / limitation	Currency conversion does not turn scenario assumptions into observed market costs
URL/DOI	https://www.cbr.ru/currency_base/dynamics/?UniDbQuery.From=01.01.2022&UniDbQuery.Posted=True&UniDbQuery.VAL_NM_RQ=R01235&UniDbQuery.mode=1&UniDbQuery.so=1	Local copy	—
Status	Official rate source; spot-checked 26 September 2026		

KUZ-001 · Bragina et al. (2014), soils on overburden dumps in Kuzbass

Type	primary research article	Subject / geography	forest steppe and mountain taiga, Kuzbass
What it supports	Compares soils/rocks, trace elements and effects of spontaneous combustion	What it does not support / limitation	A chronosequence is not repeated monitoring of one site
URL/DOI	https://doi.org/10.1134/S1064229314050032	Local copy	—
Status	Priority case		

KUZ-002 · Gorozhanina et al. (2023), forest vegetation on dumps of different ages

Type	20-year series of field observations	Subject / geography	Kuznetsk Basin
What it supports	Topography, substrate density and age are associated with different forest-vegetation trajectories	What it does not support / limitation	Forest structure is not a full assessment of soil function
URL/DOI	https://doi.org/10.1002/ece3.10276	Local copy	—
Status	Priority case		

KUZ-003 · Kupriyanov & Manakov (2016), “Patterns of vegetation-cover recovery on Kuzbass spoil heaps”

Type	primary field study	Subject / geography	Kuzbass
What it supports	Identifies eight technogenic ecotopes; succession is determined by site conditions, not calendar age alone	What it does not support / limitation	Not a trial of urban organic streams
URL/DOI	https://doi.org/10.15372/SJFS20160205	Local copy	papers/KUZ-003_Sheremet_2016_Kuzbass_vegetation.pdf
Status	Priority case		

KUZ-004 · Problems of mine-technical reclamation for stable forest stands

Type	primary article	Subject / geography	25–45-year-old Kuzbass spoil heaps
What it supports	Shows heterogeneity of potentially fertile material, quality losses during stripping/storage/application and the role of particle-size distribution	What it does not support / limitation	Presence of an applied layer does not demonstrate a stable forest
URL/DOI	https://cyberleninka.ru/article/n/problemy-gornotekhnicheskogo-etapa-rekultivatsii-otvalov-kuzbassa-v-aspekte-formirovaniya-ustoychivyh-drevesnyh-nasazhdeniy	Local copy	—
Status	Priority case		

KUZ-005 · Shipilova & Semina (2016), “Physical properties of soils in technogenic landscapes of the Kuzbass forest-steppe zone”

Type	primary field study	Subject / geography	20-year-old spoil heaps at the Bachatsky deposit
What it supports	Compares a Technosol, four types of embryozem and zonal chernozem; shows high stoniness, heterogeneous density/porosity and the role of dumping technology	What it does not support / limitation	Spatial comparison is not repeated monitoring of one trajectory; age alone does not explain differences
URL/DOI	https://doi.org/10.21440/2307-2091-2016-3-25-28	Local copy	papers/KUZ-005_Shipilova_Semina_2016_Bachatsky_physical_properties.pdf
Status	Accepted		

KUZ-006 · Kupriyanov et al. (2025), “Restoration of steppe on spoil heaps”

Type	scientific monograph with a multi-year field experiment	Subject / geography	Vinogradovsky mine and other Kuzbass spoil heaps
What it supports	Compares bare technogenic eluvium, a 10-cm layer of potentially fertile loam and a 10-cm fertile soil layer under four grass-seed mixture rates with four replicates; includes 2014/2015–2023 data	What it does not support / limitation	Does not test urban compost or manure; some author interpretations require review against current SOM concepts and table units; nature-like vegetation does not automatically mean full soil autonomy
URL/DOI	https://kuzbs.ru/images/stories/pdf/izdania/Rekonstruktsiya_na_otvalakh.pdf	Local copy	papers/KUZ-006_Rekonstruktsiya_ekosistem_na_otvalakh_Kuzbassa.pdf
Status	Accepted with limitations		

KUZ-007 · Kupriyanov et al. (2021), “Reconstruction of the soil–vegetation layer on the surface of Kuzbass spoil heaps”

