

Soil Organic Carbon Stocks Under Long-Term Rice-Wheat and Rice-Fallow Systems

Nerea Sotomayor¹ ●, Vikram Dash² ●, Nerea Olabarria³ ●

¹ Scientist, Department of Agronomy, Extremadura Centre for Dehesa Livestock Research, Plasencia, Spain. Email: n.sotomayor@ecdrl.es | ORCID: 0000-0001-0370-9750

² Scientist, Department of Agricultural Microbiology, Kaveri Delta Centre for Animal Sciences, Thanjavur, India. Email: v.dash@kdcas.ac.in | ORCID: 0000-0001-2641-4031

³ Scientist, Department of Agricultural Microbiology, Ebro Valley Institute of Crop Sciences, Tudela, Spain. Email: n.olabarria@evics.es | ORCID: 0000-0001-3039-6171

ABSTRACT

Soil organic carbon under rice-wheat and rice-fallow systems is often discussed as if a single number could describe it, yet the figures that circulate in the literature rest on choices that are rarely stated: the depth sampled, the way bulk density is handled, the baseline against which change is judged, and the number of samples behind each mean. This narrative review examines what is known about organic carbon stocks in long-term rice-based systems of South Asia and why estimates from different experiments are so hard to compare. It draws on published work on paddy soil biogeochemistry, on long-term fertiliser and manure experiments, and on the methods used to convert concentrations into stocks, and it reports no new data. The alternation of flooded rice with a drained wheat phase, or with a fallow, changes how residues decompose and how carbon is stabilised, so the same practice can behave differently in each phase. Change in stock is slow relative to sampling noise, and equal-depth comparisons can mislead when management alters bulk density. The review concludes that apparent gains and losses should be read with their method attached, and it sets out a reporting standard that would make future long-term records comparable.

Keywords: Soil organic carbon; Rice-wheat system; Rice-fallow; Long-term experiments; Equivalent soil mass; Carbon stock; Narrative review

Citation: Sotomayor, Dash and Olabarria [2019]. Soil Organic Carbon Stocks Under Long-Term Rice-Wheat and Rice-Fallow Systems. DOI: 10.62649/v7.i01.2019.pp39-48

Copyright: © 2019 by the authors. Open access under CC BY 4.0 license.

Article Information: Received: September 8, 2018 Accepted: December 18, 2018 Published: March 28, 2019

Article Class: Review Article

1. Introduction

Rice and wheat together occupy a large share of the cultivated land of the Indo-Gangetic plains, and the sequence in which one follows the other through the year has been the backbone of food production there for a long time [1]. A farmer, an agronomist or a climate analyst who asks what this sequence does to the carbon held in the soil quickly meets a difficulty. Soil organic carbon is the part of soil organic matter that matters for fertility, water holding and structure, and it is also a store that can in principle take carbon dioxide

out of the air [2, 3]. The enthusiasm for this second role has outrun the quality of the numbers on which it depends [4, 5].

The difficulty is not that carbon cannot be measured. It is that a stock, expressed in tonnes per hectare, is the product of several decisions: how deep to sample, how to convert a concentration into a mass of carbon per unit of land, what to compare the result with, and how many samples to take in a field that is far from uniform [6, 7]. Each decision can move the answer by an amount comparable with the effect that an

experiment is trying to detect. Two papers can report opposite conclusions about the same management without either being wrong about its own soil. A reader comparing two papers needs to know, before anything else, whether the two numbers were measured the same way.

Rice-based systems add a further complication. Rice is normally grown in puddled, flooded fields, and wheat or another upland crop, when it follows, is grown on soil that has been drained and allowed to dry [8]. Where nothing is grown in the second season, the field is left fallow, and the biological and chemical conditions are different again. The same residue, the same fertiliser and the same tillage can therefore produce a different carbon outcome in each phase, and a stock measured at one point in the year is a snapshot of a cycle.

This article is a narrative review. It asks what published work says about organic carbon stocks under long-term rice-wheat and rice-fallow systems, mainly in South Asia, how those stocks are calculated, and why estimates are so difficult to compare across experiments. It reports no new measurements and quotes no stock values, because a number lifted from one study is meaningless without the depth, mass basis and baseline that came with it. The aim is a fair account of what the records can and cannot say.

2. Literature Review

2.1 Why Soil Carbon Is Worth Counting

Soils hold more carbon than the atmosphere and the vegetation put together, and relatively small proportional changes in that store matter for the global balance [9]. Agricultural soils have lost carbon through cultivation in many regions, and the loss implies a capacity to recover some of it through better management [2, 9]. That argument has been summarised in policy terms in the idea of increasing soil carbon by a small fraction each year [10], and it has been tempered by authors who point out that accounting, additionality and permanence are harder to establish than the arithmetic suggests [4, 11].

For farmers the interest is more practical. Organic matter supports aggregate stability, nutrient supply and the capacity of the soil to hold water, and a decline in it is often one reason why yields of intensive systems stagnate [12, 13]. A decade or two of rice-wheat cropping with high fertiliser input and little organic return could, in principle, run down the stock without any obvious sign until yields begin to suffer [1, 8]. Whether that has happened widely is exactly the kind of question that long-term experiments were established to

answer.

