



Carbon Farming in Rice Cropping Systems for Climate Change Mitigation and the Sustainable Development Goals: A Critical Narrative Review of Mitigation Evidence, Verification and Trade-offs

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Abstract

Rice (*Oryza sativa* L.) feeds roughly half of the world's population, yet flooded paddies are among the largest agricultural sources of methane, a short-lived but potent greenhouse gas. Carbon farming, understood here as the deliberate management of farmland to reduce greenhouse gas emissions or increase durable carbon storage under rules that allow those outcomes to be quantified and rewarded, has recently been extended from soil carbon in upland systems to methane reduction in rice. This critical narrative review examines whether the evidence base is strong enough to support that extension and how rice-based carbon farming interacts with the Sustainable Development Goals. Peer-reviewed literature and authoritative institutional sources published from January 2000 onwards were identified through multidisciplinary scholarly databases, a regional index, citation chasing and targeted searches of inventory, policy and crediting documents, and were appraised for design, measurement completeness and external validity. The evidence is strongest for water management: field studies and several independent meta-analyses agree that alternate wetting and drying and mid-season drainage reduce methane emissions by roughly half, with small average yield effects when soil drying is mild. Confidence is weaker for the net climate benefit, because nitrous oxide responses, fallow-season emissions and long-term soil carbon losses are measured inconsistently and are rarely captured together. Straw removal from the growing season, low-emission cultivars, direct seeding and optimised nitrogen management show credible but context-dependent effects, whereas biochar and soil carbon gains raise unresolved questions of permanence, scale and verification. Monitoring, reporting and verification remain the principal bottleneck: emission factors, process models and satellite approaches disagree at regional scale, and farm-level verification of water management is costly. Synergies with food security, water productivity and grain arsenic reduction are well documented, but trade-offs involving nitrous oxide, cadmium, wetland biodiversity, unequal access to irrigation control and incentive design are under-studied. Rice carbon farming is therefore best regarded as a promising but conditional mitigation pathway whose credibility depends on full-season, multi-gas accounting, conservative crediting and explicit attention to social and ecological co-impacts.

Keywords: Alternate wetting and drying; methane mitigation; paddy soil organic carbon; nitrous oxide trade-off; monitoring, reporting and verification; carbon credits; sustainable intensification; smallholder adoption.

1. Introduction

Rice is the staple cereal for more than half of the global population, and most of it is grown in soils that remain flooded for much of the season (Carrijo *et al.*, 2017; Kumar & Ladha, 2011). Flooding suppresses weeds and stabilises yields, but it also creates the anoxic conditions under which methane (CH₄) is produced. Agriculture as a whole accounts for about half of anthropogenic CH₄ emissions and most anthropogenic nitrous oxide (N₂O) emissions (Smith *et al.*, 2008), and recent syntheses attribute roughly a tenth of global anthropogenic CH₄ to rice cultivation, although published shares range from below 10% to above 15% depending on period and method (Runkle *et al.*, 2019; Su *et al.*, 2015; Xuan *et al.*, 2025). The most recent global CH₄ budget places total emissions at around 575 Tg CH₄ yr⁻¹ by atmospheric inversion and around 669 Tg CH₄ yr⁻¹ by bottom-up accounting for 2010–2019, with a top-down estimate of about 228 Tg CH₄ yr⁻¹ for agriculture and waste combined (Saunio *et al.*, 2025). Rice paddies are estimated to contribute about 48% of greenhouse gas emissions from croplands, with CH₄ responsible for about 94% of the global warming potential (GWP) of paddy emissions (Qian *et al.*, 2023). A recent global analysis also linked long-term changes in rice-paddy greenhouse gas emissions to cultivated-area expansion and residue incorporation, supporting the need to consider both management and landscape-level drivers (Zhang *et al.*, 2026).

Because CH₄ has a short atmospheric lifetime, reducing its emission rate offers a comparatively rapid way to slow near-term warming. International assessments have argued that a reduction of human-caused CH₄ emissions of about 45% within the present decade is needed to remain within agreed temperature limits (United Nations Environment Programme & Climate and Clean Air Coalition, 2021), and land-based measures, including agricultural CH₄ management, have been estimated to contribute a substantial share of cost-effective mitigation to mid-century (Roe *et al.*, 2021). Rice is therefore a natural target. It is also a sector in which mitigation must coexist with food security, rural livelihoods and water stewardship, which places it at the intersection of several Sustainable Development Goals (SDGs) adopted under the 2030 Agenda (United Nations General Assembly, 2015).

The term “carbon farming” has historically referred to the sequestration of carbon in soils and vegetation, frequently with payments linked to certified gains (Milne *et al.*, 2024; Paul *et al.*, 2023). In the European Union, a certification framework adopted in 2024 now formally recognises carbon farming activities alongside permanent removals and storage in products (European Parliament & Council of the European Union, 2024). In rice systems the concept has been stretched in two directions. The first concerns soil organic carbon (SOC), since paddy soils are known to accumulate organic carbon under long-term cultivation (Kögel-Knabner *et al.*, 2010; Yang *et al.*, 2024). The second, and quantitatively more important, concerns emission avoidance, principally the reduction of CH₄ through water, residue, cultivar and nutrient management. Voluntary carbon market methodologies for rice have consequently shifted from narrowly defined water management towards broader “improved rice management” approaches that allow model-based quantification (Verra, 2025).

This expansion has outpaced critical evaluation. Field and meta-analytic evidence on individual practices is now extensive, particularly for alternate wetting and drying (AWD) and mid-season drainage (Carrijo *et al.*, 2017; Jiang, Carrijo, *et al.*, 2019; Li *et al.*, 2024; Zhao *et al.*, 2024). Yet the same literature shows that CH₄ reductions can be partly offset by increased N₂O emissions (Kritee *et al.*, 2018; Zou *et al.*, 2005), that water-saving irrigation may increase soil carbon losses (Livsey *et al.*, 2019) and that emissions outside the rice-growing season can be a large share of the annual budget (Adviento-Borbe *et al.*, 2013; LaHue *et al.*, 2016). Verification raises further difficulties. Default emission factors and scaling factors used in inventories have been revised repeatedly as new field data emerged (Jiang, Carrijo, *et al.*, 2019; Tirol-Padre *et al.*, 2018; Wang *et al.*, 2018), and regional estimates from satellites and process models can diverge from national inventories by large margins (R. Liang *et al.*, 2024;

Reavis *et al.*, 2023). Satellite-based mapping of rice-field inundation has further demonstrated that uncertainty in paddy extent and timing remains an important limitation in estimating regional methane emissions (Chen *et al.*, 2025).

A global synthesis of rice cultivation practices found that relationships between grain yield and greenhouse gas emissions vary across management practices and production contexts (Thai *et al.*, 2026). Similarly, a temperate field comparison showed that AWD could reduce methane emissions while producing contrasting changes in grain contaminant concentrations, underscoring the need to evaluate climate and food-safety outcomes together (Vitali *et al.*, 2024).

Existing reviews have addressed parts of this landscape. Quantitative syntheses have characterised the drivers of paddy emissions and the average effects of management (Nikolaissen *et al.*, 2023; Qian *et al.*, 2023), and broader reviews have catalogued mitigation options and emerging incentive mechanisms (Xuan *et al.*, 2025) or molecular and microbial approaches (Rajendran *et al.*, 2024). Assessments of soil carbon crediting have questioned the permanence and additionality of certified sequestration in upland agriculture (Oldfield *et al.*, 2022; Paul *et al.*, 2023), while separate work has highlighted that water-saving rice practices can conflict with wetland biodiversity (Pérez-Méndez *et al.*, 2026). What remains lacking is an integrated appraisal that treats rice carbon farming as a whole system: one that weighs the strength of evidence for each mitigation lever against the requirements of credible accounting, distinguishes emission avoidance from removal, and evaluates outcomes against multiple SDGs rather than climate metrics alone.

1.1 Scope, Research Gap and Objectives

This review focuses on lowland rice systems, including irrigated and rainfed paddies, rice–wheat rotations and rice–aquatic animal co-culture, in which management can alter CH₄, N₂O and SOC dynamics. Carbon farming is interpreted broadly to include practices that reduce greenhouse gas emissions or increase durable carbon storage, together with the quantification and incentive arrangements through which those outcomes may be rewarded. Upland rice, post-harvest processing, milling, transport and the energy use of irrigation pumping are discussed only where they affect the interpretation of field-level outcomes. The review does not attempt a new meta-analysis, and it does not evaluate individual commercial carbon projects.

The knowledge gap addressed here is the absence of a critical synthesis that links three bodies of evidence that are usually treated separately: agronomic and biogeochemical evidence on mitigation practices, the methodological basis for measuring and crediting their effects, and their interactions with food, water, health, biodiversity and livelihood goals. The objectives are to define the conceptual boundaries of carbon farming in rice systems; to appraise the strength and consistency of evidence for the main mitigation levers; to identify sources of disagreement among studies; to evaluate the adequacy of current approaches to monitoring, reporting and verification (MRV); to assess synergies and trade-offs with the SDGs; and to set out research priorities that would make rice carbon farming more credible and more equitable.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review design was adopted because the questions of interest span biogeochemistry, agronomy, inventory science, remote sensing, economics and policy. The relevant evidence includes field experiments, meta-analyses, process modelling, atmospheric inversions, farm surveys, randomised trials of incentives and regulatory documents. These sources measure different outcomes on different scales and cannot be combined meaningfully in a single quantitative synthesis. A systematic review or meta-analysis would have required a narrower question and a homogeneous outcome, whereas the purpose here was to interpret convergence and divergence across heterogeneous evidence and to judge how much confidence each conclusion deserves. The quality criteria of the Scale for the Assessment of Narrative Review Articles were used as a guide to transparency, in particular the explicit statement of aims, the description of the literature search, appropriate referencing and the presentation of evidence levels (Baethge *et al.*, 2019). A narrative design does not remove the need for a documented search or for critical appraisal, and both are described below.

