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Regenerative cropping systems for sustainable food production

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Abstract

Regenerative cropping systems have moved from the margins of agronomic discourse into mainstream policy language, yet the term continues to carry more optimism than operational precision. This review synthesises evidence on the biophysical mechanisms through which reduced tillage, cover cropping, crop diversification and integrated nutrient and pest management are proposed to rebuild soil organic carbon, restore aggregate stability and reestablish belowground and aboveground biological regulation in cultivated landscapes. Rather than treating regenerative agriculture as a fixed technology package, the discussion positions it as a trajectory of soil and biodiversity recovery whose pace and ceiling depend heavily on climate, texture, prior degradation and management continuity. Findings across temperate long term trials and shorter tropical and subtropical experiments are contrasted to show where consensus is genuine and where apparent agreement dissolves once yield, economic and regional variables are disaggregated. Particular attention is given to conflicting readings of conservation agriculture performance in rainfed and smallholder systems, where soil carbon gains reported under high input conditions do not translate cleanly. The review also examines how insect and microbial community responses to diversification interact with pest regulation, an area still thin relative to the volume of work on carbon metrics alone. It closes by identifying measurement, scale and definitional gaps that currently limit the comparability of studies and the confidence with which regenerative claims can be generalised across agroecological zones.

Keywords: Soil organic carbon, conservation agriculture, cover cropping, agroecological diversification, soil biodiversity, sustainable intensification

Introduction

Cultivated soils across much of South Asia, sub Saharan Africa and parts of the North American Corn Belt have lost between a quarter and a half of their original organic carbon stock since the onset of intensive tillage based agriculture, a depletion pattern that *Lal* (2004) ^[9] linked directly to declining structural resilience and rising input dependency. The response that has gathered the most institutional traction in the past decade is regenerative agriculture, a label applied loosely enough to cover everything from strict no till organic rotations to input intensive conservation tillage maize systems. *Newton et al.* (2020) ^[10], reviewing more than two hundred scholarly and practitioner sources, found no single accepted definition, only a recurring emphasis on outcomes such as improved soil health, water cycling and biodiversity rather than a prescribed set of practices. This ambiguity is not a semantic curiosity, it shapes how evidence gets interpreted, because two trials both labelled regenerative may differ in tillage intensity, cover crop diversity and synthetic input use to an extent that undermines direct comparison.

The premise shared across most framings is that degraded arable soils can be pushed back toward a self organising state in which biological processes, rather than purchased inputs, drive nutrient cycling and structural stability. *Schreefel et al.* (2020) ^[14] framed this as a soil centred systems argument, positioning cropping decisions as levers that act on carbon inputs, disturbance frequency and living root presence, three variables with well established mechanistic links to aggregate formation and microbial biomass. In the Indian context, where *Bhattacharyya et al.* (2015) ^[2] estimated that roughly a third of the geographical area is affected by some form of soil degradation, largely from erosion, nutrient mining and waterlogging under continuous rice wheat rotations, the appeal of a low input recovery pathway is understandable, though the

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evidence base for such systems under monsoon dependent, smallholder conditions remains considerably thinner than that assembled from temperate research stations.

This review does not attempt an exhaustive practice by practice inventory. It instead follows three threads that recur across the literature and that, taken together, expose where the regenerative claim is mechanistically sound, where it is empirically contested and where it has simply outrun the data. The first concerns the soil carbon and aggregate turnover pathway, the second concerns diversification driven biological regulation including insect community effects, and the third concerns the sharp disagreement over whether reduced disturbance systems actually deliver comparable yields once regional and management variation is accounted for. A closing section draws these threads together to identify where methodological standardisation, rather than further single site trials, would do the most to resolve the current impasse.