2.2 Carbon in Flooded and Drained Soils

Flooding changes decomposition. When a paddy is puddled and kept under standing water, oxygen is quickly exhausted in the soil, and organic material breaks down by slower anaerobic pathways that release less energy per unit of carbon processed [14, 15]. Reviews of paddy soil biogeochemistry also describe interactions between organic matter and iron and other minerals that are driven by the repeated cycle of reduction and reoxidation [15]. Organic matter has therefore often been found to accumulate more readily in submerged soils than in well-drained ones, though not without exceptions [14, 16].

The drained phase is a different story. When the field dries and a wheat crop is grown, oxygen returns, decomposition speeds up, and the temperature sensitivity of microbial activity becomes relevant in the warm months [17]. Rice-wheat is thus a system in which the soil is made to switch between two regimes each year, and the net outcome reflects the balance between the slow accumulation of the flooded phase and the faster turnover of the aerobic one. Where the second season is a fallow, the aerobic phase is shorter in its inputs even if the drying is similar: less crop carbon returns while decomposition continues [1, 18]. Soil that is drained after months under water behaves quite differently from soil that has stayed aerobic.

Stabilisation of carbon is not simply a matter of oxygen. The persistence of organic matter is increasingly described as a property of the soil ecosystem, not of the chemical identity of the material [19, 20]. Physical protection inside aggregates and association with mineral surfaces matter, and there are limits to how much carbon a given soil can protect [21]. A soil that has been cropped for decades may therefore approach a new level and then stop changing, and the rate observed early in an experiment cannot be extrapolated indefinitely [21, 22].

2.3 What Long-Term Rice-Wheat Experiments Have Shown

Several long-term experiments in South Asia have followed rice-wheat rotations under different fertiliser and manure regimes, and a number of them have also recorded organic carbon. One well-known experiment compared inorganic fertiliser with combinations of manure and fertiliser and reported both yield trends and changes in soil organic carbon [23]. Others have examined how organic amendments influence the

pools of carbon within the soil as well as productivity [24], and how labile fractions respond to fertiliser, straw and manure [25]. A wider set of experiments across sub-humid and semi-arid India links fertiliser and manure use with carbon storage and the sustainability of yield [26].

The general pattern in this literature is that treatments returning more organic material tend to keep or raise carbon relative to those that return less, while fertiliser alone has shown more varied results. That pattern fits the broader finding that nitrogen fertilisation helps sustain organic matter mostly by increasing the amount of crop residue returned [13], and it also fits the sceptical view that fertiliser nitrogen does not by itself build carbon [27]. Neither reading can be settled by a single site, because the soils, climates and sampling methods differ, and the experiments were designed to compare treatments within a site, not to rank sites.

Two reviews of long-term rice-wheat records are worth singling out because they concern what the experiments can be trusted to say. One assessed how extensive declines in yield have been across long-term trials in Asia and noted how much depends on the way the data were recorded and analysed [8]. The other set the system's productivity problems in a wider frame of nutrient, residue and water management [1]. Both remind us that conclusions about carbon from the same experiments inherit the same strengths and weaknesses.

2.4 Continuous Rice and Rice-Fallow Evidence

Evidence for rice systems without a wheat phase comes from a different set of studies. Records of long-term continuous lowland rice have described changes in soil carbon and nitrogen under repeated flooded cropping [28], and surveys of paddy topsoils at regional scale have estimated how much carbon they hold and how much more they might hold [16]. A chronosequence of paddy soil development gives a longer view of accumulation than any experiment can, but it substitutes soil age for time, so it cannot control for differences between sites [15].

Rice-fallow systems are less well documented. Where the dry season is left uncropped, the fallow gives no crop residue and may carry weeds that return some biomass, but the evidence on the net effect on stock is thin, and most of what can be said comes by inference from the contrast between flooded and drained phases [1, 14]. A reader should therefore treat claims about rice-fallow carbon as hypotheses informed by the

biogeochemistry, not as measured outcomes.

2.5 From Concentration to Stock

A laboratory reports a concentration of organic carbon, typically as a mass fraction of the fine soil. To obtain a stock, the concentration is multiplied by the mass of soil in the layer, which is the product of bulk density and thickness [6]. The conversion looks trivial, but it carries two uncertainties: the bulk density is itself measured with error, and it can differ between treatments because management compacts or loosens the soil [29, 30]. A treatment that increases bulk density packs more soil, and hence more carbon, into the same depth, even if the carbon concentration has not changed.

The laboratory method matters too. Wet oxidation by the chromic acid method, introduced early in the last century, does not oxidise all organic carbon, and a correction factor is often applied to compensate [31]. Dry combustion measures total carbon and needs a separate step to remove carbonate where it is present. Results from the two approaches do not always agree, and a comparison of stocks across papers that used different methods carries that disagreement along with it [31, 32]. Small differences in method can therefore outweigh the differences in management that a study set out to measure.