2.2 Information Sources

Literature was identified through Crossref, Europe PMC, OpenAIRE, the Directory of Open Access Journals (DOAJ), Semantic Scholar and Google Scholar. Because a large share of field research on paddy emissions and water management originates in Japan and in Japanese-supported programmes in South-East Asia, J-STAGE was searched as a regional scholarly platform to reduce geographical and language bias. Authoritative institutional sources were consulted for inventory methods, policy frameworks and crediting rules, namely the Intergovernmental Panel on Climate Change (IPCC) task force publications, United Nations documentation on the 2030 Agenda, the United Nations Environment Programme, the official legal database of the European Union and the methodology pages of the Verified Carbon Standard. Database searching was supplemented by backward citation searching of recent meta-analyses and reviews, forward citation searching of influential field studies, related-article searching and checks for corrections, expressions of concern and retractions.

2.3 Search Strategy and Search Period

Search concepts were built from five blocks: the production system; greenhouse gases and carbon pools; mitigation practices; quantification, accounting and finance; and sustainability outcomes. Blocks were combined with Boolean operators, and truncation was used where supported. A representative core search in Europe PMC was: (TITLE:(rice OR paddy OR "Oryza sativa") OR

ABSTRACT:(rice OR paddy OR "Oryza sativa")) AND ABSTRACT:(methane OR CH₄ OR "nitrous oxide" OR N₂O OR "soil organic carbon" OR "global warming potential") AND ABSTRACT:(("alternate wetting and drying" OR "mid-season drainage" OR "intermittent irrigation" OR straw OR residue OR biochar OR "direct seed*" OR cultivar* OR nitrogen OR "co-culture" OR "carbon credit*" OR "carbon farming"). Equivalent strings were adapted to the field structures of the other platforms by mapping title and abstract fields to the closest available bibliographic or keyword fields, by splitting long strings into shorter block-specific queries where a platform did not support nested Boolean logic, and by using title-only searches in J-STAGE and DOAJ to maintain specificity. Additional targeted queries combined Block A with Blocks D and E to retrieve work on emission factors, satellite monitoring, carbon credits, adoption and SDG interactions.

Candidate records were appraised qualitatively against a rubric with five criteria: relevance to rice-system mitigation or its accounting; strength of design, ranked from meta-analyses of side-by-side field comparisons, through multi-site and multi-season field studies, single-site field studies and controlled pot or incubation studies, to unvalidated modelling; completeness of measurement, judged by whether both CH₄ and N₂O were measured, whether the whole season or year was covered, and whether yield was reported; transparency of methods and uncertainty; and external validity in terms of soils, climates and farming conditions. Pot and incubation studies were used mainly to interpret mechanisms rather than to estimate field effect sizes. Eligibility was determined by the first public journal publication date, meaning the online-first or version-of-record date where available, rather than a later issue-assignment date.

The search period extended from 1 January 2000 to 14 August 2026. The starting year reflects the point at which multi-country field measurement programmes and the first syntheses of controlling variables had established the empirical basis for rice CH₄ mitigation, so that later work on management, inventories and incentives could build on comparable methods. Foundational earlier studies were consulted where needed to explain mechanisms. The last search date was 15 August 2026. Minor literature refinements were made during the review and revision stage. The query architecture is summarised in Table 1.

2.4 Eligibility Criteria

Eligible sources were peer-reviewed journal articles, peer-reviewed review articles and meta-analyses, and authoritative institutional documents that addressed CH₄, N₂O or SOC outcomes of rice management, the quantification of those outcomes, or their economic, social, health or ecological consequences. Field studies were required to compare a mitigation practice with an appropriate conventional control. Studies of upland rice, of non-agricultural wetlands and of rice processing were excluded unless they informed a mechanism or an accounting issue directly relevant to lowland paddies. Only English-language publications were included. Preprints, theses, conference abstracts, trade and promotional material, and webpages without identifiable institutional authorship were excluded. Studies published after the search end date were excluded even when they appeared during manuscript preparation.

Table 1. Query blocks used for evidence discovery and the principal evidence domains they were intended to interrogate

Query block	Representative terms combined with Boolean operators	Principal evidence domains interrogated
A. Production system	rice OR paddy OR "Oryza sativa" OR "rice–wheat" OR "rice–fish" OR "co-culture" OR lowland	Irrigated and rainfed lowland rice, rice-based rotations and integrated rice–aquatic animal systems
B. Gases and carbon pools	methane OR CH ₄ OR "nitrous oxide" OR N ₂ O OR "soil organic carbon" OR "global warming potential" OR "yield-scaled"	Emission magnitudes, controlling variables, soil carbon change, multi-gas balances and climate metrics
C. Mitigation practices	"alternate wetting and drying" OR "mid-season drainage" OR "intermittent irrigation" OR straw OR residue OR burning OR biochar OR "direct seed*" OR cultivar* OR "nitrogen management" OR "deep placement" OR "nitrification inhibitor"	Effect sizes, moderators, agronomic performance and side effects of management levers
D. Quantification, accounting and finance	"carbon farming" OR "carbon credit*" OR offset OR "emission factor" OR "scaling factor" OR "eddy covariance" OR "closed chamber" OR "remote sensing" OR satellite OR DNDC OR "process model" OR inventory	Inventory methods, field measurement, modelling, satellite monitoring, crediting rules, additionality and permanence
E. Sustainability outcomes	"Sustainable Development Goal*" OR "water productivity" OR arsenic OR cadmium OR biodiversity OR adoption OR income OR smallholder* OR incentive* OR equity	Food security, water, food safety, air quality, biodiversity, livelihoods, adoption barriers and policy

Note. CH₄, methane; N₂O, nitrous oxide; DNDC, Denitrification–Decomposition model. Blocks were combined as A AND B AND C for practice-level evidence, and A AND (D OR E) for accounting, finance and sustainability evidence. Field names and truncation were adapted to each platform as described in Section 2.3

2.5 Screening, Duplicate Handling and Study Selection

Titles and abstracts were screened for relevance, and full texts or complete abstracts were examined for records that passed the first stage. Duplicate records arising from overlapping databases, from versions held in repositories and from supplementary-material identifiers were removed by comparing Digital Object Identifiers, titles, author lists and publication years, and the version of record was retained. Records for which bibliographic metadata could not be confirmed, or whose abstracts and full texts could not be accessed sufficiently to verify the claims for which they would be cited, were excluded. Bibliographic details were checked against registration-agency metadata and publisher records, and each source was checked for retraction or correction notices. A narrative review does not require the procedural elements of a systematic review, such as reported screening counts, deduplication counts, dual independent screening or formal inter-reviewer agreement, and no such counts are reported. Selection remained bounded by the eligibility criteria and appraisal rubric described above.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was organised thematically around mitigation levers, accounting methods and sustainability outcomes rather than by individual study. For each theme, convergent findings across independent syntheses were identified first, after which divergent results were examined for plausible explanations, such as differences in soil drying severity, soil carbon status, climate, organic inputs, measurement period or the global warming metric used. Greater weight was given to meta-analyses based on paired field comparisons and to multi-site field studies, while recognising that meta-analyses inherit the geographical and methodological biases of their primary studies. Confidence in each conclusion was described qualitatively according to the consistency, quantity and design quality of supporting evidence. No formal risk-of-bias scores were assigned, because no single validated tool fits the diversity of designs considered. Where evidence was mixed, the disagreement is reported explicitly rather than resolved artificially.

The query blocks listed in Table 1 define the search architecture and the evidence domains each block was designed to interrogate. The table shows that the strategy deliberately extended beyond agronomic mitigation into accounting, finance and sustainability outcomes, which is where most existing syntheses are thinnest. It records the structure of evidence discovery rather than database-specific yields, which are not required for a narrative review.

3. Conceptual and Biogeochemical Foundations of Carbon Farming in Rice Systems

3.1 Emission Avoidance, Carbon Removal and the Meaning of Carbon Farming in Paddies

Carbon farming in upland systems is usually framed as carbon removal: management increases SOC or woody biomass, and the incremental stock is credited as a removal of carbon dioxide (CO₂) from the atmosphere (Paul *et al.*, 2023). Rice systems differ because their dominant climate impact is CH₄ emission rather than net CO₂ exchange (Qian *et al.*, 2023). Most rice mitigation is therefore emission avoidance, in which each season of improved management prevents a flow of CH₄ that would otherwise have occurred. Avoided CH₄ cannot be reversed in the way that sequestered carbon can be lost, but it also does not accumulate as a stock; the benefit persists only as long as the practice continues. This distinction matters for crediting, since the permanence concerns that dominate debates on soil carbon certificates (Oldfield *et al.*, 2022; Paul *et al.*, 2023) apply to SOC gains in paddies but not directly to avoided CH₄, whereas additionality and baseline definition matter for both.

Recent policy instruments reflect this hybrid character. The European certification framework distinguishes permanent removals, carbon farming and carbon storage in products (European Parliament & Council of the European Union, 2024), while the main voluntary-market methodology for rice treats CH₄ reduction, N₂O reduction and avoided residue burning as eligible activities and requires safeguards against SOC losses (Verra, 2025). Analyses of carbon farming in other regions have argued that “co-benefits” should be understood more neutrally as co-impacts, because the same activity can generate gains for some actors and costs or risks for others (Milne *et al.*, 2024). That framing is particularly apt for rice, where a practice that reduces CH₄ may increase N₂O, alter grain contaminant levels, change water availability downstream or affect wetland species.