Type	two-year field experiment	Subject / geography	Pervomaysky mine / Mayskoye mine administration, Kuzbass
What it supports	40 cm loess-like loam plus 20/40/60 cm fresh soil–vegetation layer; 200 m ² per treatment; 2019–2020: 43–50 species, mean cover up to about 80%, less ruderal biomass than natural revegetation	What it does not support / limitation	Treatments lacked independent plot replicates; ten subsamples within a plot do not replace replication; donor layer was stripped from licensed land before mining; two years and biomass do not demonstrate long-term soil function
URL/DOI	https://doi.org/10.18796/0041-5790-2021-2-46-52	Local copy	papers/KUZ-007_Ugol_2021_soil_vegetation_layer.pdf
Status	Accepted with strong limitation		

KUZ-008 · Protasov, Portola & Seregin (2025), “Effects of seasonal atmospheric-temperature fluctuations on spontaneous-combustion centres in waste-rock dumps”

Type	four-year instrumental monitoring	Subject / geography	active spontaneous-combustion centre on a Kuzbass spoil heap
What it supports	At depths of 0.5–2.5 m, temperature persisted and changed independently of the seasonal surface; maximum reached 500 °C and 2.5-m boreholes did not determine the depth of the source	What it does not support / limitation	One source; does not compare extinguishing methods and does not imply that all spoil heaps burn
URL/DOI	https://doi.org/10.15372/FTPRPI20250210	Local copy	papers/KUZ-008_Protasov_2025_spontaneous_combustion.pdf
Status	Hard basis for the engineering gate: organic material is excluded until the source is eliminated		

KUZ-009 · Vorobieva et al. (2022/2023), “Assessment of chemical and sanitary indicators in coal-spoil material in the southern Kuznetsk Basin”

Type	one-time comparison of three zones	Subject / geography	Korchakol coal-spoil heap, southern Kuzbass
What it supports	Shows heterogeneity in pH, moisture, Ba, enzyme activity, organic contaminants and sanitary-bacteriological indicators among zones of a 5–30-year-old heap; some indicators exceeded benchmark values	What it does not support / limitation	Zones differed in age, rock and reclamation, so this is not a clean chronosequence; the authors' recommendation of biological preparations was not tested in the study; one season and one site
URL/DOI	https://doi.org/10.23859/estr-220603	Local copy	papers/KUZ-009_Vorobieva_2022_chemical_sanitary_indicators.pdf
Status	Accepted as baseline-screening evidence, not treatment evidence		

KUZ-010 · **Kuzbass Ministry of Natural Resources (2026), report on the state of the environment in 2025**

Type	official regional report	Subject / geography	Kemerovo Region — Kuzbass
What it supports	At the end of 2025, 123.634 thousand ha of disturbed land; during the year 4.620 thousand ha disturbed and 1.265 thousand ha reclaimed; provides regional water/waste/land baseline and a list of current studies	What it does not support / limitation	Aggregated numbers do not show restoration quality, age/type of each spoil heap or a causal treatment effect
URL/DOI	https://kuzbasseco.ru/doklady/o-sostoyanii-okruzhayushhej-sredy-kemerovskoj-oblasti/	Local copy	papers/KUZ-010_Kuzbass_environment_report_2025.pdf
Status	Mandatory regional baseline		

FLOW-001 · **Kuzbass newspaper (21 May 2024), environmental-forum report citing the regional minister of agriculture**

Type	regional newspaper / secondary account of an official statement	Subject / geography	Kemerovo Region — Kuzbass
What it supports	Reports an order of magnitude: at least 1.7 million t of manure and poultry litter per year from more than 130 farms; 52% cattle, 35% pigs, 12% poultry; 580,000 t in Novokuznetsk District	What it does not support / limitation	Not a primary statistical table; wet/dry basis, current uses, available surplus, quality and distances to spoil heaps are unknown; the number cannot be treated as available mass
URL/DOI	https://kuzbass85.ru/wp-content/uploads/2024/05/kuzbass-21-maya-2024.pdf	Local copy	—
Status	Context; requires primary verification for mass balance		

EXP-001 · **Gann et al. (2019), *International Principles and Standards for the Practice of Ecological Restoration*, 2nd ed.**

Type	international practice standard	Subject / geography	global
What it supports	Defines a reference ecosystem, measurable recovery attributes, monitoring and the distinction between restoration and simple rehabilitation/greening	What it does not support / limitation	Does not determine a safe amendment dose or establish applicability to a particular spoil heap
URL/DOI	https://www.ser.org/page/SERStandards	Local copy	papers/EXP-001_SER_2019_International_Restoration_Standards.pdf
Status	Accepted as outcome framework		

EXP-002 · **Laushman et al. (2021), *Protocol for Installing and Monitoring a RestoreNet Restoration Field Trial Network Site***