Fractionation of carbon into labile and stable pools is another route. Methods that separate carbon by its degree of oxidation or by particle size reveal changes in the active fraction well before the total moves [33, 34]. For long-term rice-wheat records, such fractions have shown that management can alter the quality of the carbon even when its total quantity appears steady [24, 25]. They are useful additional evidence but not a replacement for a carefully computed stock.

3. Materials and Methods

3.1 Scope and Question

The review asks one question in three parts: what do long-term experiments say about organic carbon stocks under rice-wheat and rice-fallow systems in South Asia, how are those stocks calculated, and how far do the calculation choices limit comparison between studies? The question was divided into the points a reader would need in order to interpret a reported stock: the sampling depth, the treatment of bulk density, the baseline, the carbon method, the replication and the phase of the cropping cycle at which sampling took place. None of these steps is demanding, but each is easy to leave undocumented.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: the biogeochemistry of paddy and rice-based soils; long-term fertiliser, manure and tillage experiments, with emphasis on rice-wheat; methods for computing and monitoring soil carbon stocks; and the wider debate on soil carbon as a climate measure. Sources were chosen for relevance, standing in the field and clarity of method. Work from other regions and cropping systems is used for what it teaches about method and limits, not as evidence of what happens in South Asian paddies.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement. The practical consequence is that the review is a better guide to how a stock should be measured and reported than to the exact size of any gain or loss, and it avoids quoting stock values from individual experiments that could not be checked against the primary papers for this article.

3.3 Appraisal Framework

To judge how far a reported stock change can be trusted, we asked six questions of each line of evidence. Was the depth of sampling stated and was it adequate [5, 35]? Was the stock expressed on a fixed-depth or an equivalent-mass basis [36, 37]? What was the baseline? How was carbon measured? How many samples stood behind each mean, relative to the spatial variation [38, 39]? And at what point in the rice-wheat cycle were samples taken? Table 1 gathers these choices with what should accompany each.

4. Results

4.1 Fixed Depth Versus Equivalent Soil Mass

The most consequential choice is the way a stock is expressed. A fixed-depth stock sums the carbon in, say, the top layer of soil down to a chosen depth. If management changes the bulk density of that layer, the same depth contains a different mass of soil at the end of the experiment from that at the beginning, and part of any apparent change in carbon is simply a change in the amount of soil being sampled [6, 36]. The equivalent-mass approach avoids this by comparing the carbon in the same mass of soil, so that layers are adjusted to a common reference [6, 37].

Table 1. Choices that shape a stock estimate and what to report with it.

Choice	How it affects the estimate	What to report
Sampling depth	Deeper layers add carbon and change comparisons between systems [9, 35]	Depth intervals, not only the total
Bulk density	Management can alter it, so equal depth is not equal mass [6, 30]	Method and layer-wise values
Mass basis	Equivalent soil mass removes the bulk-density artefact [36, 37]	Reference mass used
Baseline	Change is judged against an earlier state or a control [4, 7]	Year, depth and how archived
Carbon method	Wet oxidation and dry combustion do not agree fully [31, 32]	Method, any correction factor
Replication	Spatial variation can exceed real change [38, 39]	Samples per plot, plots per system

Note: Qualitative summary of the methodological literature; no stock values are given because they depend on site and method.

This matters especially for puddled rice soils, where puddling and years of repeated wetting and drying change the physical structure of the layers near the surface and the plough pan below them [15, 18]. Simple corrections for bulk density have been shown to fail in some circumstances, and the problem is not removed merely by applying a ratio [30]. Misuse of bulk density in the calculation can also bias stocks upwards [29]. Figure 1 illustrates the idea: two profiles that contain the same mass of soil in their upper layers differ in depth when one is compacted. A gain that vanishes when the sampling depth is changed is not a gain the soil itself would register.

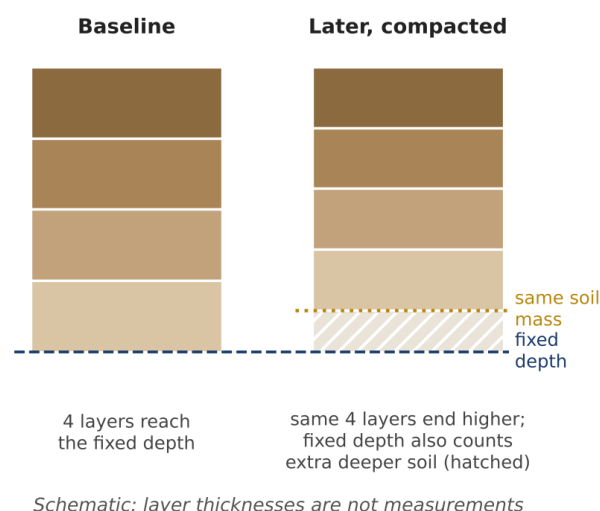


Figure 1. Why equal depth is not equal soil mass (schematic, not data).