3.2 Methane Production, Oxidation and Transport in Paddy Soils

Paddy soils are the largest anthropogenic wetlands on Earth (Kögel-Knabner *et al.*, 2010). After flooding, microbial respiration depletes oxygen and successively uses nitrate, manganese, ferric iron and sulphate as electron acceptors, after which methanogenesis becomes the terminal step of organic matter decomposition (Kögel-Knabner *et al.*, 2010). Methane is produced mainly from acetate and from hydrogen plus CO₂, and when organic matter such as straw is completely degraded the stoichiometry of fermentation constrains acetate-derived methanogenesis to about two-thirds of production (Conrad, 2020). The supply of labile carbon, whether from incorporated residues, manures or root exudates, therefore exerts first-order control on CH₄ production, which is why organic amendment and water regime consistently emerge as the two strongest predictors of field emissions in statistical syntheses (Nikolaisen *et al.*, 2023; Wang *et al.*, 2018; Yan *et al.*, 2005).

Net emission is the balance between production and oxidation. Methanotrophic bacteria oxidise a substantial fraction of the CH₄ produced in the oxic surface layer and the rhizosphere, where oxygen transported through the aerenchyma of rice plants creates microsites favourable to oxidation (Kögel-Knabner *et al.*, 2010). Rice plants thus act both as conduits and as regulators of CH₄. Early in the season CH₄ escapes mainly by ebullition and diffusion from flooded soil, but once the canopy develops most is transported through the plant (Aulakh *et al.*, 2001). Differences among cultivars in exudation, root porosity and transport capacity provide the mechanistic basis for cultivar-based mitigation (Aulakh *et al.*, 2001; Jiang *et al.*, 2017; Rajendran *et al.*, 2024). Drying cycles also change methanotroph activity, and laboratory work has shown that conventional methanotrophs in paddy soil can acquire the capacity to oxidise atmospheric CH₄ after exposure to high CH₄ concentrations (Cai *et al.*, 2016). That finding is mechanistically interesting, but it was obtained in microcosms and does not establish that drained paddies act as net CH₄ sinks under field conditions.

The mechanistic picture is well established in broad terms. Less certain is how processes scale from microsites to fields, which explains why field fluxes vary over orders of magnitude among sites with apparently similar management (Itoh *et al.*, 2011; Tirol-Padre *et al.*, 2018). Statistical models based on soil, climate, water regime and organic inputs explain only part of this variation, and a recent global model fitted to independent data achieved an R² of 0.47, compared with values of 0.01 to 0.09 for previously published models (Nikolaisen *et al.*, 2023). These figures indicate both that management variables matter greatly and that a large share of site-level variance remains unexplained.

3.3 Soil Organic Carbon in Paddies and the Permanence Problem

Long-term flooding slows decomposition, and paddy soils often accumulate more organic carbon than comparable upland soils. Chronosequence studies have documented accelerated decalcification and greater accumulation of modern organic carbon on mineral surfaces under paddy management (Wissing *et al.*, 2014), and redox oscillation is thought to promote the retention of dissolved organic matter by iron oxyhydroxides (Kögel-Knabner *et al.*, 2010). A resurvey of 104 continuously cultivated sites across China found that topsoil SOC content increased by 48% and SOC density by 39% between the 1980s and the 2010s, with recalcitrant fractions increasing faster than labile fractions (Yang *et al.*, 2024). These data support the view that paddies can store carbon, but the observed increase reflects multiple simultaneous changes in yields, residue return and fertilisation, and it cannot be attributed to any single practice that might be credited.

The more pressing question for carbon farming is whether CH₄-reducing practices erode this stock. A meta-analysis of water-saving irrigation found that AWD and mid-season drainage reduced CH₄ emissions by 52.3% and increased CO₂ emissions by 44.8%, reducing combined CO₂-equivalent emissions by 18.6% while increasing the soil-to-atmosphere carbon flux by 25% (Livsey *et al.*, 2019). Only 12 studies provided data adequate to constrain the soil carbon balance in both irrigation regimes (Livsey *et al.*, 2019), so this conclusion rests on thin evidence. By contrast, multi-season trials at four South-East Asian sites found no significant decline in soil carbon content under AWD (Tirol-Padre *et al.*, 2018), although three years is far too short to detect slow changes in SOC. The available evidence therefore does not show that water-saving irrigation depletes paddy SOC, but neither does it rule out a gradual loss that could offset part of the CH₄ benefit over decades. The inclusion of SOC safeguards in recent crediting methodology implicitly acknowledges this uncertainty (Verra, 2025).

3.4 Climate Metrics, Baselines and the Methane–Nitrous Oxide Trade-off

The net climate effect of a rice practice depends on how CH₄ and N₂O are combined. Most field studies express outcomes as 100-year GWP or as yield-scaled GWP, which normalises emissions by grain output (Pittelkow *et al.*, 2014; van Groenigen *et al.*, 2013). The choice of metric is not neutral. Because CH₄ is short-lived and N₂O is long-lived, a practice that reduces CH₄ but increases N₂O can appear beneficial on a 100-year basis while having a smaller or different long-term warming effect (Kritee *et al.*, 2018). Warming-equivalent approaches such as GWP* have been proposed to represent the different temperature responses to sustained changes in short-lived and long-lived pollutants (Lynch *et al.*, 2020). For crediting, such metrics raise unresolved questions about how avoided CH₄ should be valued relative to permanent CO₂ removal.

Baselines raise a related issue. Emissions depend strongly on the water status and organic inputs of the preceding season, and fields flooded during the previous season can emit more than twice as much CH₄ as fields drained for a long fallow (Wang *et al.*, 2018; Yan *et al.*, 2005). Fallow-season emissions can account for between 7% and 53% of annual CH₄ or GWP in direct-seeded systems (Adviento-Borbe *et al.*, 2013; LaHue *et al.*, 2016), and flooding during the fallow raised CH₄ emissions in the subsequent rice crop in tropical field trials (Sander *et al.*, 2014). Crediting systems that measure only the growing season, or that define the baseline without reference to fallow management, may therefore misstate the effect of a practice.

Table 2. Conceptual distinctions among rice carbon-farming pathways, their mechanisms and principal uncertainties

Pathway	Dominant mechanism	Main gases or pools affected	Reversibility and permanence	Principal uncertainty	Supporting references
Water-regime change (alternate wetting and drying, mid-season drainage)	Periodic aeration suppresses methanogenesis and stimulates CH ₄ oxidation	CH ₄ decreases; N ₂ O often increases; soil CO ₂ efflux may increase	Avoided flow; benefit lasts only while practice continues	Magnitude of N ₂ O offset and long-term SOC loss; drying severity in practice	(Jiang, Carrijo, <i>et al.</i> , 2019; Kögel-Knabner <i>et al.</i> , 2010; Livsey <i>et al.</i> , 2019; Zhao <i>et al.</i> , 2024)
Organic input management (straw timing, removal, composting)	Reduces labile carbon available to methanogens during flooding	CH ₄ decreases; residue burning adds CH ₄ and N ₂ O; SOC may decline if residues are exported	Avoided flow; SOC effects reversible	Fate of removed residues; acclimation of emissions over time	(Jiang, Qian, <i>et al.</i> , 2019; Romasanta <i>et al.</i> , 2017; Wang <i>et al.</i> , 2018; Yan <i>et al.</i> , 2005)
Biochar application	Stable carbon addition; altered redox and microbial communities	SOC increases; CH ₄ effects variable	Stock change with long residence time	Field persistence, interaction with nitrogen inputs and lifecycle emissions of production	(Huang <i>et al.</i> , 2026; Jeffery <i>et al.</i> , 2016; Wang <i>et al.</i> , 2016)
Cultivar selection and breeding	Changes in root exudation, aerenchyma oxygen supply and carbon allocation	CH ₄ decreases in some soils	Avoided flow	Soil dependence of cultivar effects; generalisability beyond tested environments	(Aulakh <i>et al.</i> , 2001; Jiang <i>et al.</i> , 2017; Su <i>et al.</i> , 2015)
Nitrogen source, rate and placement	Sulphate and nitrification inhibition alter redox chemistry; rate controls N ₂ O	N ₂ O and CH ₄ ; yield-scaled emissions	Avoided flow	Trade-off between sources that lower CH ₄ and those that raise N ₂ O	(Linquist <i>et al.</i> , 2012; Pittelkow <i>et al.</i> , 2014)
Paddy soil carbon accrual	Slow decomposition and mineral stabilisation under flooding	SOC	Stock change; reversible with drainage or land-use change	Attribution to specific practices; detectability within crediting periods	(Wissing <i>et al.</i> , 2014; Yang <i>et al.</i> , 2024)

Note. CH₄, methane; N₂O, nitrous oxide; CO₂, carbon dioxide; SOC, soil organic carbon. Directions indicate the predominant response reported in the cited syntheses and are not invariant across sites

The conceptual distinctions and mitigation pathways discussed in this section are summarised in Table 2. Its central message is that rice carbon farming combines avoided flows, with no reversal risk but no accumulation, and stock changes, with permanence risk, and that each pathway has a characteristic uncertainty that determines how it should be quantified and rewarded.

4. Water Management as the Principal Mitigation Lever

4.1 Convergent Evidence on Methane Reduction

Water management is the most intensively studied and the most consistently effective rice mitigation option. Independent meta-analyses using different but overlapping sets of paired field comparisons have reached similar conclusions. One synthesis of 52 studies found that non-continuous flooding reduced CH₄ emissions by 53% relative to continuous flooding (CF), increased N₂O emissions by 105% and reduced GWP by 44% (Jiang, Carrijo, *et al.*, 2019). A later synthesis of 72 studies reported CH₄ reductions of 43% and GWP reductions of 37% under AWD (L. Li *et al.*, 2024), and another reported reductions of 51.6% in CH₄ and 46.9% in GWP, together with a 44.0% increase in N₂O (Zhao *et al.*, 2024). A broad review attributed average CH₄ reductions of about 41% to AWD and about 24% to mid-season drainage (Xuan *et al.*, 2025), while a global review of rice emissions estimated an average GHG reduction of 44% from non-continuous flooding (Qian *et al.*, 2023). Statistical analyses of emission databases similarly show that single and multiple drainage events reduce CH₄ flux to roughly 55–71% of that under CF (Wang *et al.*, 2018; Yan *et al.*, 2005).