Type	official reproducible field protocol	Subject / geography	arid degraded land, USA
What it supports	Provides a blocked/randomised field-trial architecture, standardised plot measurements, baseline and repeat monitoring	What it does not support / limitation	Not mine-specific and does not test organic amendments; plot sizes/replication cannot be copied without power analysis and site constraints
URL/DOI	https://doi.org/10.3133/tm2A18	Local copy	papers/EXP-002_USGS_RestoreNet_Protocol.pdf
Status	Accepted as design reference		

REG-002 · **Russian Government Resolution No. 800 of 10 July 2018, former Rules for Land Reclamation and Conservation**

Type	repealed regulation	Subject / geography	Russian Federation
What it supports	Historical framework for projects approved before 1 September 2025 where the transitional provision of No. 781 applies	What it does not support / limitation	Repealed from 1 September 2025; not the current baseline for a new project
URL/DOI	https://government.ru/docs/all/117418/	Local copy	—
Status	Historical / transitional context only		

REG-003 · **Russian Government Resolution No. 781 of 29 May 2025, Rules for Land Reclamation and Conservation**

Type	current regulation	Subject / geography	Russian Federation
What it supports	Effective from 1 September 2025 to 1 September 2031; requires a project, target land quality and technical/biological measures; paragraph 9 separately regulates use of certain waste classes and creates no general permission for compost/biosolids	What it does not support / limitation	Does not automatically classify a particular organic product as permitted; waste/product status, sanitary requirements, environmental review and site-specific approval require separate analysis
URL/DOI	https://publication.pravo.gov.ru/document/0001202505290054	Local copy	—
Status	Current legal baseline; full legal pathway remains unresolved		

MIC-001 · Dadzie et al. (2024), <i>Inoculating native microorganisms improved soil function and altered the microbial composition of a degraded soil</i>			
Type	peer-reviewed primary field experiment	Subject / geography	severely degraded post-mining soil, Pilbara, Australia
What it supports	1 g native natural soil → 25 ml broth for seven days → serial transfer for seven days → culture in extruded granules; bacteria increased total N by 75% and SIR by 147%, whereas bacteria plus cyanobacteria did not improve measured soil properties	What it does not support / limitation	Culturable fraction, not the whole microbiome; 28 weeks; no mature-compost carrier or long-term persistence; treatment replicates were pooled into blocks
URL/DOI	https://doi.org/10.1111/rec.14025	Local copy	—; full author manuscript checked
Status	Key direct analogue: small donor → cultured inoculum → carrier → post-mining soil		
MIC-002 · Wawrik et al. (2005), <i>Effect of Different Carbon Sources on Community Composition of Bacterial Enrichments from Soil</i>			
Type	peer-reviewed primary enrichment experiment	Subject / geography	four soils, laboratory
What it supports	Standard culture captures a small part of soil diversity; carbon source selected the composition of enriched communities more strongly than differences among source soils	What it does not support / limitation	Bacteria only, laboratory and an older molecular method; demonstrates selection bias, not restoration outcome
URL/DOI	https://doi.org/10.1128/AEM.71.11.6776-6783.2005	Local copy	—; PubMed/PMC checked
Status	Accepted for cultivation-bias mechanism		
MIC-003 · Kaminsky et al. (2023), <i>Leveraging microbiome rediversification for the ecological rescue of soil function</i>			
Type	peer-reviewed controlled microcosm experiment	Subject / geography	agricultural and forest soils, USA
What it supports	High-diversity whole-community additions restored nitrification and associated taxa/genes; low-diversity inoculum failed; dilution and environmental matching mattered	What it does not support / limitation	Sterilised/recolonised microcosms, not post-mining soil or field; one target function
URL/DOI	https://doi.org/10.1186/s40793-023-00462-4	Local copy	—; full PMC checked
Status	Key evidence that simplification can remove functional capacity		

MIC-004 · Douds, Nagahashi & Hepperly (2010), *On-farm production of inoculum of indigenous arbuscular mycorrhizal fungi and assessment of diluents of compost for inoculum production*

Type	peer-reviewed primary propagation experiment	Subject / geography	on-farm AMF production, USA
What it supports	Indigenous AMF inoculum can be amplified with host plants in diluted compost-based media, reducing the need for wholesale donor-soil removal	What it does not support / limitation	Agricultural system; yield depends on host, initial propagules and substrate; not a direct mine-land restoration trial
URL/DOI	https://doi.org/10.1016/j.biortech.2009.11.071	Local copy	—; PubMed checked
Status	Accepted as scalable method for local AMF		

MIC-005 · *Inoculum potential of arbuscular mycorrhizal fungi in iron ore tailings areas under rehabilitation (2026)*