4.2 Depth, Baseline and Where the Carbon Sits

Depth is the second large source of disagreement. Management often changes the distribution of carbon down the profile, not only its total, and a study that samples only the upper layers may miss a compensating change deeper down [5, 35]. This was a central lesson from the tillage debate: conclusions drawn from shallow sampling did not always survive deeper sampling [4, 5]. In rice systems the question is complicated by the plough pan, which limits root and residue penetration and may concentrate carbon above it [14, 15].

The baseline raises a similar difficulty. Many long-term experiments did not measure carbon at the start, so change must be inferred by comparing treatments with each other or with an untreated control, which gives a difference between treatments, not a change over time [7, 40]. A treatment can look as if it has built carbon only because the control lost it. Where archived samples exist, they offer a direct baseline, but even then the storage and the original method need to be known [39, 40]. Without these details a reported sequestration rate is a statement about contrast, not accumulation. The point is not that a long-term record is poor, only that its headline figure travels less far than its abstract suggests.

Global analyses of sequestration rates have shown how much rates vary with climate, soil and management, and how many of them rest on paired comparisons [41, 42]. Applying a rate from a temperate dataset to a tropical rice-wheat field is therefore an extrapolation. Even within South Asia, the sites that supplied the long-term data are few relative to the diversity of soils in the plain, and the extent to which they represent the region is not known [23, 26].

4.3 Two Phases, Two Regimes

The way the cycle is split between flooded and drained phases is where rice-wheat stands apart from most systems for which carbon methods were developed. In the flooded phase, anaerobic conditions favour accumulation, and the system also releases methane, which has its own climate cost [43, 44]. In the drained phase, decomposition is faster, and the wheat crop supplies a second pulse of residue, which is frequently removed from the field or burned [1, 18]. Table 2 contrasts the two systems on the processes that bear on carbon.

A single stock number for the whole year hides this alternation (Figure 2). Samples taken just after the rice harvest and samples taken after wheat can differ for reasons that have nothing to

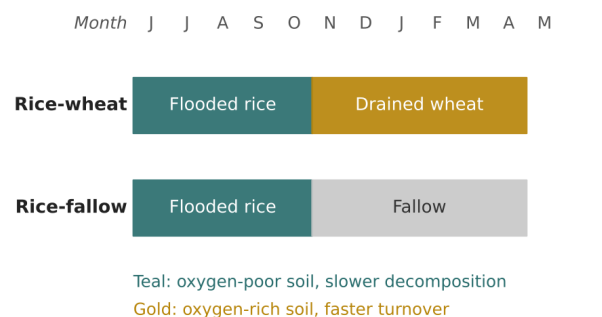
do with management, such as fresh residue, undecomposed roots or the state of drying, and a protocol that does not fix the sampling date cannot separate management from season [7, 38]. Because decomposition responds to temperature, warm-season sampling can reflect a different balance from cool-season sampling [17].

Table 2. Rice-wheat and rice-fallow systems compared on processes that bear on carbon.

Feature	Rice-wheat	Rice-fallow
Flooded phase	Puddled rice season, residues break down slowly under water [14, 15]	Same flooded season, and often rainfed
Drained phase	Wheat grown on aerobic soil; faster decomposition [1, 8]	Fallow or weeds; little crop carbon input
Residue return	Two residue pulses, often removed or burned [13, 18]	One pulse from rice only
Methane risk	Flooded phase emits methane [43, 44]	Same, plus emissions on any weedy fallow
Evidence base	Several long-term trials [23, 24]	Fewer controlled records

Note: Qualitative contrast drawn from the cited literature; actual behaviour varies with soil, climate and water management.

There is also a net-climate question that a carbon stock alone cannot answer. A gain in soil carbon under flooded rice may be partly or wholly offset by methane emitted from the same fields, so the relevant balance is of greenhouse gases and not of carbon in the soil only [43, 44]. For rice-fallow systems, where the soil is flooded but the second crop is missing, the methane side of the account is present while the carbon-input side is smaller, which is an argument for measuring both rather than assuming that carbon storage is always a good outcome.



Schematic of the idea; season lengths vary by site and are not data

Figure 2. Annual cycle of a rice-wheat and a rice-fallow system (schematic timeline, not data).

4.4 Change Is Slow and Noise Is Not

Even a well-chosen method must contend with the arithmetic of detection. Soil carbon changes slowly

against a large background stock, and the field-to-field and within-field variation in carbon is large [32, 39]. The time needed before a real change can be distinguished from sampling noise therefore depends on how variable the soil is, how many samples are taken and how fast the change is occurring, and for modest rates it can be longer than the duration of many experiments [32]. A record that shows no significant change after a few years does not demonstrate stability [7, 38]. Read this way, the lack of a detectable change in a short record is not proof that nothing changed.

The converse also holds. A statistically significant difference in a short record can arise from a few extreme samples, from a shift in bulk density or from sampling at different times in the cycle. Monitoring guidance for agricultural soils stresses stratified sampling, adequate replication and repeated measurement at fixed locations or, where that is not possible, careful pairing [7, 38]. Few rice-wheat studies describe their sampling design in the detail that such guidance would require. Figure 3 sketches the problem in schematic terms.