Field studies using contrasting methods corroborate these averages. Eddy covariance measurements over production-scale fields in the mid-southern United States estimated a 64.5% reduction in seasonal CH₄ under AWD (Runkle *et al.*, 2019), which is important because it avoids the small-plot artefacts of chamber methods. Multi-site trials in Japan showed that prolonging mid-season drainage reduced seasonal CH₄ emissions to about 70% of conventional management while maintaining yields (Itoh *et al.*, 2011), and a two-year Californian study found that a single mid-season drainage reduced CH₄ emissions by 38–66%, with each 1% reduction in gravimetric soil water during drainage associated with a 2.5% decrease in seasonal CH₄ (Perry *et al.*, 2022). In tropical Colombia, AWD reduced cumulative CH₄ by 72–100% over four seasons (Loaiza *et al.*, 2024).

The convergence of these results across continents, methods and decades supports high confidence that well-implemented periodic drainage reduces CH₄ emissions substantially. The more important questions concern the conditions under which the reduction is achieved, its size in farmers' fields and the extent to which it is offset by other changes.

4.2 Moderators of Effectiveness

The size of the CH₄ reduction varies widely. Meta-regression indicates that it increases with the number of drying events, the severity of soil drying and the number of unflooded days (Jiang, Carrijo, *et al.*, 2019), and that it is moderated by precipitation, SOC content, crop duration and nitrogen input (Zhao *et al.*, 2024). Timing matters as well. Modelling combined with field observations suggests that the optimal time to drain is earlier in organically amended fields than in unamended fields, around 20 and 50 days after transplanting respectively, with mean potential reductions of about 45% and 35% (Souza *et al.*, 2021). Prolonged drainage is particularly effective where organic matter has been incorporated before cultivation, because it suppresses the early-season emission peak (Itoh *et al.*, 2011).

Climate and hydrology often limit implementation. In multi-site trials in Vietnam, Indonesia, Thailand and the Philippines, AWD reduced CH₄ by 25–37% overall, but at two sites reductions occurred only in the dry season, because rainfall kept fields flooded during the wet season (Tirol-Padre *et al.*, 2018). The same synthesis estimated a mean AWD scaling factor of 0.69, appreciably higher (implying less mitigation) than the IPCC multiple-aeration factor of 0.52 (Tirol-Padre *et al.*, 2018). By contrast, the global meta-analysis of paired studies suggested that the multiple-drainage scaling factor should be lowered to 0.36 (Jiang, Carrijo, *et al.*, 2019). The two estimates are not contradictory so much as indicative of the different evidence they draw on: field trials under monsoon conditions in which drainage could not always be imposed, as opposed to experiments in which drying was controlled. For inventory and crediting purposes, this disagreement means that default scaling factors should be applied with caution and supported, where possible, by evidence that drying actually occurred.

Regional evidence from Asia adds historical depth. Process modelling indicated that the shift from CF to mid-season drainage in China reduced national paddy CH₄ by about 40% but increased N₂O by about 50% (C. Li *et al.*, 2005), and a recent long-term inventory concluded that Chinese rice CH₄ emissions peaked in 1976, fell by 42% over the following two decades and have remained near 5.8 Tg yr⁻¹ since 2003, with water-saving irrigation a major cause of decoupling from production (Y. Li *et al.*, 2025). The same analysis noted that the influence of most drivers has plateaued (Y. Li *et al.*, 2025), suggesting that further reductions in already-drained systems will be harder to achieve than first-generation gains.

4.3 The Nitrous Oxide Counter-Signal and Yield-Scaled Outcomes

Nearly every synthesis shows that drainage increases N₂O, typically by 40–105% on average (Jiang, Carrijo, *et al.*, 2019; L. Li *et al.*, 2024; Zhao *et al.*, 2024). In most temperate and subtropical datasets the absolute increase is small relative to the CH₄ reduction, and N₂O contributes on average about 12% of combined GWP under non-continuous flooding (Jiang, Carrijo, *et al.*, 2019). Field studies in California found that N₂O accounted for less than 15% of annual GWP even under AWD (LaHue *et al.*, 2016), and Colombian trials reported reductions in N₂O when soil moisture was managed around fertiliser application (Loaiza *et al.*, 2024).

The principal challenge to this reassuring picture comes from southern India, where field measurements under intermittent flooding indicated N₂O emissions 30–45 times higher than previously reported under continuous flooding, with the implication that the net climate benefit of drainage could be much smaller than commonly assumed (Kritee *et al.*, 2018). These measurements came from a

limited number of sites with particular soils and management regimes, and their representativeness of wider South Asian conditions is uncertain. They are nonetheless consistent with evidence that N₂O responses are larger in soils with high organic carbon or after manure additions (Jiang, Carrijo, *et al.*, 2019) and with the event-driven nature of N₂O pulses after fertiliser application, drying and re-flooding (Gaihe *et al.*, 2015; Zou *et al.*, 2005). The same study estimated that net climate impacts could be reduced by up to 90% if water, nitrogen and carbon were managed jointly (Kritee *et al.*, 2018). The defensible conclusion is that N₂O does not usually negate the benefit of drainage, but it can do so under certain combinations of soil, nitrogen management and drying severity, and the sparse measurement of N₂O at the necessary temporal resolution in South Asia makes it impossible to say how common those combinations are.

Yield matters because emissions per unit of food are more relevant to food security than emissions per hectare. Across 56 studies, AWD reduced yields by 5.4% on average, but mild AWD, in which soil water potential stayed at or above -20 kPa or the field water level did not drop more than 15 cm below the surface, generally had no significant yield penalty and reduced water use by 23.4%, whereas severe AWD reduced yields by 22.6% (Carrijo *et al.*, 2017). Other syntheses report average yield changes from -3.6% to +1.5% (Jiang, Carrijo, *et al.*, 2019; L. Li *et al.*, 2024). An analysis of 1,187 paired observations concluded that variation in the yield response was explained mainly by the lowest soil water potential reached during drying (Bo *et al.*, 2024). Yield-scaled GWP therefore falls by roughly the same proportion as area-scaled GWP under mild AWD (Jiang, Carrijo, *et al.*, 2019). Under future atmospheric conditions, however, the greenhouse gas intensity of rice is projected to rise because elevated CO₂ stimulates CH₄ more than yield and warming reduces yield (van Groenigen *et al.*, 2013), so practices that seem adequate today may need to deliver larger reductions simply to hold intensity constant.

4.4 Water Productivity, Food Safety, Soil Carbon and Biodiversity

Water saving is the original rationale for AWD and remains its most immediate benefit to farmers. Field trials have shown improvements in water-use efficiency of 18–63% (Linguist *et al.*, 2015) and water savings of 19–56% in Colombia (Loaiza *et al.*, 2024), and modelling indicates that soil water potential-guided AWD could increase water productivity across 37% of the global irrigated rice area, with the greatest potential in India, Bangladesh and central China (Bo *et al.*, 2024).

Effects on grain contaminants are more complex. Aerobic periods reduce arsenic mobility, and AWD has reduced grain arsenic by up to 64% (Linguist *et al.*, 2015) and by 59–65% in direct-seeded systems (LaHue *et al.*, 2016). The effect depends on drying severity: in a two-year field study, AWD regimes that dried the root zone substantially reduced grain total arsenic by 41–68%, whereas a “safe” AWD regime that kept the root zone saturated produced no reduction (C. Li *et al.*, 2019). The same work cautioned that soil drying can increase cadmium bioavailability (C. Li *et al.*, 2019), so the food-safety outcome depends on which contaminant is limiting in a given soil. Severity thus links three outcomes in tension: deeper drying increases CH₄ and arsenic reduction but raises yield risk (Carrijo *et al.*, 2017; Linguist *et al.*, 2015), potentially increases N₂O (Zhao *et al.*, 2024) and may increase cadmium uptake (C. Li *et al.*, 2019).

Biodiversity is the least considered dimension. Flooded paddies provide habitat for amphibians, invertebrates and waterbirds, and a recent analysis argued that widely promoted water-saving practices can harm freshwater biodiversity, calling for spatially and seasonally targeted strategies rather than blanket promotion (Pérez-Méndez *et al.*, 2026). Evidence on the magnitude of such effects remains limited, and it is not yet possible to say which drying regimes are compatible with which taxa.

4.5 From Field Trials to Farms: Adoption and Incentives

The gap between experimental potential and achieved mitigation is substantial. AWD was developed and promoted with a simple perforated field water tube, and in early dissemination programmes it reduced irrigation inputs by up to 38% without yield reductions when correctly implemented, increased farm income by 17–38% in Bangladesh, the Philippines and southern Vietnam, and generated an estimated benefit–cost ratio of 7:1 for research investment (Lampayan *et al.*, 2015). Quasi-experimental analysis in the Philippines found that safe AWD reduced irrigation hours by about 38% without significant losses in yield or profit, but the authors warned that unobserved selection bias might account for part of the apparent impact (Rejesus *et al.*, 2011).