Soil Organic Carbon and Aggregate Turnover as the Structural Foundation

The mechanistic backbone of most regenerative claims rests on the aggregate hierarchy model described by *Six et al.* (2000) ^[15], in which fresh particulate organic matter binds mineral particles into macroaggregates that subsequently break down into more stable microaggregates, each step sequestering carbon in progressively less accessible physical pockets. Practices that increase carbon inputs while reducing mechanical disturbance are expected to accelerate this turnover and raise the equilibrium carbon stock, and a substantial body of meta analytic work supports the general direction of this prediction. *Poeplau and Don* (2015) ^[12], synthesising 139 comparisons across Europe, reported an average annual soil organic carbon accrual of roughly 0.32 tonnes per hectare where cover crops replaced fallow periods, though the range spanned from negligible change to more than one tonne depending on cover crop biomass and soil texture. A more recent global synthesis by *Jian et al.* (2020) ^[16] confirmed the positive direction of the effect but flagged that most trials sampled only the upper fifteen to thirty centimetres of the profile, a depth restriction that *Tautges et al.* (2019) ^[16] showed can materially overstate whole profile gains, since their twenty two year California trial found that surface carbon increases under cover cropped, compost amended systems were partly offset by comparatively smaller changes below fifty centimetres.

Organic management more broadly shows a similar pattern of consistent direction but variable magnitude. *Gattinger et al.* (2012) ^[4], pooling 74 studies, reported topsoil carbon stocks under organic farming exceeding conventional counterparts by an average of 0.18 percent of soil mass, a figure that translates into meaningful sequestration only where organic matter inputs are sustained over multiple decades rather than a single rotation cycle. What is less often stated plainly in review literature is that these gains are asymptotic. Systems do not accumulate carbon indefinitely, they approach a new equilibrium set by climate, texture and input rate, and *Poeplau and Don* (2015) ^[12] estimated that most of the measurable change occurs within the first two decades, after which further practice continuity yields diminishing returns. This has a practical implication for how regenerative outcomes should be communicated to practitioners, since early adopter enthusiasm built on rapid initial gains risks being followed by a plateau that is mechanistically expected rather than evidence of programme failure.

Structural recovery follows a broadly parallel trajectory. Reduced disturbance allows fungal hyphal networks and

earthworm burrowing, notably by anecic species such as *Lumbricus terrestris* in temperate systems, to persist across seasons rather than being severed by annual ploughing, and this biological engineering is the principal driver of the improved water infiltration reported in several syntheses. *Basche and DeLonge* (2019) ^[1], reviewing 89 site comparisons, found infiltration rates under cover cropped or reduced till management averaging 60 to 90 percent higher than conventionally tilled controls, an effect large enough to matter for runoff and erosion risk even where carbon gains are modest. The consistency of this infiltration signal across a wide range of pedoclimatic settings is one of the more robust findings in the regenerative literature, arguably more robust than the carbon sequestration numbers themselves, because infiltration responds quickly to macropore continuity whereas carbon accrual is a slow, input dependent process that is far more sensitive to baseline degradation status.

Diversification, Belowground Biology and Insect Mediated Pest Regulation

Where the soil carbon literature is dominated by biogeochemical framing, a smaller but analytically distinct body of work has examined how crop and non crop diversification reshapes aboveground arthropod communities in ways that feed back into pest management outcomes. *LaCanne and Lundgren* (2018) ^[8], comparing regeneratively managed maize fields against neighbouring conventional fields in the northern United States, reported insect pest pressure on regenerative fields roughly ten times lower than on conventional fields, alongside soil organic matter that was consistently higher and profitability that was not compromised despite lower yields, because input costs fell more than revenue did. Their explanation invoked the resource concentration and enemies hypotheses jointly, structurally and botanically diverse fields dilute the apparency of the focal crop to specialist herbivores while simultaneously supporting higher densities of generalist predators such as Carabidae and Coccinellidae that benefit from extended floral and residue resources across the season.

This finding sits reasonably well within the broader agroecological diversification literature. *Kremen and Miles* (2012) ^[7], contrasting biologically diversified and conventional farming systems across multiple ecosystem service categories, concluded that pest and disease regulation services were consistently stronger under diversification, though yield outcomes varied enough by crop and region that the authors explicitly cautioned against generalising a uniform productivity verdict. What remains under examined, and this is a genuine gap rather than a settled finding glossed over for brevity, is the mechanistic separation between reduced pest pressure arising from habitat driven natural enemy enhancement and reduced pest pressure arising simply from lower host plant apparency in intercropped or rotated systems. Few studies isolate these pathways experimentally, most report a net pest suppression outcome without partitioning its biological origin, which limits the transferability of management recommendations from one insect pest complex to another.

