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Legume integration in cropping systems and its bearing on soil carbon, nitrogen and the carbon-to-nitrogen ratio

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Abstract

The inclusion of legumes within cereal-dominated and horticultural cropping sequences has repeatedly been associated with measurable gains in soil organic carbon and total nitrogen, alongside a narrowing of the soil carbon-to-nitrogen ratio relative to continuous non-legume systems. This synthesis draws together evidence from long-term rotation trials, intercropping experiments, green manure studies and cover crop meta-analyses to examine the mechanistic basis of these changes and to weigh the areas where the literature agrees against those where it does not. Biological nitrogen fixation supplies a direct, atmospherically derived nitrogen input that bypasses soil nitrogen mining, while legume residues, distinguished by comparatively low carbon-to-nitrogen ratios and elevated soluble nitrogen fractions, decompose rapidly and contribute disproportionately to labile soil organic matter pools. Comparative trials across temperate and semi-arid tropical settings converge on the direction of change but diverge sharply on magnitude, with rotation duration, residue management, tillage regime and soil texture all modulating outcomes. Several studies report soil carbon gains without proportional nitrogen accrual, producing inconsistent carbon-to-nitrogen responses that complicate simple mechanistic narratives. Constrain cross-study comparison, and it argues for standardised protocols before the magnitude of legume-driven soil change can be generalised across agroecological zones.

Keywords: Legume-based cropping systems, biological nitrogen fixation, soil organic carbon, soil carbon-to-nitrogen ratio, residue decomposition, nutrient cycling

Introduction

The carbon-to-nitrogen ratio of agricultural soils is not a passive descriptive statistic; it governs the rate at which microbial decomposers immobilise or release nitrogen during residue breakdown, and it therefore shapes the nitrogen economy of the whole cropping system (Kumar and Goh, 2000). Soils with wide carbon-to-nitrogen ratios tend toward net immobilisation, tying up plant-available nitrogen in microbial biomass, whereas soils that narrow over time release nitrogen more readily and support faster nutrient cycling (Franzluebbers, 2002). Cropping systems that repeatedly return carbon-rich, nitrogen-poor cereal stover to the soil, without a compensating nitrogen input, tend to sustain or widen this ratio over successive seasons.

Legumes occupy a distinctive position among crop options because they combine two properties rarely found together in a single functional group. Their symbiotic association with rhizobia allows a substantial share of their nitrogen requirement to be met through atmospheric fixation rather than soil mineral nitrogen, and their tissues, roots as much as shoots, carry markedly lower carbon-to-nitrogen ratios than cereal biomass (Peoples *et al.*, 2009). When such tissue is returned to the soil as stubble, green manure or intercrop residue, it introduces both an external nitrogen source and a readily decomposable carbon substrate, a combination that several long-term rotation studies link to simultaneous increases in soil organic carbon and total nitrogen (Jensen and Hauggaard-Nielsen, 2003) [11, 7, 14, 10].

The direction of this response is not seriously contested in the literature. What remains unsettled is its magnitude, its persistence beyond the experimental window, and the extent to which it depends on legume species, rotation architecture and regional soil conditions. Some authors report carbon-to-nitrogen narrowing driven primarily by nitrogen accrual, with carbon gains lagging behind (Gregorich *et al.*, 2001) [9], while others attribute the response chiefly to

enhanced carbon retention from legume-derived labile organic matter, with nitrogen gains proving more modest and slower to appear (Six *et al.*, 2006) ^[18]. This review works through the mechanistic evidence for both pathways, weighs the comparative trials that have attempted to separate species and system effects, and closes by identifying the methodological gaps that presently prevent a fully generalisable account of how legume integration reshapes soil carbon and nitrogen stoichiometry.

Biological Nitrogen Fixation as the Primary Route to Soil Nitrogen Enrichment

Symbiotic nitrogen fixation remains the most direct explanation for the nitrogen gains recorded under legume-integrated systems, and its scale is not trivial. Field-based estimates compiled across grain legume species place fixed nitrogen inputs anywhere between roughly 50 and 450 kilograms per hectare per season, a range wide enough to reflect genuine species and management variation rather than measurement noise alone (Peoples *et al.*, 2009). Soybean, faba bean and several forage legumes sit toward the upper end of this range under favourable rhizobial inoculation and soil moisture, while short-duration pulses such as mungbean and lentil typically fix less in absolute terms, partly a function of their shorter vegetative period.