Despite such evidence, adoption has been uneven. In Bangladesh, AWD has been promoted by the government for more than a decade, yet it has not been widely adopted (Pearson *et al.*, 2018). Survey-based analysis identified household education, access to weather information, landownership, topography and soil type as determinants of adoption (Alauddin *et al.*, 2020). The decisive constraint, however, may be the structure of water charges. Two randomised controlled trials in Bangladesh showed that AWD saved water only when farmers faced marginal prices for irrigation, and that offering farmers the option to switch voluntarily to hourly pumping charges did not reduce water use (Chakravorty *et al.*, 2023). Where farmers pay a fixed seasonal fee, they have little private incentive to reduce irrigation, so the water-saving benefit that underpins the economic case for AWD disappears. A twenty-year review of AWD scaling in the Philippines reached a complementary conclusion: national policy adoption was achieved, but a focus on technology transfer neglected contextual factors, and mismatches between incentives, institutions and the scale of gravity-fed irrigation systems diminished impact (Enriquez *et al.*, 2021). In gravity-fed systems, individual farmers often cannot control when their fields are drained.

Field and institutional context therefore shapes mitigation as much as agronomy. In Nepal, AWD maintained yields with 57% less irrigation water, yet local social research suggested that adoption was unlikely under prevailing conditions (Howell *et al.*, 2015). In An Giang Province in the Mekong Delta, AWD users reported water savings and reduced lodging, and mid-elevation fields were judged most suitable because higher fields drained too quickly and lower fields drained poorly (Yamaguchi *et al.*, 2017). In the United States, by contrast, some AWD regimes were economically competitive without any payment for emission reduction or water conservation (Nalley *et al.*, 2015). In Thailand, water shortages forced AWD-like management on all treatments in the dry season, irrespective of extension advice (Stuart *et al.*, 2018).

Table 3. Representative evidence on water-regime management in rice systems

Evidence and setting	Design	CH ₄ response	N ₂ O and GWP response	Yield and co-outcomes	Main limitations	Supporting references
Global paired field studies	Meta-analysis, 52 studies	–53% vs CF	N ₂ O +105%; GWP –44%; yield-scaled GWP –42%	Yield –3.6%	Heterogeneous drying regimes; bias towards East Asia	(Jiang, Carrijo, <i>et al.</i> , 2019)
Global paired field studies	Meta-analysis, 72 studies	–43%	N ₂ O +43%; GWP –37%	Yield +1.5%	Overlapping primary studies with other syntheses	(L. Li <i>et al.</i> , 2024)
Global paired field studies	Meta-analysis	–51.6%	N ₂ O +44.0%; GWP –46.9%	Moderated by soil, climate and nitrogen	Same	(Zhao <i>et al.</i> , 2024)
Global yield and water studies	Meta-analysis, 56 studies	Not assessed	Not assessed	Mild AWD: no significant yield loss, water –23.4%; severe AWD: yield –22.6%	Yield effects depend on soil pH and carbon	(Carrijo <i>et al.</i> , 2017)
Mid-southern United States, production fields	Eddy covariance, three years	–64.5%	Not reported	Large-footprint measurement	Two fields only	(Runkle <i>et al.</i> , 2019)
Japan, nine sites	Multi-site field trials	Reduced to about 70% of conventional	GWP about 72% of conventional	Yields maintained	Temperate single-crop systems	(Itoh <i>et al.</i> , 2011)
South-East Asia, four sites	Multi-site, multi-season trials	–25% to –37%; some sites only in dry season	GWP reduced significantly at two sites	No significant yield or soil carbon decline	Three years; rainfall limited drainage	(Tirol-Padre <i>et al.</i> , 2018)
Southern India, field sites	Intensive field measurement	Reduced	N ₂ O 30–45 times higher than reported under CF	Net climate impact strongly management-dependent	Limited sites; representativeness uncertain	(Kritee <i>et al.</i> , 2018)
California and Arkansas, United States	Multi-site field trials	Reduced with drying severity	GWP –45% to –90%	Yield –1% to –13%; grain arsenic up to –64%	Severity–yield trade-off	(Linguist <i>et al.</i> , 2015)
Colombia, tropical lowland	Four-season field trial	–72% to –100%	N ₂ O –12% to –70%; GWP –25% to –73%	Water –19% to –56%	Single region	(Loaiza <i>et al.</i> , 2024)
Global soil carbon balance	Meta-analysis, 12 studies	–52.3%	CO ₂ +44.8%; CO ₂ -equivalent –18.6%	Soil-to-atmosphere carbon flux +25%	Very few studies with carbon balances	(Livsey <i>et al.</i> , 2019)

Note. AWD, alternate wetting and drying; CF, continuous flooding; CH₄, methane; N₂O, nitrous oxide; CO₂, carbon dioxide; GWP, global warming potential of CH₄ and N₂O. Percentages are mean or reported ranges relative to CF controls as stated in each source and are not directly comparable because of differences in design, metric and period

These observations bear directly on carbon farming. Payments for CH₄ reduction are most likely to change behaviour where farmers control drainage and where the private cost of AWD is positive but modest; they are least likely to matter where drainage is already practised for water or pumping reasons, which raises additionality concerns, or where hydrological and institutional conditions prevent drainage regardless of incentives. The evidence on adoption is drawn largely from observational surveys and a small number of randomised trials, and confidence in generalising any particular adoption model across countries is low.

Table 3 brings together representative evidence on water management, illustrating the consistency of CH₄ reductions across designs and regions alongside the variable N₂O, yield and food-safety responses discussed above. The limitations column highlights that most estimates derive from controlled experiments in which drying was deliberately imposed, which may overstate reductions achievable on farms.

5. Organic Inputs, Residue Management and Biochar

5.1 Straw Incorporation, Timing and Acclimation

Organic amendment is the second major control on paddy CH₄ and arguably the most tractable after water. Statistical analysis of Asian field data indicated that incorporating rice straw at 6 t ha⁻¹ shortly before transplanting increased seasonal CH₄ emissions about twofold (Yan *et al.*, 2005), and a later global analysis estimated that applying the same amount in the preceding off-season halved emissions compared with application shortly before transplanting (Wang *et al.*, 2018). A more recent global model estimated that applying straw off-season rather than in-season decreased emissions by 48% (Nikolaisen *et al.*, 2023), and a global review estimated that straw removal strategies reduced GHG emissions by 46% on average (Qian *et al.*, 2023). Field experiments confirm the direction and scale of these responses. In a three-year study in Jiangsu Province, China, evenly incorporating wheat straw before rice increased CH₄ emissions by a factor of 3.9 to 10.5 relative to no straw, while ditch or strip mulching reduced CH₄ by 23–32% compared with incorporation (Ma *et al.*, 2009). In another Chinese field trial, residue incorporation increased CH₄ emissions by 252% under one of the water regimes tested (Zou *et al.*, 2005).

These effects are well established, yet two complications limit their direct translation into credited mitigation. First, CH₄ responses to straw may diminish over time. Evidence from fields with repeated straw return indicates that the stimulatory effect of straw incorporation on CH₄ emissions declined with years of continued straw return, because CH₄ consumption in the soil increased (Jiang, Qian, *et al.*, 2019). Short-term experiments, which dominate the literature, may therefore overstate the long-run emission penalty of straw return and, by extension, the long-run benefit of removing it. Second, the alternatives are not neutral. Straw mulching that lowered CH₄ increased N₂O by factors of 1.4 to 5.1 relative to incorporation in the Jiangsu study (Ma *et al.*, 2009), and the fate of removed straw determines whether emissions are avoided or simply displaced.

5.2 Residue Burning and Its Alternatives

Open burning is the most problematic alternative to incorporation. It is widespread in India, Thailand and the Philippines and is a major source of air pollutants (Gadde *et al.*, 2009). Although CO₂ released by burning is usually treated as part of the annual biogenic carbon cycle, burning also emits CH₄ and N₂O; combustion experiments estimated emission factors of 4.51 g CH₄ and 0.069 g N₂O per kg of dry straw (Romasanta *et al.*, 2017). In India, national inventory estimates attributed about 250 Gg CH₄ and 6.5 Gg N₂O in 2007 to field burning of agricultural residues (Bhatia *et al.*, 2013). In the rice–wheat systems of north-western India, burning persists because the interval between rice harvest and wheat sowing is short. Economic analysis of alternatives has indicated that in-field residue management combined with direct sowing of the following crop can raise farm profits and improve air quality relative to burning (Shyamsundar *et al.*, 2019).

For carbon farming, the policy implication is that avoided burning is an eligible activity in recent rice methodologies (Verra, 2025), but its net climate effect depends on the counterfactual and on what replaces burning. If burning is replaced by incorporation before a flooded rice crop, CH₄ emissions from the soil may increase; if it is replaced by surface retention before an upland crop such as wheat, they may not. The climate case for avoided burning is therefore strongest where it is coupled with residue retention in aerobic phases of the rotation, whereas its public health case is strong irrespective of the greenhouse gas balance.

5.3 Biochar: Methane Suppression Versus Carbon Removal

Biochar occupies a distinctive place because it is simultaneously proposed as a CH₄ mitigation measure and as a durable carbon removal. A meta-analysis across soils found that biochar tended to reduce CH₄ emissions from flooded paddy soils and acidic soils, but could weaken the CH₄ sink of non-flooded neutral or alkaline soils (Jeffery *et al.*, 2016). A broad review attributed an average CH₄ reduction of about 29% to biochar in rice (Xuan *et al.*, 2025). More recent evidence qualifies this optimism. A network meta-analysis of 146 observations from 51 studies, supported by a field experiment, found that biochar produced the lowest CH₄ emissions among organic materials but that the effect depended strongly on mineral nitrogen input; above an input of about 291 kg N ha⁻¹, biochar tended to increase rather than decrease CH₄ emissions (Huang *et al.*, 2026). In a pot experiment on an Andosol paddy soil in Japan, rice husk charcoal did not significantly increase CH₄ emissions, increased soil carbon in proportion to the application rate and, at the highest rate, resulted in a net sink on a 100-year GWP basis (Koyama *et al.*, 2016). Pot results of this kind are useful for mechanism but cannot establish field-scale effects.