Labile fractions respond faster than the total and have been used as early indicators of management effects [33, 34]. In long-term rice-wheat trials, fractions of active carbon have separated treatments that the total could not [24, 25]. They are, however, defined operationally by the method used, and numbers from different fractionation schemes cannot be compared directly, which is one more way in which method sits behind the headline figure.

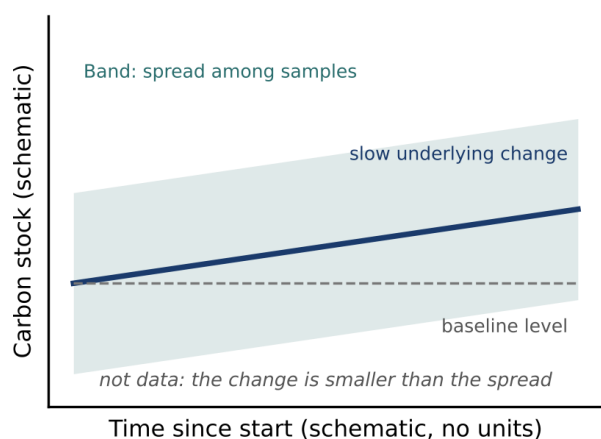


Figure 3. Slow change against sampling noise (schematic of the idea, not data).

4.5 Quality of the Evidence

Long-term experiments are valuable precisely because they run long enough for slow processes to show [12, 40]. They are also few, often confounded by changes in cultivars and operations during their lifetime, and designed for yield and

nutrient questions more than for carbon. Table 3 summarises the kinds of evidence available and the weaknesses most often discussed.

Table 3. Kinds of long-term evidence on carbon in rice-based systems and their main weaknesses.

Evidence	What it offers	Main weakness
Long-term fertiliser trials	Controlled treatments over decades [12, 40]	Few sites; sampling often shallow
Paired farm surveys	Many farms at one time [16, 26]	Space substituted for time
Chronosequences	Long time span in paddy soils [15]	Different soils at each age
Archived-sample re-analysis	Direct stock change over time [39]	Storage, method drift, bulk density lost
Model simulation	Projections under scenarios [10, 11]	Depends on assumptions and inputs

Note: Strengths and weaknesses are those discussed in the cited literature, not attributed to any single study.

Time itself is a confounder in these records. Over several decades cultivars change, machinery and sowing dates change, laboratories change their methods or their staff, and the people who took the early samples are rarely the people who analyse the late ones [12, 40]. A carbon difference between the first and last sampling can therefore partly reflect a change in procedure. This is the main argument for keeping archived soil and for re-running old and new samples side by side, which is the only way to separate a shift in the soil from a shift in the method [39].

Put plainly, the literature supports a cautious statement. Treatments that return more organic material to rice-wheat soils tend to maintain or raise organic carbon relative to those that return less, flooded phases favour accumulation of organic matter, and the total effect of the system depends on the drained phase and on what is done with residues. The size of any gain per year is not established by evidence that can be cited with confidence, and it is probably smaller and more variable than headline figures in advisory material suggest. That is a modest claim, but it is the one the evidence currently supports.

5. Discussion

5.1 Interpretation and Practical Reading

The main finding of this review is conditional. Reported carbon gains under rice-wheat are credible in direction but uncertain in size, and the uncertainty comes less from the soil than from the way the soil has been sampled and the stock calculated. That fits the more general call for clearer accounting of soil carbon change in

agriculture [4, 11], and it implies that the useful question for a researcher is not whether a system sequesters carbon but how the claim was measured. Nothing here argues against building soil carbon; it argues for measuring it in a way others can check.

A second conditional concerns time. Because stocks change slowly, a rice-wheat experiment that is long by agronomic standards may still be short by the standards of carbon detection [32]. This does not argue for abandoning short studies; it argues for being honest that they can detect only large effects, and for archiving samples so that later analysts can compute change over a longer span [39, 40].

A third point is that the carbon story and the greenhouse-gas story are separate accounts. A system that stores carbon in flooded soil but emits methane from the same field has to be judged on the combined balance [43, 44]. In the same way, residue management that keeps carbon in the soil but delays the next crop or demands extra labour has costs that the stock figure does not show [1, 18]. These cautions apply to any cropping system, not only to rice-based ones.

Residue handling deserves its own mention because it is where agronomy and carbon accounting meet most awkwardly. In many rice-wheat fields the straw of one crop is removed, burned or incorporated in a hurry to make the next sowing date, and each choice has a different carbon consequence [1, 18]. Incorporation returns carbon but may slow early crop growth if it is badly timed, removal gives the carbon to another use, and burning loses most of it to the air. A stock comparison between fields that differ in residue practice therefore compares farmers' decisions as much as soil responses, and the decision rarely appears in the data table.