A share of this fixed nitrogen never leaves the field as harvested grain. Rhizodeposition, the release of nitrogen-rich exudates, sloughed root cells and decaying nodules into the surrounding soil during crop growth, contributes a belowground nitrogen

pool that is easy to overlook when only aboveground biomass is sampled (Jensen and Hauggaard-Nielsen, 2003). Studies using isotopic tracing in West African cropping systems attribute a meaningful fraction of the nitrogen benefit accruing to a subsequent cereal crop to this belowground pathway rather than to visible residue incorporation alone (Sanginga, 2003). Wani *et al.*, (1995) ^[17, 10] reached a broadly similar conclusion working across semi-arid Indian legume systems, arguing that nodule turnover and root decay account for soil nitrogen gains that residue removal at harvest would otherwise erase from the balance sheet.

Disagreement surfaces once the discussion moves from the existence of a nitrogen benefit to its transfer efficiency into subsequent crops. Chalk (1998) reviewed legume-cereal rotation data and concluded that apparent nitrogen benefit to a following cereal is frequently smaller than the quantity of nitrogen fixed would predict, a discrepancy he attributed to gaseous losses, leaching and continued immobilisation within microbial biomass rather than to fixation estimates being inflated. Anglade *et al.*, (2015) ^[3, 1] arrived at a related but distinct conclusion when modelling European legume-based systems, proposing that fixation estimates derived from the nitrogen difference method systematically overstate true symbiotic input because they fail to account for legume uptake of soil mineral nitrogen alongside fixed nitrogen. Reconciling these positions requires treating fixation quantity and nitrogen transfer efficiency as separate questions, since a large fixation estimate does not guarantee a proportionally large soil nitrogen increment once losses and partitioning are accounted for.

Table 1: Reported biological nitrogen fixation and residue carbon-to-nitrogen characteristics of major grain and forage legume species used in cropping system integration, compiled from field and review studies.

Legume species	Common role in system	Reported N fixed (kg N/ha/season)	Typical residue C:N ratio	References
Soybean (<i>Glycine max</i>)	Grain rotation / sole crop	45-330	18-24	Peoples <i>et al.</i> , 2009 ^[15]
Faba bean (<i>Vicia faba</i>)	Grain rotation / intercrop	100-330	15-20	Peoples <i>et al.</i> , 2009 ^[14]
Chickpea (<i>Cicer arietinum</i>)	Grain rotation, semi-arid	25-140	20-27	Wani <i>et al.</i> , 1995 ^[21]
Pigeon pea (<i>Cajanus cajan</i>)	Deep-rooted intercrop / agroforestry	40-280	18-25	Ghosh <i>et al.</i> , 2007 ^[8]
Mungbean (<i>Vigna radiata</i>)	Short-duration catch crop	30-110	16-22	Wani <i>et al.</i> , 1995 ^[21]
Cowpea (<i>Vigna unguiculata</i>)	Grain / green manure, tropics	35-240	15-19	Sanginga, 2003 ^[17]
Lentil (<i>Lens culinaris</i>)	Grain rotation, temperate	40-115	19-25	Peoples <i>et al.</i> , 2009 ^[14]
Groundnut (<i>Arachis hypogaea</i>)	Grain rotation, semi-arid	35-125	18-23	Ghosh <i>et al.</i> , 2007 ^[8]
Pea (<i>Pisum sativum</i>)	Grain rotation, temperate	50-200	17-22	Jensen and Hauggaard-Nielsen, 2003 ^[10]
Lucerne / alfalfa (<i>Medicago sativa</i>)	Perennial forage rotation	150-450	13-18	Peoples <i>et al.</i> , 2009 ^[14]
Berseem clover (<i>Trifolium alexandrinum</i>)	Winter green manure	80-220	14-19	Fageria, 2007 ^[6]
Vetch (<i>Vicia villosa</i>)	Winter cover crop	70-210	13-17	Kuo <i>et al.</i> , 1997 ^[12]
Cluster bean / guar (<i>Cyamopsis tetragonoloba</i>)	Rainfed rotation, semi-arid	20-90	20-26	Ghosh <i>et al.</i> , 2007 ^[8]
Black gram (<i>Vigna mungo</i>)	Short-duration catch crop	25-100	17-22	Ghosh <i>et al.</i> , 2007 ^[8]