The removal argument rests on persistence. A meta-analysis of isotopically traced biochar decomposition estimated mean residence times of about 108 days for a labile pool comprising about 3% of biochar carbon and about 556 years for the remaining 97%, with slightly negative average priming of native soil organic matter (Wang *et al.*, 2016). The global technical potential of sustainable

biochar systems has been estimated at up to 1.8 Pg CO₂-carbon equivalent per year, under constraints intended to protect food security and habitats (Woolf *et al.*, 2010). Inventory guidance now includes a method, presented as a basis for future development, for estimating changes in mineral soil carbon stocks from biochar amendments (Intergovernmental Panel on Climate Change, 2019). Interest has also turned to biochar's capacity to address co-contamination; machine-learning analysis has been used to tailor biochar properties to reduce cadmium uptake and CH₄ emissions simultaneously in paddy soils (Yin *et al.*, 2024).

The critical gaps for rice carbon farming are scale and accounting rather than mechanism. Decomposition estimates are derived largely from incubation and short-term studies extrapolated over centuries (Wang *et al.*, 2016). Field data on CH₄ responses are heterogeneous and sensitive to nitrogen management (Huang *et al.*, 2026), the feedstock is usually crop residue whose alternative uses must be considered, and the supply chain emissions of pyrolysis are rarely included in field studies. Biochar is plausibly the only rice-system intervention capable of generating a durable carbon stock on a meaningful scale, but the evidence does not yet support confident claims of net benefit across typical smallholder conditions.

5.4 Manures and Organic Fertilisers

Replacing mineral nitrogen with manure is often presented as a soil-building, circular practice. In paddies it carries a CH₄ cost. In a six-year field study, combining pig manure with urea increased GWP by almost 60% relative to urea alone, because both CH₄ and N₂O emissions increased, and the lowest yield-scaled GWP was obtained with urea at the rate needed for maximum yield (X. Q. Liang *et al.*, 2013). Manure additions also amplify the N₂O response to drainage (Jiang, Carrijo, *et al.*, 2019). Organic inputs that build SOC in upland systems can therefore increase net emissions in flooded systems, and any carbon farming claim based on organic amendments in rice needs to account for the CH₄ generated by the added labile carbon. Composting before application or application during aerobic phases are plausible ways to reduce this penalty, but they have not been tested widely enough to support general recommendations.

6. Crop Establishment, Cultivars, Nutrients and Integrated Systems

6.1 Direct Seeding and Conservation Agriculture

Puddled transplanting is labour-, water- and energy-intensive and contributes to CH₄ emission, which has motivated a shift towards direct-seeded rice (DSR) in many parts of Asia (Kumar & Ladha, 2011). A global meta and mixed-model analysis of 3,878 paired observations found that direct seeding under wet tillage increased yields by 1.3–4.7%, increased net returns by 13% and saved 15% of water relative to puddled transplanting, and that alternative establishment practices reduced CH₄ emissions but increased N₂O emissions (Chakraborty *et al.*, 2017). Soil texture strongly influenced the relative yield advantage, implying that DSR must be tailored to local conditions (Chakraborty *et al.*, 2017).

Evidence from the Indo-Gangetic Plains illustrates both the promise and the system-level complexity. In Haryana in the north-west, field measurements suggested that switching rice establishment from conventional to conservation agriculture-based practices could reduce the GWP of rice by 23%, equivalent to about 1.26 Tg CO₂-equivalent per year across the state, and that N₂O emissions could be avoided by applying nitrogen to wet soil or irrigating within a day of application (Tirol-Padre *et al.*, 2016). Medium-term trials in the same region showed that sustainable intensification scenarios combining zero tillage, diversification and precision management could be more productive than business-as-usual rice–wheat systems (Kumar *et al.*, 2018). In the eastern Indo-Gangetic Plains, DSR yielded 16.2% less than transplanted rice in the first two years but caught up by the fourth year, used 6.8% less water and contributed to 10.8% higher net returns at the system level (Mishra *et al.*, 2021). These results indicate that yield penalties during the transition, weed pressure and uneven crop establishment are real constraints (Kumar & Ladha, 2011), and that carbon farming schemes rewarding DSR need multi-year commitments and support during the transition.

The CH₄ benefit of DSR is mechanistically plausible because the crop spends fewer days flooded, but the evidence is weaker than for AWD, because many DSR studies report yield and water outcomes without full-season multi-gas measurements, and because the N₂O increase may be substantial where the crop experiences repeated wetting and drying (Chakraborty *et al.*, 2017).

6.2 Cultivar Selection and Breeding for Lower Emissions

Rice cultivars differ in their capacity to transport CH₄ and in the quantity of carbon they release to the rhizosphere (Aulakh *et al.*, 2001). Experiments with 33 cultivars in China showed that, in a high-carbon soil, a 10% increase in biomass was associated with a 10.3% decrease in CH₄ emissions, apparently because high-yielding cultivars with larger and more porous root systems promoted CH₄ oxidation; a supporting meta-analysis found that high-yielding cultivars strongly reduced emissions from soils with high organic carbon (Jiang *et al.*, 2017). A global review estimated an average GHG reduction of 24% from new variety selection (Qian *et al.*, 2023). Genetic engineering has provided proof of concept: rice expressing the barley transcription factor SUSIBA2 allocated more photosynthate to above-ground biomass and seeds and reduced CH₄ emissions in three years of field trials in China, possibly through reduced root exudation (Su *et al.*, 2015).

These findings are encouraging but conditional. The cultivar–CH₄ relationship in the Chinese study was strongest in soils rich in organic carbon (Jiang *et al.*, 2017), and molecular reviews emphasise that microbial communities associated with methanogenesis and methanotrophy vary with cultivar in ways that are not yet predictable (Rajendran *et al.*, 2024). Transgenic approaches face regulatory and acceptance barriers that differ widely among rice-producing countries. For carbon farming, cultivar-based mitigation is attractive because it requires little change in farm practice and is easy to verify through seed records, but it is difficult to credit without robust, soil-specific emission coefficients for each cultivar.

Table 4. Comparative appraisal of non-water mitigation levers in rice systems

Lever	Reported greenhouse gas effect	Strength and consistency of evidence	Principal trade-offs or risks	Verification feasibility	Supporting references
Off-season straw application or removal	Off-season application roughly halves CH ₄ relative to application shortly before transplanting; removal strategies reduce GHG by 46% on average	High for direction; moderate for long-term magnitude	Emissions displaced if straw is burned; possible SOC decline; acclimation reduces long-run benefit	Moderate; timing observable, but quantity incorporated hard to verify	(Jiang, Qian, <i>et al.</i> , 2019; Nikolaisen <i>et al.</i> , 2023; Qian <i>et al.</i> , 2023; Wang <i>et al.</i> , 2018)
Avoided residue burning	Avoids combustion CH ₄ and N ₂ O	High for air pollution; moderate for net greenhouse gas balance	Incorporation before flooding may raise soil CH ₄	Moderate; burning events observable, counterfactual uncertain	(Bhatia <i>et al.</i> , 2013; Romasanta <i>et al.</i> , 2017; Shyamsundar <i>et al.</i> , 2019)
Biochar	CH ₄ reduction in many paddy studies; durable carbon stock	Moderate; strongly moderated by nitrogen input	Feedstock competition, production emissions, field persistence uncertain	Moderate for application; low for long-term stock	(Huang <i>et al.</i> , 2026; Jeffery <i>et al.</i> , 2016; Wang <i>et al.</i> , 2016)
Manure or organic fertiliser	Increases CH ₄ and GWP relative to urea in flooded soils	Moderate	Higher N ₂ O after drainage; conflict with SOC-building aims	Moderate	(Jiang, Carrijo, <i>et al.</i> , 2019; X. Q. Liang <i>et al.</i> , 2013)
Direct seeding and conservation agriculture	Reduced CH ₄ , increased N ₂ O; rice GWP reduction of about 23% estimated for Haryana	Moderate; few full-season multi-gas studies	Weed pressure, transition yield penalty, N ₂ O increase	High for establishment method	(Chakraborty <i>et al.</i> , 2017; Mishra <i>et al.</i> , 2021; Tirol-Padre <i>et al.</i> , 2016)
Low-emission cultivars	CH ₄ reduction of about 24% on average; larger in high-carbon soils	Moderate; soil-dependent	Unclear generalisability; regulatory barriers for transgenic lines	High for cultivar identity, low for cultivar-specific factors	(Jiang <i>et al.</i> , 2017; Qian <i>et al.</i> , 2023; Su <i>et al.</i> , 2015)
Nitrogen source and inhibitors	Ammonium sulphate –40% CH ₄ ; dicyandiamide –18% CH ₄ and –29% N ₂ O	Moderate	Ammonium sulphate may raise N ₂ O; cost	Moderate	(Linguist <i>et al.</i> , 2012)
Optimised nitrogen rate and placement	Yield-scaled GWP minimised at yield-maximising rate; urea deep placement raises yield without raising N ₂ O under AWD	Moderate to high for yield-scaled outcomes	N ₂ O pulses after drying and re-flooding	Moderate	(Islam <i>et al.</i> , 2018; Pittelkow <i>et al.</i> , 2014)
Rice–aquatic animal co-culture	CH ₄ per hectare often increases; SOC +11.6%; lower agrochemical use	Moderate; site-specific	Higher area-based CH ₄ ; outcome depends on functional unit	Moderate	(Bhattacharyya <i>et al.</i> , 2013; Datta <i>et al.</i> , 2009; S. Li <i>et al.</i> , 2024; Xie <i>et al.</i> , 2011)

Note. AWD, alternate wetting and drying; CH₄, methane; N₂O, nitrous oxide; GHG, greenhouse gas; GWP, global warming potential; SOC, soil organic carbon. Evidence strength is a qualitative judgement based on the number, design and consistency of field studies and syntheses reviewed here

6.3 Nitrogen Source, Rate and Placement

Nitrogen management affects both gases. A quantitative review found that replacing urea with ammonium sulphate at the same nitrogen rate reduced CH₄ emissions by 40%, consistent with the role of sulphate as a competing electron acceptor in reduced soils (Kögel-Knabner *et al.*, 2010), but could increase N₂O; the nitrification inhibitor dicyandiamide reduced both CH₄ and N₂O, by 18% and 29% respectively (Linguist *et al.*, 2012). Fertiliser rate had smaller and more variable effects on CH₄ (Linguist *et al.*, 2012), and a synthesis of yield-scaled GWP showed that N₂O increased exponentially at nitrogen surpluses, while yield-scaled GWP was minimised at the nitrogen rate that maximised yield, being 21% lower than without nitrogen (Pittelkow *et al.*, 2014). Field trials in drill-seeded systems in the United States likewise found that CH₄ dominated GWP and that increasing nitrogen rate contributed to N₂O emissions mainly during non-flooded periods (Adviento-Borbe *et al.*, 2013).