Three findings would change this reading. A set of rice-wheat sites sampled to depth, on an equivalent-mass basis and with a measured baseline, that all showed gains under residue retention would strengthen the case for the practice considerably. A set that showed no change once bulk density was handled properly would suggest that earlier gains were partly an artefact of method [30, 37]. And evidence that stabilisation at depth in puddled soils is limited by the plough pan would shift attention from the topsoil to the profile as a whole [15, 35].

5.2 Limitations

This is a narrative review and shares the limitations of that form. The selection of sources

reflects judgement, no formal search or quality scoring was done, and the review does not quote stock values from individual experiments, because these could not be checked against the primary reports for this article. A reader who needs a number should consult the original studies, applying the questions in Table 1, or wait for a formal systematic review with a meta-analysis of paired comparisons, for which methods exist [41, 42].

The review also draws on evidence from other regions, on global analyses and on conceptual work about stabilisation, which are imperfect proxies for particular rice-wheat sites. Those sources describe what is plausible and what can go wrong with measurement; they do not substitute for site-specific data. The conclusions should be read in that light. Reviews are more useful when they say where the evidence stops than when they smooth the gaps over.

5.3 Implications for Reporting and Design

A long-term study intended to inform carbon questions should sample to a depth that captures the layers management can affect, record bulk density by layer, report stocks on an equivalent-mass basis alongside the fixed-depth value, and state the reference mass [36, 37]. It should say how carbon was measured, give the correction factor if wet oxidation was used, and archive samples [31, 40]. It should fix the sampling date relative to the crop cycle, describe the replication and report the spread of the data, not only means [7, 38].

On the system side, the study should record the residue left or removed in each season, the organic inputs, the fertiliser applied and the water regime, because these determine carbon input and loss. Where possible it should pair stock measurements with an account of methane and nitrous oxide, so that the net climate effect can be judged [43, 44]. These requirements are demanding but not exotic; they are largely what the methodological literature on carbon stock monitoring already asks [38, 42].

A reporting standard of this kind would also help those who must combine records. Syntheses of paired comparisons can only be as consistent as the studies feeding them [41, 42], and a database in which depth, mass basis, baseline and carbon method are recorded for every entry would allow differences in method to be separated from differences in management. Until that exists, the sensible course for anyone using a published sequestration rate is to ask what it is a rate of, over what depth, against what comparison and

measured how.

None of this requires new instruments. Most of what is missing from the published record is documentation: the sampling depth written down, the bulk density kept, a sample put in a jar and labelled. Experiments already under way can adopt these habits at no great cost, and the value of that small effort grows with every additional year of the record [7, 40].

5.4 Directions for Future Work

Three needs stand out. First, re-analysis of archived samples from long-term rice-wheat experiments on an equivalent-mass basis, where samples and bulk density records survive, to test how many earlier conclusions hold [37, 39]. Second, deliberate comparison of rice-wheat with rice-fallow and continuous rice in the same landscape, with matched soils and sampling dates [16, 28]. Third, work on deeper carbon in puddled profiles and on the stability of the gains over decades, not years [21, 35].

6. Conclusion

Organic carbon under long-term rice-wheat and rice-fallow systems is shaped by a seasonal alternation between flooded and drained soil, by the quantity of organic material returned, and by what is done with residues. The evidence summarised here supports the direction of several effects but does not establish how large they are, and the main reason is methodological: stocks depend on depth, bulk density treatment, baseline, laboratory method and replication, and these are often unreported. Readers should treat any single stock or sequestration rate with caution until the method behind it is clear.

For the practitioner the message is practical rather than discouraging. Returning organic material to the soil is sound for fertility whatever the carbon arithmetic turns out to be, provided the methane and residue costs are weighed. For the researcher the opportunity is a set of records that are deep enough, long enough and reported plainly enough to turn a plausible account into a measured one that other people can use and check.

7. Acknowledgements

The authors thank colleagues who commented on earlier drafts of this review.

8. Funding

This work received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

N.S. conceived the review and wrote the sections on soil carbon methods and stock calculation. V.D. wrote the sections on paddy soil processes and long-term experiments. N.O. wrote the sections on appraisal and reporting standards. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human participants or animals were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