Type	peer-reviewed primary field sampling and trap-culture experiment	Subject / geography	Fundão iron-tailings rehabilitation, Mariana, Brazil
What it supports	50 g field material in a 1,000 ml vessel with autoclaved sand and three host plants for four months demonstrated host-assisted AMF multiplication and allowed recovery of propagules to be assessed	What it does not support / limitation	A propagation experiment, not a per-hectare product or field application; AMF recovery remained below reference and depended on revegetation age
URL/DOI	https://doi.org/10.1590/1413-7054202650014625	Local copy	—; full SciELO HTML checked
Status	Key mining-context scale-up analogue		

MIC-006 · *Soil biological recovery and plant growth under arbuscular mycorrhizal fungi inoculation in iron mining tailings and soil mixtures (2026)*

Type	peer-reviewed greenhouse experiment	Subject / geography	iron-tailings/natural-soil mixtures, Brazil
What it supports	AMF-spore inoculation increased root colonisation but did not improve enzyme activity or glomalin; successive plant cycles and labile organic input supported microbiota	What it does not support / limitation	Two 45-day maize cycles; 1:1 natural soil and tailings mixture; not mature compost and not field
URL/DOI	https://doi.org/10.1590/1413-7054202650016325	Local copy	—; full SciELO HTML checked
Status	Accepted as negative/context-dependent AMF result		

MIC-007 · **Mallon et al. (2024), *Niche availability and competitive loss by facilitation control proliferation of bacterial strains intended for soil microbiome interventions***

Type	peer-reviewed primary mechanistic experiment	Subject / geography	bacterial soil inocula
What it supports	Introduced strains may fail not only through direct competition but by facilitating growth of native competitors; culture viability does not guarantee establishment	What it does not support / limitation	Mechanistic laboratory system, not a restoration field trial
URL/DOI	https://doi.org/10.1038/s41467-024-46933-1	Local copy	—; full PMC checked
Status	Accepted for non-establishment risk mechanism		

MIC-008 · **Crawford, Dice & Clark (2026), *Why, when, and how microbes can benefit ecological restorations***

Type	peer-reviewed review	Subject / geography	terrestrial restoration, global
What it supports	Compares commercial taxa, consortia and whole-soil microbiomes; emphasises donor-site damage, compatibility, handling and the need for field validation	What it does not support / limitation	A review, not a primary trial; used to map technologies and locate primary studies
URL/DOI	https://doi.org/10.1111/nph.70995	Local copy	—; full publisher HTML checked
Status	Accepted for synthesis and navigation		

MIC-009 · ***Does soil inoculation truly steer the composition of native soil communities?* (2026)**

Type	peer-reviewed primary field study	Subject / geography	grassland under restoration
What it supports	Shift towards the donor community occurred mainly in the inoculated layer; deeper native bacteria/nematodes did not converge uniformly and fungal response depended on donor origin	What it does not support / limitation	Grassland, not mining substrate; cultured inoculum was not tested
URL/DOI	https://doi.org/10.1016/j.soilbio.2026.110105	Local copy	—; publisher abstract/method summary checked
Status	Accepted for limitation on spatial persistence		

AUTH-001 · **Natalia Zubkova, author record of her visit to the Maiminskaya solar power plant in winter 2019 and proposal to use sheep for vegetation control**

Type	participant testimony / author-supplied record	Subject / geography	Maiminskaya SPP, Altai Republic
What it supports	Records Natalia's recollection of the visit and proposal; Denis Shakin is named as a potential witness	What it does not support / limitation	Not an independent record of the conversation; Denis Shakin's testimony is not in the corpus; does not establish a causal link with later Hevel actions
URL/DOI	—	Local copy	—
Status	Accepted only as author testimony with an explicit boundary		

AUTH-002 · **Video of Natalia Zubkova visiting the Maiminskaya SPP, winter 2019**

Type	visual record described by the author	Subject / geography	Maiminskaya SPP, Altai Republic
What it supports	Confirms Natalia's presence at the site	What it does not support / limitation	The proposal to use sheep is not recorded; video is not included in the current scientific archive and was not rechecked for this package
URL/DOI	—	Local copy	not included in research/soil-restoration
Status	Accepted only for the fact of the visit as described by the author		

AUTH-003 · ***Kommersant Krasnoyarsk* (29 June 2020), “Sheep to graze at a solar power plant in the Altai Republic”**