Urea deep placement (UDP) has been promoted in South Asia to improve nitrogen use efficiency. In Bangladesh, N₂O emissions were sporadic and event-driven, with peaks after broadcast urea application, during dry periods and after re-flooding (Gaihre *et al.*, 2015). When UDP was combined with AWD, seasonal N₂O emissions did not differ from broadcast urea, while yields increased by 28% and nitrogen recovery efficiency by 167% (Islam *et al.*, 2018). Large-scale programmes for maize, rice and wheat in China have demonstrated that integrated soil-crop management can raise rice yields without additional nitrogen while lowering environmental costs (Chen *et al.*, 2014), and that millions of smallholders can adopt such practices, increasing average cereal yields by about 11% while reducing nitrogen application by about 15–18% (Cui *et al.*, 2018). These programmes show that nutrient optimisation can deliver food security and emission benefits together, but they reported reactive nitrogen and integrated environmental indicators rather than field-measured CH₄, so their direct relevance to CH₄-centred carbon farming is limited.

6.4 Integrated Packages and the System of Rice Intensification

Integrated management packages often combine intermittent irrigation with changes in planting density, seedling age and organic inputs. The system of rice intensification (SRI) is the best known, but early critical assessments concluded that SRI-type techniques are not necessary for achieving yields near the potential in favourable environments, that the reported extraordinary yields were likely to reflect error, and that its benefits may be confined to resource-poor farmers on poor soils (Dobermann, 2004; Sheehy *et al.*, 2004). Because SRI combines several practices, any CH₄ benefit is likely to derive mainly from its water regime, and the presence of organic amendments may offset part of that benefit. In Thailand, a package of cost-reducing best management practices reduced fertiliser use by 50–64% without yield penalty and increased net income by 26% (Stuart *et al.*, 2018), illustrating that integrated packages can be economically attractive even when their greenhouse gas outcomes are not measured directly.

6.5 Rice–Aquatic Animal Co-culture and Rotational Systems

Co-culture of rice with fish, crustaceans, amphibians or ducks is an established practice in parts of Asia, and the rice–fish system of southern China has been maintained for more than a millennium. Field surveys and experiments showed that rice–fish co-culture required 68% less pesticide and 24% less chemical fertiliser than rice monoculture while maintaining yield and yield stability (Xie *et al.*, 2011). A meta-analysis of 200 field experiments found that co-culture increased SOC content by 11.6% on average, with larger effects in temperate regions and with japonica than indica rice (S. Li *et al.*, 2024).

The CH₄ consequences are less favourable. In rainfed lowlands of eastern India, stocking Indian major carps, *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*, together with *Puntius gonionotus*, increased CH₄ emissions by 74–112% depending on the rice cultivar, while reducing N₂O emissions (Datta *et al.*, 2009). A subsequent study found that rice–fish co-culture increased seasonal CH₄ by 26% overall and by 36% with common carp (*Cyprinus carpio* L.), although emissions per unit of combined rice and fish yield were similar to or lower than those of rice alone (Bhattacharyya *et al.*, 2013). Co-culture therefore illustrates the importance of the functional unit: per hectare, it can increase CH₄, but per unit of food produced it may not, and it can raise SOC and reduce agrochemical use. Whether it should be considered carbon farming depends on which metric a scheme adopts.

The mitigation evidence for the non-water levers discussed in Sections 5 and 6 is compared in Table 4. The table shows that each lever has a credible mechanism and some field support, but that confidence is limited by soil dependence, by trade-offs with N₂O or by difficulty of verification, and that only water management combines strong evidence with relatively low per-unit cost of implementation.

7. Quantification, Monitoring, Reporting and Verification

7.1 Inventory Approaches, Emission Factors and Scaling Factors

National inventories estimate rice CH₄ by multiplying harvested area and season length by a baseline emission factor adjusted with scaling factors for water regime, pre-season water status and organic amendment, following IPCC guidance that has been refined in successive editions (Intergovernmental Panel on Climate Change, 2019). Using the earlier Tier 1 method, global rice CH₄ in 2000 was estimated at 25.6 Tg yr⁻¹, with a 95% uncertainty range of 14.8–41.7 Tg yr⁻¹, much of which arose from poor information on organic amendments and on the area under continuous flooding (Yan *et al.*, 2009). The same analysis estimated that draining every continuously flooded field at least once per season would reduce emissions by 4.1 Tg yr⁻¹, and that off-season straw application would yield a further 4.1 Tg yr⁻¹ (Yan *et al.*, 2009). An updated global analysis estimated a default emission factor of 1.19 kg CH₄

ha⁻¹ d⁻¹ for continuously flooded fields without organic amendment, with lower regional values for South Asia and North America (Wang *et al.*, 2018).

These parameters are under continuing revision. Paired field comparisons suggest that the multiple-drainage scaling factor should be lower than the IPCC default, implying greater mitigation (Jiang, Carrijo, *et al.*, 2019), whereas multi-site trials in South-East Asia suggest a higher one, implying less (Tirol-Padre *et al.*, 2018). A model fitted to an expanded dataset emphasised that pre-season water management must be represented explicitly to capture differences between tropical and temperate systems (Nikolaisen *et al.*, 2023). At national scale, Indian rice fields were estimated to emit about 3.37 Mt CH₄ in 2007, using state-specific emission coefficients for upland, rainfed, irrigated and deepwater ecosystems (Bhatia *et al.*, 2013). In the United States, a regionalised Tier 2 approach produced estimates 7% and 42% lower than two national and international inventories but 63% higher than methods lacking regional context (Reavis *et al.*, 2023). The magnitude of these differences is comparable to the reductions that carbon farming aims to credit, which is the core difficulty for verification.

7.2 Field Measurement

Closed chambers remain the dominant field method, but a review of 155 studies found no commonly accepted standard for chamber deployment, sampling frequency, time of day or intervals between sampling days (Sander & Wassmann, 2014). Because N₂O emissions are episodic and often follow fertilisation or re-flooding (Gaihre *et al.*, 2015; Zou *et al.*, 2005), low-frequency sampling can miss the events that determine seasonal totals, and this is a plausible reason why N₂O estimates under AWD differ so widely (Kritee *et al.*, 2018). Eddy covariance avoids the spatial limitations of chambers and has confirmed large CH₄ reductions under AWD at production scale (Runkle *et al.*, 2019), but it is expensive, requires homogeneous fields and is unsuitable for the small, fragmented plots typical of Asian smallholdings. Neither method is practical for verifying emission reductions on thousands of farms, which is why crediting relies on models, default factors and evidence that the practice was implemented.

7.3 Process Models and Satellite Approaches

Process-based models translate management and environmental data into emission estimates and are central to recent crediting methodologies (Verra, 2025). Early applications of the Denitrification–Decomposition model to China estimated both the CH₄ reduction and the N₂O increase associated with mid-season drainage at national scale (C. Li *et al.*, 2005). A recent global application of the CH₄MOD model, validated against 986 flux observations with a correlation coefficient of 0.76, identified water regime as the most important driver and showed that global rice CH₄ could range from 8 to 78 Tg yr⁻¹ depending on management assumptions (Hu *et al.*, 2024). That nearly tenfold range is a reminder that model outputs are only as reliable as the management data supplied to them, and that the extent of drainage and residue return across Asia is poorly documented.

Satellite approaches offer independent constraints. Inversion of observations from the Tropospheric Monitoring Instrument for Heilongjiang Province estimated rice CH₄ emissions of 0.85 Tg yr⁻¹ in 2021 and suggested that widely used global and national inventories were biased low by a factor of two to four for that region; the inversion reduced uncertainty in regional emissions by 73% compared with bottom-up estimates (R. Liang *et al.*, 2024). At continental scale, spatial and seasonal consistency between paddy area, rice growth and column-averaged CH₄ in monsoon Asia was interpreted as a fingerprint of rice paddies (Zhang *et al.*, 2020), an interpretation challenged on the grounds that such correlations do not by themselves establish causation (Zeng *et al.*, 2021). The exchange illustrates that atmospheric observations can test inventory estimates at regional scale but cannot yet attribute emission changes to practices on individual farms.

7.4 Carbon Crediting: Methodologies, Additionality and Integrity

The architecture of rice crediting has changed rapidly. The voluntary-market methodology released in February 2025 for improved management in rice production replaced an earlier Clean Development Mechanism methodology for adjusted water management, which the standard had inactivated in March 2023, and it extends eligibility to shorter flooding, low-emission or short-duration cultivars, improved nitrogen management and avoided residue burning, with flexible quantification approaches that include biogeochemical models (Verra, 2025). A revised version activated in July 2026 requires baseline reassessment every five years and safeguards against SOC losses (Verra, 2025). These features respond to several of the weaknesses identified above, but they leave unresolved the issues that have undermined confidence in soil carbon credits more generally.