Residue Quality, Decomposition Kinetics and the Accrual of Soil Carbon

The carbon side of the equation rests on a different mechanism, one governed less by atmospheric input and more by the biochemical composition of legume residue itself. Legume tissue characteristically carries a narrower carbon-to-nitrogen ratio, often falling somewhere between 15 and 25, against cereal straw values that regularly exceed 60 (Kumar and Goh, 2000). This compositional difference dictates decomposition behaviour under field conditions, narrow-ratio residues undergo faster

microbial breakdown and release nitrogen into the soil solution within weeks rather than the many months typical of cereal stover.

Drinkwater *et al.*, (1998) offered one of the more widely cited demonstrations of this dynamic, comparing legume-based and conventionally fertilised maize systems across paired commercial farms and reporting that the legume-based systems retained more carbon and nitrogen per unit of nitrogen input despite lower absolute yields, a finding they linked to reduced losses through leaching and volatilisation rather than to superior

residue return alone. Kuo *et al.*, (1997) ^[12] documented a comparable pattern in a winter cover crop trial, finding that legume cover crops raised particulate organic carbon fractions measurably faster than non-legume covers over a comparatively short two-year window, an outcome attributed to the ease with which soil fauna and microbes process nitrogen-rich residue into stabilised organic fragments.

Not every study finds legume residues superior for carbon accrual once the full decomposition trajectory is considered. Because labile, nitrogen-rich material decomposes quickly, a substantial share of the carbon it contributes may be respired as carbon dioxide within the first growing season rather than incorporated into more persistent soil organic matter pools. Six *et al.*, (2006) ^[18] raised this concern directly, arguing that fungal-dominated decomposition pathways, more typical of carbon-rich, slowly decomposing residues, contribute disproportionately to long-term carbon sequestration through the production of recalcitrant microbial byproducts, whereas rapidly mineralised

legume residue may support short-term biomass flushes without commensurate gains in stable carbon fractions. Poeplau and Don (2015) ^[15], synthesising cover crop trials across a wide range of climates, reported a small but statistically detectable positive effect of legume and mixed cover crops on topsoil carbon stocks, yet noted that the effect size shrank considerably once trial duration exceeded a decade, consistent with an early flush of labile carbon gain that does not necessarily compound indefinitely.

Sainju *et al.*, (2005) ^[16] attempted to reconcile these positions using biculture cover crop systems that paired a legume with a non-legume species, reporting that the combination produced greater total biomass carbon and nitrogen than either component grown alone, a result that suggests the carbon stability argument and the rapid nitrogen release argument are not mutually exclusive but instead operate on different fractions of the same residue input, the labile fraction cycling quickly while a smaller recalcitrant fraction accumulates more slowly.

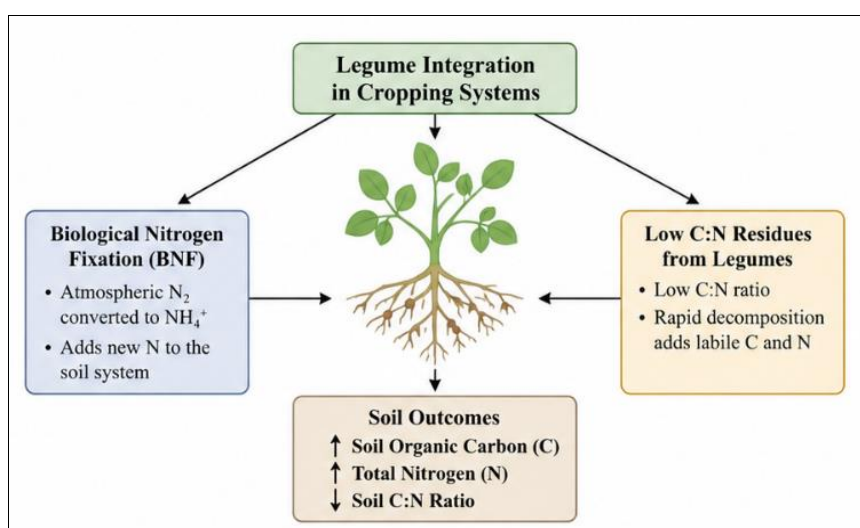


Fig 1: Mechanisms by which legume integration improves soil organic carbon, total nitrogen and reduces the soil carbon to nitrogen ratio