13. References

- [1] Timsina, J., & Connor, D. J. (2001). Productivity and management of rice-wheat cropping systems: Issues and challenges. *Field Crops Research*, 69(2), 93-132. DOI: [10.1016/S0378-4290\(00\)00143-X](https://doi.org/10.1016/S0378-4290(00)00143-X)
- [2] Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623-1627. DOI: [10.1126/science.1097396](https://doi.org/10.1126/science.1097396)
- [3] Lal, R. (2002). Soil carbon dynamics in cropland and rangeland. *Environmental Pollution*, 116(3), 353-362. DOI: [10.1016/S0269-7491\(01\)00211-1](https://doi.org/10.1016/S0269-7491(01)00211-1)
- [4] Powlson, D. S., Whitmore, A. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science*, 62(1), 42-55. DOI: [10.1111/j.1365-2389.2010.01342.x](https://doi.org/10.1111/j.1365-2389.2010.01342.x)
- [5] Baker, J. M., Ochsner, T. E., Venterea, R. T., & Griffis, T. J. (2007). Tillage and soil carbon sequestration—What do we really know? *Agriculture, Ecosystems & Environment*, 118(1-4), 1-5. DOI: [10.1016/j.agee.2006.05.014](https://doi.org/10.1016/j.agee.2006.05.014)
- [6] Ellert, B. H., & Bettany, J. R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, 75(4), 529-538. DOI: [10.4141/cjss95-075](https://doi.org/10.4141/cjss95-075)
- [7] VandenBygaart, A. J., & Angers, D. A. (2006). Towards accurate measurements of soil organic carbon stock change in agroecosystems. *Canadian Journal of Soil Science*, 86(3), 465-471. DOI: [10.4141/S05-117](https://doi.org/10.4141/S05-117)
- [8] Ladha, J. K., Dawe, D., Pathak, H., et al. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research*, 81(2-3), 159-180. DOI: [10.1016/S0378-4290\(03\)00081-1](https://doi.org/10.1016/S0378-4290(03)00081-1)

- [10.1016/S0378-4290\(02\)00219-8](https://doi.org/10.1016/S0378-4290(02)00219-8)
- [9] Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, 123(1-2), 1-22. DOI: [10.1016/j.geoderma.2004.01.032](https://doi.org/10.1016/j.geoderma.2004.01.032)
- [10] Minasny, B., Malone, B. P., McBratney, A. B., et al. (2017). Soil carbon 4 per mille. *Geoderma*, 292, 59-86. DOI: [10.1016/j.geoderma.2017.01.002](https://doi.org/10.1016/j.geoderma.2017.01.002)
- [11] Chabbi, A., Lehmann, J., Ciais, P., et al. (2017). Aligning agriculture and climate policy. *Nature Climate Change*, 7(5), 307-309. DOI: [10.1038/nclimate3286](https://doi.org/10.1038/nclimate3286)
- [12] Johnston, A. E., Poulton, P. R., & Coleman, K. (2009). Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy*, 101, 1-57. DOI: [10.1016/S0065-2113\(08\)00801-8](https://doi.org/10.1016/S0065-2113(08)00801-8)
- [13] Ladha, J. K., Reddy, C. K., Padre, A. T., & van Kessel, C. (2011). Role of nitrogen fertilization in sustaining organic matter in cultivated soils. *Journal of Environmental Quality*, 40(6), 1756-1766. DOI: [10.2134/jeq2011.0064](https://doi.org/10.2134/jeq2011.0064)
- [14] Sahrawat, K. L. (2004). Organic matter accumulation in submerged soils. *Advances in Agronomy*, 81, 169-201. DOI: [10.1016/S0065-2113\(03\)81004-0](https://doi.org/10.1016/S0065-2113(03)81004-0)
- [15] Kögel-Knabner, I., Amelung, W., Cao, Z., et al. (2010). Biogeochemistry of paddy soils. *Geoderma*, 157(1-2), 1-14. DOI: [10.1016/j.geoderma.2010.03.009](https://doi.org/10.1016/j.geoderma.2010.03.009)
- [16] Pan, G., Li, L., Wu, L., & Zhang, X. (2004). Storage and sequestration potential of topsoil organic carbon in China's paddy soils. *Global Change Biology*, 10(1), 79-92. DOI: [10.1046/j.1365-2486.2003.00717.x](https://doi.org/10.1046/j.1365-2486.2003.00717.x)
- [17] Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081), 165-173. DOI: [10.1038/nature04514](https://doi.org/10.1038/nature04514)
- [18] Gathala, M. K., Ladha, J. K., Kumar, V., Saharawat, Y. S., et al. (2011). Tillage and crop establishment affects sustainability of South Asian rice-wheat system. *Agronomy Journal*, 103(4), 961-971. DOI: [10.2134/agronj2010.0394](https://doi.org/10.2134/agronj2010.0394)
- [19] Schmidt, M. W. I., Torn, M. S., Abiven, S., et al. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478(7367), 49-56. DOI: [10.1038/nature10386](https://doi.org/10.1038/nature10386)
- [20] Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, 528(7580), 60-68. DOI: [10.1038/nature16069](https://doi.org/10.1038/nature16069)
- [21] Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241(2), 155-176. DOI: [10.1023/A:1016125726789](https://doi.org/10.1023/A:1016125726789)
- [22] Jenkinson, D. S. (1990). The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society B*, 329(1255), 361-368. DOI: [10.1098/rstb.1990.0177](https://doi.org/10.1098/rstb.1990.0177)
- [23] Yadav, R. L., Dwivedi, B. S., Prasad, K., et al. (2000). Yield trends, and changes in soil organic-C and available NPK in a long-term rice-wheat system under integrated use of manures and fertilisers. *Field Crops Research*, 68(3), 219-246. DOI: [10.1016/S0378-4290\(00\)00126-X](https://doi.org/10.1016/S0378-4290(00)00126-X)
- [24] Majumder, B., Mandal, B., Bandyopadhyay, P. K., et al. (2008). Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal*, 72(3), 775-785. DOI: [10.2136/sssaj2006.0378](https://doi.org/10.2136/sssaj2006.0378)
- [25] Benbi, D. K., Brar, K., Toor, A. S., & Sharma, S. (2015). Sensitivity of labile soil organic carbon pools to long-term fertilizer, straw and manure management in rice-wheat system. *Pedosphere*, 25(4), 534-545. DOI: [10.1016/S1002-0160\(15\)30034-5](https://doi.org/10.1016/S1002-0160(15)30034-5)
- [26] Manna, M. C., Swarup, A., Wanjari, R. H., et al. (2005). Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research*, 93(2-3), 264-280. DOI: [10.1016/j.fcr.2004.10.006](https://doi.org/10.1016/j.fcr.2004.10.006)
- [27] Khan, S. A., Mulvaney, R. L., Ellsworth, T. R., & Boast, C. W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality*, 36(6), 1821-1832. DOI: [10.2134/jeq2007.0099](https://doi.org/10.2134/jeq2007.0099)
- [28] Pampolino, M. F., Laureles, E. V., Gines, H. C., & Buresh, R. J. (2008). Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. *Soil Science Society of America Journal*, 72(3), 798-807. DOI: [10.2136/sssaj2006.0334](https://doi.org/10.2136/sssaj2006.0334)
- [29] Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *SOIL*, 3(1), 61-66. DOI: [10.5194/soil-3-61-2017](https://doi.org/10.5194/soil-3-61-2017)
- [30] Lee, J., Hopmans, J. W., Rolston, D. E., Baer, S. G., & Six, J. (2009). Determining soil carbon stock changes: Simple bulk density corrections fail. *Agriculture, Ecosystems & Environment*, 134(3-4), 251-256. DOI: [10.1016/j.agee.2009.07.006](https://doi.org/10.1016/j.agee.2009.07.006)
- [31] Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29-38. DOI: [10.1097/00010694-193401000-00003](https://doi.org/10.1097/00010694-193401000-00003)
- [32] Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, 10(11), 1878-1883. DOI: [10.1111/j.1365-2486.2004.00854.x](https://doi.org/10.1111/j.1365-2486.2004.00854.x)
- [33] Blair, G. J., Lefroy, R. D. B., & Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research*, 46(7), 1459-1466. DOI: [10.1071/AR951459](https://doi.org/10.1071/AR951459)