Belowground, diversification interacts with mycorrhizal and rhizosphere microbial communities in ways that are mechanistically plausible but harder to demonstrate at field scale. Species such as *Funneliformis mosseae* and other arbuscular mycorrhizal fungi form more extensive hyphal networks under continuous living root cover than under fallow or monoculture, and this network has been linked to improved phosphorus acquisition and, in some but not all studies, to

induced systemic resistance against foliar and soil borne pathogens. The difficulty is that most of this mechanistic work derives from pot or mesocosm studies, and the handful of field trials that have attempted to trace mycorrhizal colonisation through to a measurable pest or disease outcome under regenerative field management report effect sizes considerably smaller and more variable than the controlled environment literature would predict, a discrepancy that has received less critical attention than it warrants given how frequently the mycorrhizal argument is invoked in regenerative extension material.

Comparative and Conflicting Evidence on Yield and Systemic Performance

The sharpest disagreement in the literature concerns whether reduced disturbance, diversified cropping actually sustains yields comparable to conventional intensive management, and here the picture is genuinely contested rather than merely under studied. *Pittelkow et al. (2015)* ^[11], analysing a global meta dataset of 5,463 paired yield observations under conservation agriculture, reported an average yield reduction of 5.1 percent relative to conventional tillage, with the penalty concentrated in rainfed, non arid environments and largely absent, or even reversed into a small gain, in dry climates once no till was combined with residue retention and crop rotation for more than a decade. Their conclusion was cautious rather than dismissive, no till without complementary rotation and residue management underperformed consistently, but the full conservation agriculture package approached parity given sufficient time and dryland conditions.

Giller et al. (2015) ^[5] pushed this qualification further, arguing that much of the enthusiasm for conservation agriculture in tropical smallholder contexts had outrun the agronomic reality on the ground, since residue retention competes directly with livestock feed demand in mixed crop livestock systems, and the promised yield stability often failed to materialise within the three to five year horizon over which most donor funded trials were evaluated, well short of the decade or more that *Pittelkow et al. (2015)* ^[11] identified as necessary for benefits to accrue. This tension between the timescale over which biological benefits are expected to emerge and the much shorter timescale over which most field programmes are funded and assessed is, in the present author's reading, the single most consequential source of apparent contradiction in the comparative literature, more consequential than any genuine disagreement about underlying mechanism.

Organic and regenerative comparisons tell a related but not identical story. *Reganold and Wachter (2016)* ^[13], reviewing organic agriculture performance across environmental, economic and social dimensions, found yield gaps averaging 10 to 20 percent below conventional systems in most direct comparisons, narrower in favourable rainfall years and wider under drought stress in some crops though notably reversed for others, since deeper rooting and higher soil water holding capacity under organically managed soils can buffer yield during moisture deficit. *LaCanne and Lundgren (2018)* ^[8] reported a similar direction, lower gross yield offset by lower input cost such that net profitability favoured the regenerative fields in

their sample, a result that reframes the debate away from yield per hectare as the sole performance metric and toward net return per hectare, a shift that several authors argue is analytically more appropriate but that remains inconsistently applied across the wider evidence base. Reconciling these threads, the fair reading is that regenerative and conservation systems are not universally yield competitive, they are conditionally competitive, and the conditions, principally management duration, climate and the completeness of the practice bundle, are precisely the variables most reviews compress into a single average effect size.

Gaps, Limitations and Directions for Methodological Convergence

Three limitations recur across this literature and, taken together, explain why confident generalisation remains premature. The first is definitional. Because *Newton et al. (2020)* ^[10] found no consensus practice definition, aggregate yield or carbon effect sizes reported in meta analyses combine systems of genuinely different disturbance intensity and input reliance under a single regenerative label, which mechanically widens confidence intervals and obscures whether a null average effect reflects true equivalence or simply heterogeneous practice bundling. *Fenster et al. (2021)* ^[3] attempted to address this by proposing a composite, ranked scoring system for regenerative practice intensity rather than a binary classification, an approach that has not yet been widely adopted but that would materially improve cross study comparability if it were.

The second limitation is temporal and spatial scale. Most of the mechanistic soil carbon and structural evidence derives from temperate, well resourced research stations with multi decade trial continuity, a luxury rarely available in South Asian or sub Saharan smallholder contexts where land tenure insecurity and fragmented holdings make sustained multi year practice adherence difficult to guarantee, let alone to measure consistently across replicated plots. *Bhattacharyya et al. (2015)* ^[2] noted this gap explicitly for Indian conditions, observing that most locally generated soil health data comes from short duration trials that cannot capture the aggregate turnover dynamics described by *Six et al. (2000)* ^[15], since macroaggregate to microaggregate carbon stabilisation genuinely requires a decade or more to manifest measurably.