Comparative Evidence Across Rotation, Intercropping and Green Manure Systems

Meta-analytic work provides the clearest picture of how consistently these mechanisms translate into measurable soil change, though even here the picture is not uniform. Tonitto *et al.*, (2006) ^[20] pooled data from cover crop trials replacing bare fallow and found that legume cover crops reduced nitrate leaching substantially relative to fallow while producing comparable or superior yields to conventionally fertilised systems in a majority of the trials examined, a result they read as support for legume-based nitrogen cycling being both agronomically and environmentally favourable. McDaniel *et al.*, (2014) ^[13] took a broader diversification angle, examining crop rotation length and composition across many long-term trials, and reported that greater rotational diversity, of which legume inclusion was a major driver, correlated positively with both microbial biomass and soil organic carbon, though the strength of this relationship varied considerably by climate zone and was weaker in cooler, wetter regions than in warmer ones.

Intercropping trials add a further layer of comparison because they test simultaneous rather than sequential legume presence. Cong *et al.*, (2015) ^[4] compared maize-legume intercrops against sole maize across multiple site-years in China and reported significant increases in both soil organic carbon and total nitrogen under intercropping, attributing the gain to a combination of belowground nitrogen transfer during the

growing season and greater total residue return from the additional crop component. This result sits comfortably alongside the rotation-based findings, though the mechanism differs somewhat, intercropping compresses the nitrogen transfer window into a single overlapping growing season rather than distributing it across a multi-year sequence.

Indian semi-arid systems offer a useful counterpoint because green manuring, rather than grain legume rotation, dominates much of the regional evidence base. Ghosh *et al.*, (2007), reviewing legume effects across major Indian cropping systems, concluded that pulse and green manure legumes consistently improved nitrogen use efficiency of the subsequent cereal crop and raised soil organic carbon in the majority of trials surveyed, but flagged considerable site-to-site variability tied to baseline soil fertility, with the poorest-fertility soils showing the largest relative gains and already fertile soils showing comparatively little additional benefit. Fageria (2007) ^[6], reviewing green manuring more broadly, reached a similar conclusion regarding diminishing marginal returns on higher-fertility soils, while also noting that green manure incorporation timing relative to the following crop strongly influences whether the nitrogen released is captured by the crop or lost before root systems can access it. Snapp *et al.*, (2005) and Blanco-Canqui *et al.*, (2015) ^[19, 2], working from temperate United States cover crop data, both caution against treating legume cover crop benefits as automatic. Snapp *et al.*, (2005) ^[19] found that legume cover crop

performance depended heavily on niche fit within the existing rotation, species selected for a poor climatic or seasonal fit produced negligible biomass and correspondingly negligible soil benefit regardless of their theoretical nitrogen fixation potential. Blanco-Canqui *et al.*, (2015) ^[2] extended this caution to soil carbon specifically, noting that several well-controlled trials found no detectable change in soil organic carbon under legume cover cropping within a five-year window, a result at odds with the more optimistic findings from longer-duration or more fertility-limited systems discussed above. Taken together, the comparative literature agrees that legume integration moves soil carbon and nitrogen in a favourable direction on average, but the size of that average conceals substantial variation driven by baseline soil fertility, trial duration and how well the chosen legume fits the local growing season.

Reconciling the Carbon-to-Nitrogen Response and Its Site Dependence

Because soil organic carbon and total nitrogen do not always rise in step, the net effect on the carbon-to-nitrogen ratio is more variable across studies than either component considered alone. Gregorich *et al.*, (2001) ^[9], working with long-term maize monoculture and legume-based rotation plots in Ontario, reported a narrower carbon-to-nitrogen ratio under the legume rotation driven primarily by nitrogen accrual outpacing carbon gain, a pattern consistent with rapid mineralisation of labile legume nitrogen entering the total nitrogen pool faster than new carbon stabilises into organic matter. Six *et al.*, (2006) ^[18], by contrast, described situations in which carbon gain outpaces nitrogen gain, particularly where fungal-dominated decomposition pathways are favoured by reduced tillage, producing a narrowing effect through the carbon denominator

changing more slowly while nitrogen accumulates, or in some cases a ratio that barely shifts because both pools move in tandem.