- [34] Cambardella, C. A., & Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, 56(3), 777-783. DOI: [10.2136/sssaj1992.03615995005600030017x](https://doi.org/10.2136/sssaj1992.03615995005600030017x)
- [35] Stockmann, U., Adams, M. A., Crawford, J. W., et al. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, 164, 80-99. DOI: [10.1016/j.agee.2012.10.001](https://doi.org/10.1016/j.agee.2012.10.001)
- [36] Gifford, R. M., & Roderick, M. L. (2003). Soil carbon stocks and bulk density: Spatial or cumulative mass coordinates as a basis of expression? *Global Change Biology*, 9(11), 1507-1514. DOI: [10.1046/j.1365-2486.2003.00677.x](https://doi.org/10.1046/j.1365-2486.2003.00677.x)
- [37] Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, 64(1), 58-65. DOI: [10.1111/ejss.12002](https://doi.org/10.1111/ejss.12002)
- [38] Conant, R. T., Ogle, S. M., Paul, E. A., & Paustian, K. (2011). Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Frontiers in Ecology and the Environment*, 9(3), 169-173. DOI: [10.1890/090153](https://doi.org/10.1890/090153)
- [39] Ellert, B. H., Janzen, H. H., & Entz, T. (2002). Assessment of a method to measure temporal change in soil carbon storage. *Soil Science Society of America Journal*, 66(6), 1687-1695. DOI: [10.2136/sssaj2002.1687](https://doi.org/10.2136/sssaj2002.1687)
- [40] Richter, D. D., Jr., Hofmockel, M., Callahan, M. A., Powlson, D. S., & Smith, P. (2007). Long-term soil experiments: Keys to managing Earth's rapidly changing ecosystems. *Soil Science Society of America Journal*, 71(2), 266-279. DOI: [10.2136/sssaj2006.0181](https://doi.org/10.2136/sssaj2006.0181)
- [41] West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal*, 66(6), 1930-1946. DOI: [10.2136/sssaj2002.1930](https://doi.org/10.2136/sssaj2002.1930)
- [42] Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72(1), 87-121. DOI: [10.1007/s10533-004-0360-2](https://doi.org/10.1007/s10533-004-0360-2)
- [43] Yan, X., Akiyama, H., Yagi, K., & Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles*, 23(2), GB2002. DOI: [10.1029/2008GB003299](https://doi.org/10.1029/2008GB003299)
- [44] Linquist, B., van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, 18(1), 194-209. DOI: [10.1111/j.1365-2486.2011.02502.x](https://doi.org/10.1111/j.1365-2486.2011.02502.x)