Type	identifiable publication directly quoting Hevel's press service; original Hevel press-release page not found	Subject / geography	Ust-Kanskaya SPP; possible expansion to Ust-Koksinskaya, Maiminskaya and Ongudayskaya SPPs
What it supports	Reports a flock of 50 sheep for the summer season and conveys the company's statement that the practice might be used at other plants, including Maiminskaya; a separate <i>MK Barnaul</i> item from the same day independently repeats the number 50 and attribution to Hevel's press service	What it does not support / limitation	Not the preserved primary Hevel press release; does not establish the origin of the idea or a causal link to Natalia's proposal
URL/DOI	https://www.kommersant.ru/doc/4397338	Local copy	—
Status	Accepted as identifiable near-primary provenance with explicit boundary		

Identifier rules

- **SUB-** — substrate and disturbance types;
- **CHEM-** — chemistry and biogeochemistry;

- BIO- — soil biology;
- ORG- — organic streams and composting;
- SAN- — sanitary streams and contaminants;
- PAP- — paper and pulp;
- CASE- — field case;
- FAIL- — failure or substantial adverse effect;
- KUZ- — Kuzbass;
- ECO- — economics and logistics;
- EXP- — experiment design;
- HYP- — specialised sources on pre-inoculated living substrate;
- MIC- — cultured and whole native microbiomes, carriers and inoculum scale-up;
- AUTH- — author testimony and materials on the origin of the idea, which do not replace an independent scientific source;
- REG- — regulatory document.

V1.0 supplement: stripping ratio

ECO-005 · Kuzbass Fuel Company, publication of consolidated IFRS financial statements for 2010			
Type	primary corporate reporting	Subject / geography	KTK Group opencast production, Kuzbass; Q4 and full year 2010
What it supports	Production table reports stripping ratios of 6.1 m³/t for Q4 2010, 7.3 m³/t for 2010 and 7.1 m³/t for 2009; defined as overburden volume per tonne of coal	What it does not support / limitation	Company-period aggregate, not a ratio for a particular spoil heap, a universal Kuzbass value or an Apanas characteristic
URL/DOI	https://ktk.company/press-release/publikatsiya-konsolidirovannoy-finansovoy-otchetnosti-po-standartam-ifrs-za-god-okonchivshiysya-31-dekabrya-2010-goda	Local copy	—
Status	Accepted as primary support for lower bound of scenario range		

ECO-006 · D. S. Kostyuchenko (2017), dissertation abstract, “Justification of parameters for a combined-system technology for mining a suite of gently dipping coal seams”, KuzSTU

Type	primary academic calculation document / dissertation abstract	Subject / geography	opencast development of gently dipping seams, central Kuzbass
What it supports	Reports an observed current stripping-ratio range of 9.3–12.3 m ³ /t, design practice of 10–12 m ³ /t and a value of 11.5 m ³ /t used in calculations	What it does not support / limitation	11.5 m ³ /t is a boundary calculation parameter for a particular class of development, not a universal average or an Apanas measurement
URL/DOI	https://science.kuzstu.ru/wp-content/docs/OAD/Soresearchers/2017/zlo/aut.pdf	Local copy	—
Status	Accepted as support for upper bound with explicit limitation		

ECO-007 · A. V. Selyukov (2016), “Assessment of the land intensity of opencast coal mines by modifying the surface-mining system”, *News of the Ural State Mining University*, 3(43), 82–86

Type	peer-reviewed engineering article	Subject / geography	overseas mines and coal mines in Kemerovo Region
What it supports	Provides variability context: Kemmerer 4.6 m ³ /t, Quintette 3.5–6.4 m ³ /t, Cerrejón 5–6 m ³ /t; separately warns that different geological and technical conditions require additional calculations	What it does not support / limitation	Does not independently demonstrate the 6.1–11.5 bounds and does not describe Apanas
URL/DOI	https://doi.org/10.21440/2307-2091-2016-3-82-86	Local copy	—
Status	Accepted as transferability and variability context; erroneous local-copy link to another study removed during V1.0 QA		

ELEPICUP

The Elephant in a Cup Method

The large source is the **elephant**. The context available to an AI is the **cup**.

The method is intended not merely to pass a fragment to an AI, but to preserve the ability to determine:

- where it came from;
- its evidence status;
- the conditions of the result;
- its limitations and boundaries of applicability;
- the uncertainty;
- what remains unknown.

The key principle:

A piece of the elephant should not pretend to be the whole elephant.

ElepiCup — the Elephant in a Cup Method — is an experimental method of the *Experiment* project. Its effectiveness has not yet been demonstrated and will be tested. No claim is made to absolute novelty, priority or the status of an established discipline.

Author of the method: Natalia Zubkova.

This PDF is the first implementation of the method's **full mode**: a rigorously structured evidence document for the `document → AI → human` pathway.