Tillage regime interacts with legume effects in ways that complicate simple predictions. Reduced or zero tillage tends to slow residue incorporation and favour surface accumulation of organic matter, which several authors link to more fungal-dominated decomposition and greater long-term carbon stability, while conventional tillage accelerates residue mixing and initial mineralisation, favouring faster but potentially less persistent nitrogen release (Six *et al.*, 2006). McDaniel *et al.*, (2014) ^[18, 13] found that the positive association between rotational diversity and soil carbon held more strongly under reduced tillage than under conventional tillage across the trials they examined, suggesting that legume benefits and tillage benefits are not simply additive but partly dependent on one another.

Soil texture and baseline fertility further modulate outcomes. Clay-rich soils with greater mineral surface area for organic matter stabilisation tend to retain a larger share of legume-derived carbon than coarse-textured soils, where labile carbon is more readily mineralised and lost as carbon dioxide before stabilisation can occur (Franzluebbers, 2002). Fageria (2007) and Ghosh *et al.*, (2007) ^[18, 6] both report the largest relative carbon-to-nitrogen improvements on soils that began the trial period already depleted, an observation consistent with a law of diminishing returns rather than a fixed, universally applicable magnitude of legume benefit. The practical implication is that a single carbon-to-nitrogen response coefficient for legume integration cannot be extrapolated confidently across soil types, climates and tillage systems without accounting for these interacting variables.

Table 2: Reported direction and approximate magnitude of change in soil organic carbon, total nitrogen and carbon-to-nitrogen ratio under legume-integrated systems relative to non-legume comparators in selected long-term and meta-analytic studies.

Study	Region	Change in SOC	Change in total N	Change in C:N ratio	Source
Legume-based vs conventional maize rotation	North-eastern USA, multi-year	Increase	Increase	Narrowing	Drinkwater <i>et al.</i> , 1998 ^[5]
Legume vs non-legume winter cover crop	USA, 2-year trial	Moderate increase	Increase	Narrowing	Kuo <i>et al.</i> , 1997 ^[12]
Maize-legume intercrop vs sole maize	China, multi-site	Increase	Increase	Narrowing	Cong <i>et al.</i> , 2015 ^[4]
Cover crop meta-analysis (legume and mixed)	Multiple climates, cross-study	Small increase, attenuates over time	Not separately reported	Not separately reported	Poeplau and Don, 2015 ^[15]
Rotational diversity meta-analysis	Multiple long-term trials	Increase, climate-dependent	Increase in microbial N pools	Narrowing, variable strength	McDaniel <i>et al.</i> , 2014 ^[13]
Legume vs cereal monoculture rotation	Ontario, Canada, long-term	Slight increase	Increase	Narrowing, N-driven	Gregorich <i>et al.</i> , 2001 ^[9]
Cover crop replacing bare fallow	Multiple temperate sites, meta-analysis	Not primary focus	Reduced leaching, higher retention	Not directly reported	Tonitto <i>et al.</i> , 2006 ^[20]
Legume and pulse-based systems	Semi-arid India, multi-site review	Increase, fertility-dependent	Increase, larger on poor soils	Narrowing, site-variable	Ghosh <i>et al.</i> , 2007 ^[8]
Green manure incorporation	Multiple regions, review	Increase, diminishing on fertile soils	Increase, timing-dependent	Narrowing	Fageria, 2007 ^[6]
Legume cover crop, 5-year controlled trial	Temperate USA	No detectable change	Increase, modest	Little change	Blanco-Canqui <i>et al.</i> , 2015 ^[2]
Biculture legume-cereal cover crop	Southern USA	Increase, greater than either sole cover	Increase, greater than either sole cover	Narrowing	Sainju <i>et al.</i> , 2005 ^[16]
Fungal-dominated decomposition pathway comparison	Cross-system synthesis	Increase, more persistent fraction	Modest, slower accrual	Narrowing, carbon-driven	Six <i>et al.</i> , 2006 ^[18]