The third and, in the present author's assessment, the most tractable limitation concerns the insect and broader biotic regulation pathway discussed in the diversification section above. The evidence that diversified, reduced disturbance systems suppress pest pressure is directionally consistent but mechanistically under resolved, and almost no published work integrates entomological monitoring with the soil carbon and aggregate metrics that dominate the wider literature, despite both outcomes plausibly sharing a common driver in sustained living cover and reduced disturbance frequency. A genuinely integrated trial design, tracking soil carbon accrual, aggregate stability, mycorrhizal colonisation and arthropod community composition within the same replicated plots over a minimum ten year horizon, would do more to resolve the current fragmentation of evidence than another isolated single season comparison, however well replicated that single comparison might be within its own narrow scope.

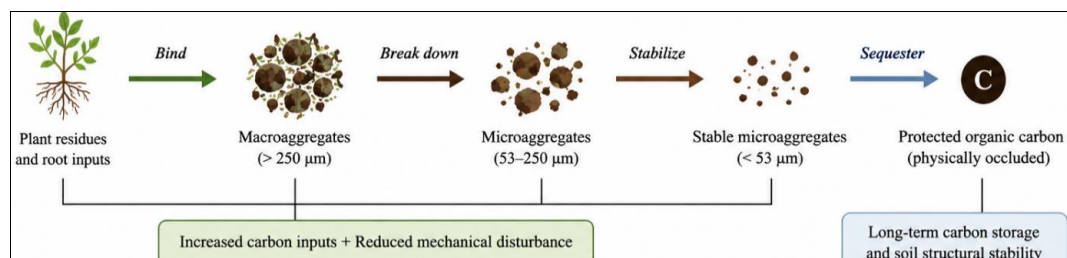


Fig 1: Aggregate hierarchy model and carbon sequestration pathway

Table 1: Synthesis of reported regenerative and conservation practice effects on soil, biological and agronomic parameters across representative studies

Practice	Parameter measured	Reported direction / magnitude	Region / system	Source
No till + residue retention	Soil organic carbon (0-15 cm)	Increase, variable magnitude	Global meta-analysis	Six <i>et al.</i> (2000) ^[15]
Cover cropping replacing fallow	Soil organic carbon accrual	+0.32 t C/ha/yr average	Europe, 139 comparisons	Poeplau and Don (2015) ^[12]
Cover cropping, global synthesis	Cropland soil carbon change	Positive, surface-biased sampling	Global meta-analysis	Jian <i>et al.</i> (2020) ^[6]
Cover crop + compost, 22-yr trial	Whole-profile carbon (0-100 cm)	Surface gain partly offset below 50 cm	California, long-term trial	Tautges <i>et al.</i> (2019) ^[16]
Organic management	Topsoil carbon stock	+0.18% soil mass vs conventional	74 studies, mixed regions	Gattinger <i>et al.</i> (2012) ^[4]
Cover cropping / reduced till	Water infiltration rate	+60 to 90% vs tilled control	89 site comparisons	Basche and DeLonge (2019) ^[1]
Conservation agriculture (full package)	Grain yield	-5.1% average, parity in dry climates >10 yr	Global, 5,463 paired observations	Pittelkow <i>et al.</i> (2015) ^[11]
Conservation agriculture, smallholder	Yield stability, residue trade-off	Inconsistent gains within 3-5 yr horizon	Sub-Saharan Africa, tropical smallholder	Giller <i>et al.</i> (2015) ^[5]
Organic systems, multi-metric review	Yield gap vs conventional	-10 to 20%, narrower in wet years	Global review	Reganold and Wachter (2016) ^[13]
Regenerative maize management	Insect pest pressure	Approximately 10-fold lower	Northern USA, paired fields	LaCanne and Lundgren (2018) ^[8]
Regenerative maize management	Soil organic matter, net profit	Higher SOM; higher profit despite lower yield	Northern USA, paired fields	LaCanne and Lundgren (2018) ^[8]
Diversified vs conventional farming	Pest and disease regulation service	Consistently stronger under diversification	Multi-region synthesis	Kremen and Miles (2012) ^[7]
Aggregate hierarchy model	Macroaggregate to microaggregate carbon stabilisation	Mechanistic pathway, decade-scale	Conceptual / temperate soils	Six <i>et al.</i> (2000) ^[15]
Indian arable soils, mixed management	Extent of soil degradation	Roughly one-third of geographical area affected	India, national assessment	Bhattacharyya <i>et al.</i> (2015) ^[2]