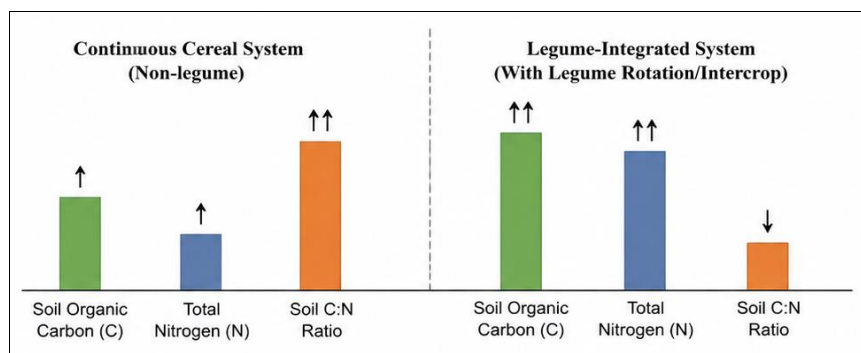


Fig 2: Comparative effects of continuous cereal systems versus legume integrated systems on soil organic carbon, total nitrogen and the soil carbon to nitrogen ratio

Methodological Gaps and Limitations in the Current Evidence Base

Several recurring weaknesses limit how confidently the findings summarised above can be generalised. Sampling depth is the most persistent of these. A considerable share of the trials cited restrict soil carbon and nitrogen measurement to the uppermost fifteen or twenty centimetres, a depth convention that favours detection of legume effects because residue incorporation and root turnover concentrate near the surface, while potentially missing subsoil changes in either direction that deeper-rooted legume species such as pigeon pea or lucerne might induce. Reviews that do sample below thirty centimetres report smaller or, in some cases, statistically undetectable effects relative to shallow-sampled studies, raising the possibility that published effect sizes carry a systematic shallow-sampling bias rather than reflecting the true whole-profile response.

Trial duration presents a related problem. Several of the more optimistic carbon accrual findings derive from experiments running five years or fewer, a window that, as Poeplau and Don (2015)^[15] note, tends to capture an early labile carbon flush that does not necessarily persist once soil organic matter pools approach a new equilibrium. Conversely, some of the longer-duration trials, including several referenced in this review, do not report carbon-to-nitrogen ratio directly, publishing carbon and nitrogen concentrations separately and leaving the ratio to be back-calculated by readers, a practice that introduces avoidable inconsistency into cross-study comparison and complicates meta-analytic synthesis.

Regional representation also skews the evidence base. Temperate systems, particularly from North America and Western Europe, dominate the peer-reviewed literature on legume cover cropping and rotation carbon dynamics, while tropical and semi-arid systems are comparatively underrepresented relative to their agricultural importance, notwithstanding valuable contributions from Indian and West African trials cited throughout this review. Given that decomposition rates, microbial community composition and baseline soil organic matter levels differ substantially between these climatic zones, extrapolating temperate-derived response magnitudes to tropical smallholder systems, or the reverse, carries real risk of overstatement or understatement depending on direction.

Finally, inconsistent legume species selection across trials makes species-level generalisation difficult. A study using soybean cannot be assumed to predict the response of a deep-rooted perennial forage legume, yet reviews and even some meta-analyses occasionally pool such species together under a single legume category. Disaggregating future trials by rooting depth, residue carbon-to-nitrogen ratio at incorporation and

nitrogen fixation capacity, rather than treating legumes as a functionally uniform group, would sharpen the precision of any future synthesis considerably.

Conclusion

The weight of evidence supports a genuine and mechanistically explicable improvement in soil carbon, soil nitrogen and the carbon-to-nitrogen ratio when legumes are integrated into cropping systems, whether through rotation, intercropping or green manuring. Biological nitrogen fixation supplies an external nitrogen input largely decoupled from soil mineral nitrogen mining, while the comparatively narrow carbon-to-nitrogen ratio of legume residue accelerates decomposition and nitrogen release relative to cereal-dominated residue streams. Where the literature disagrees is not on direction but on magnitude and persistence, with carbon and nitrogen gains proving uneven across soil types, tillage regimes, trial durations and legume species, such that no single coefficient can yet describe the expected benefit across agroecological contexts. Closing this gap will depend less on additional confirmatory trials repeating existing designs and more on deliberate methodological standardisation, consistent sampling depth extending below the plough layer, trial durations long enough to distinguish transient labile flushes from durable equilibrium shifts, and routine reporting of the carbon-to-nitrogen ratio itself rather than its two components in isolation. A more disaggregated, species- and depth-explicit evidence base of this kind would allow the agronomic promise of legume integration to be translated into region-specific management recommendations with considerably greater confidence than the current literature permits.

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