Table 2: Regional trajectories of soil organic carbon change under regenerative and conservation practice bundles

Region	Baseline SOC status	Practice bundle	Reported SOC change trajectory	References
Temperate Europe, mixed arable	Moderately depleted	Cover crops replacing fallow	Gradual increase, plateauing after ~20 yr	Poeplau and Don (2015) ^[12]
Mediterranean / semi-arid Europe	Low baseline SOC	Reduced tillage + cover crops	Modest, texture-dependent increase	Jian <i>et al.</i> (2020) ^[6]
California, irrigated row crop	Moderately depleted	Cover crop + compost, 22 years	Surface increase, subsurface near-neutral	Tautges <i>et al.</i> (2019) ^[16]
Global, organic vs conventional	Variable	Organic nutrient management	Small but consistent positive differential	Gattinger <i>et al.</i> (2012) ^[4]
Global drylands	Low baseline SOC	No till + rotation + residue, >10 yr	Yield parity, carbon gains slow	Pittelkow <i>et al.</i> (2015) ^[11]
Sub-Saharan Africa, smallholder	Highly depleted	Partial conservation agriculture	Inconsistent within short trial windows	Giller <i>et al.</i> (2015) ^[5]
Indo-Gangetic Plain, rice-wheat	Substantially degraded	Mixed, largely conventional	Continued net decline in most areas	Bhattacharyya <i>et al.</i> (2015) ^[2]
Northern USA, maize systems	Moderately depleted	Diversified regenerative rotation	Higher SOM than paired conventional fields	LaCanne and Lundgren (2018) ^[8]
Multiple biomes, biodiversified farms	Variable	Crop and habitat diversification	Improved regulating services, SOC not isolated	Kremen and Miles (2012) ^[7]
Global, infiltration-focused synthesis	Variable	Cover crops / reduced tillage	Structural (infiltration) gain precedes carbon gain	Basche and DeLonge (2019) ^[1]
Conceptual, temperate soils	N/A	Aggregate turnover framework	Macroaggregate carbon precedes microaggregate stabilisation	Six <i>et al.</i> (2000) ^[15]
Global, organic multi-metric	Variable	Full organic system	Positive but asymptotic, decade-scale	Reganold and Wachter (2016)

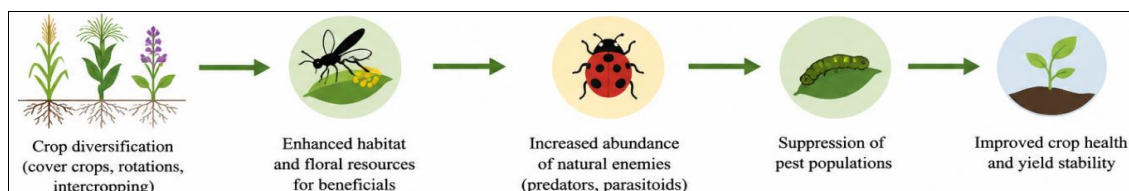


Fig 2: Diversification of biological regulation pathway

Conclusion

Regenerative cropping systems rest on mechanisms that are individually well supported, aggregate stabilisation through reduced disturbance and sustained carbon input, biological regulation through habitat and dietary diversification, and structural recovery through persistent root and faunal activity. Where the literature struggles is not in demonstrating that these mechanisms operate, it is in demonstrating that they operate at a pace, and to a degree, that matches the timeframes over which farmers and funding programmes actually make decisions. The clearest way forward is not another single season comparison but longer, better integrated trials that track soil, microbial and arthropod outcomes within the same plots, alongside a shared practice classification that allows genuinely different management bundles to stop being compressed into one label. Until that convergence happens, regenerative agriculture will continue to be simultaneously well evidenced at the level of mechanism and poorly evidenced at the level of guaranteed, generalisable outcome, a gap that policy language has so far outpaced considerably faster than the underlying science has closed it.

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