Experience with agricultural soil carbon protocols shows that methods differ widely in their treatment of quantification, additionality, permanence and leakage, and that regional consistency is necessary for credit integrity (Oldfield *et al.*, 2022). Analysis of private soil carbon certificates concluded that they fall short of expectations for climate change mitigation, largely because the permanence of sequestration cannot be guaranteed and because additionality and leakage are difficult to demonstrate (Paul *et al.*, 2023). In rice, additionality is a particular concern because drainage is already widespread in some regions for agronomic reasons, as the history of Chinese water management shows (Y. Li *et al.*, 2025), and because water shortages force drying irrespective of incentives in others (Stuart *et al.*, 2018). Verification is also challenging where farmers cannot control drainage in gravity-fed systems (Enriquez *et al.*, 2021). The evidence reviewed here suggests that credible crediting would need conservative baselines, documented evidence of drying at critical periods, explicit accounting for N₂O and fallow emissions, and discounting for model uncertainty. None of these requirements has yet been evaluated empirically across a portfolio of projects.

Table 5 compares the main approaches to quantification and verification. It shows a clear trade-off between precision and scalability: methods that measure emissions directly are accurate but local and costly, while scalable approaches rely on activity data and parameters whose uncertainty can exceed the reductions being credited.

Table 5. Approaches to quantifying and verifying greenhouse gas outcomes of rice carbon farming

Approach	Spatial scale	Main strengths	Main limitations	Suitability for crediting	Supporting references
IPCC Tier 1 emission and scaling factors	National to regional	Simple, transparent, consistent with inventories	Large uncertainty; scaling factors disputed; poor data on drainage and organic inputs	Low unless supported by activity evidence	(Intergovernmental Panel on Climate Change, 2019; Jiang, Carrijo, <i>et al.</i> , 2019; Tirol-Padre <i>et al.</i> , 2018; Yan <i>et al.</i> , 2009)
Tier 2 regional or country-specific factors	Regional to national	Captures soil, climate and pre-season water status	Requires representative field data; estimates diverge from other inventories	Moderate	(Bhatia <i>et al.</i> , 2013; Nikolaisen <i>et al.</i> , 2023; Reavis <i>et al.</i> , 2023; Wang <i>et al.</i> , 2018)
Closed-chamber Plot field measurement		Direct measurement of CH ₄ and N ₂ O	No common protocol; misses episodic N ₂ O if sampling is infrequent; costly	Calibration and validation only	(Kritee <i>et al.</i> , 2018; Sander & Wassmann, 2014)
Eddy covarianceField		Continuous, large footprint, no chamber artefacts	Expensive; needs large homogeneous fields	Validation only	(Runkle <i>et al.</i> , 2019)
Process-based models (DNDC, global CH ₄ MOD)	Field to national, global	Represent interactions and N ₂ O; enable scenario analysis	Output depends on uncertain management inputs; wide scenario ranges	Moderate to high if calibrated and independently validated	(Hu <i>et al.</i> , 2024; C. Li <i>et al.</i> , 2005; Verra, 2025)
Satellite atmospheric inversion	Regional	Independent top-down constraint; reduces regional uncertainty	Cannot attribute to individual farms or practices; attribution disputed	Programme-level checks	(R. Liang <i>et al.</i> , 2024; Zeng <i>et al.</i> , 2021; Zhang <i>et al.</i> , 2020)
Practice-based activity verification	Farm to programme	Low cost; scalable	Additionality hard to demonstrate; implementation fidelity uncertain	Moderate with conservative discounting	(Enriquez <i>et al.</i> , 2021; Oldfield <i>et al.</i> , 2022; Paul <i>et al.</i> , 2023)

Note. IPCC, Intergovernmental Panel on Climate Change; CH₄, methane; N₂O, nitrous oxide; DNDC, Denitrification–Decomposition model; CH₄MOD, a process-based model of methane emissions from rice paddies. Suitability ratings are qualitative judgements derived from the evidence reviewed

8. Carbon Farming and the Sustainable Development Goals: Synergies and Trade-offs

8.1 Climate Action and Food Security

The clearest synergy concerns SDG 13 on climate action and SDG 2 on zero hunger. Mild AWD reduces CH₄ emissions by roughly a half, and single or prolonged mid-season drainage by roughly a third to two-thirds, with little or no average yield penalty (Carrijo *et al.*, 2017; Itoh *et al.*, 2011; Jiang, Carrijo, *et al.*, 2019; Perry *et al.*, 2022). Yield-scaled outcomes are therefore usually favourable. Large programmes in China show that integrated nutrient and crop management can raise yields while reducing environmental costs (Chen *et al.*, 2014; Cui *et al.*, 2018), and an assessment of 40 land-based practices concluded that most land management options can be applied without competing for land (Smith *et al.*, 2020). The synergy is conditional on avoiding severe drying, which reduces yields substantially (Carrijo *et al.*, 2017), and on recognising that warming and rising CO₂ concentrations are projected to increase the greenhouse gas intensity of rice (van Groenigen *et al.*, 2013), so that mitigation measures may need to intensify merely to keep pace.

8.2 Water, Health and Ecosystems

Water saving links rice carbon farming to SDG 6. The evidence of reduced irrigation demand is strong and spans Asia, the Americas and Nepal (Bo *et al.*, 2024; Howell *et al.*, 2015; Lampayan *et al.*, 2015; Loaiza *et al.*, 2024). Whether field-level savings translate into basin-level gains is less certain, because water drained from one field may recharge groundwater or supply downstream users, and the economic benefit depends on how water is priced (Chakravorty *et al.*, 2023). Links to SDG 3 on health operate through grain arsenic, which declines under sufficiently severe drying (C. Li *et al.*, 2019; Linquist *et al.*, 2015), through the potential increase in cadmium under aerobic conditions (C. Li *et al.*, 2019) and through reduced air pollution when residue burning is avoided (Gadde *et al.*, 2009; Shyamsundar *et al.*, 2019). SDG 15 on life on land, interpreted here to include wetland-dependent biodiversity, is the area of greatest potential conflict, since drying may harm species that depend on flooded fields (Pérez-Méndez *et al.*, 2026), whereas co-culture systems can enhance SOC and reduce pesticide use (S. Li *et al.*, 2024; Xie *et al.*, 2011).

8.3 Livelihoods, Incentives and Equity

Links to SDG 1 on poverty and SDG 10 on reduced inequalities depend on who bears the costs and receives the benefits of mitigation. Where farmers pay for pumping, AWD can increase incomes by reducing water and fuel costs (Lampayan *et al.*, 2015), but where water charges are fixed, the private water saving disappears and adoption depends on external payments (Chakravorty *et al.*, 2023). Adoption correlates with education, landownership and access to information (Alauddin *et al.*, 2020), suggesting that carbon payments could favour better-resourced farmers unless programmes are designed explicitly for smallholders and tenants. Farmers in gravity-fed systems may be unable to adopt AWD individually, so collective action and irrigation governance become preconditions for participation (Enriquez *et al.*, 2021). The literature retrieved for this review contained little empirical evidence on gender-differentiated labour, decision-making or benefit-sharing in rice carbon farming. Implications for SDG 5 cannot therefore be assessed from current evidence, and the absence of such evidence should not be read as evidence of neutral effects. The 2030 Agenda frames the goals as integrated and indivisible (United Nations General Assembly, 2015), and scoring frameworks that classify interactions from mutually reinforcing to counteracting provide a means of making such trade-offs explicit (Nilsson *et al.*, 2016).

Table 6. Interactions between principal rice carbon-farming practices and selected Sustainable Development Goals

Practice	SDG 2 Zero hunger	SDG 6 Clean water	SDG 3 Health	SDG 13 Climate action	SDG 15 Life on land and SDG 1 or 10 livelihoods and equity	Confidence and main caveat	Supporting references
Mild alternate wetting and drying or single mid-season drainage	Neutral to positive yield; positive yield-scaled outcomes	Positive at field scale; basin effects uncertain	Arsenic reduction only with sufficient drying; possible cadmium increase	Strongly positive for CH ₄ ; N ₂ O offset usually partial	Possible harm to wetland biodiversity; income gains depend on water pricing and control of drainage	High for CH ₄ and yield; low for biodiversity and equity	(Carrijo <i>et al.</i> , 2017; Chakravorty <i>et al.</i> , 2023; Jiang, Carrijo, <i>et al.</i> , 2019; C. Li <i>et al.</i> , 2019; Pérez-Méndez <i>et al.</i> , 2026; Perry <i>et al.</i> , 2022)
Severe drying	Negative yield	Strongly positive	Larger arsenic reduction	Larger CH ₄ reduction; larger N ₂ O risk	Higher biodiversity risk	Moderate; trade-offs explicit	(Carrijo <i>et al.</i> , 2017; Linquist <i>et al.</i> , 2015; Zhao <i>et al.</i> , 2024)
Off-season straw management and avoided burning	Neutral	Neutral	Positive through air quality when burning is avoided	Positive for CH ₄ if straw is not burned	Profit gains possible with appropriate machinery	Moderate; outcome depends on residue fate	(Gadde <i>et al.</i> , 2009; Ma <i>et al.</i> , 2009; Shyamsundar <i>et al.</i> , 2019; Wang <i>et al.</i> , 2018)
Biochar	Variable	Neutral	Possible cadmium reduction	Positive if persistence and production emissions are favourable	Feedstock competition	Low to moderate	(Huang <i>et al.</i> , 2026; Wang <i>et al.</i> , 2016; Yin <i>et al.</i> , 2024)
Direct seeding and conservation agriculture	Transition yield penalty then parity	Positive	Neutral	Positive for CH ₄ ; N ₂ O increase	Labour and cost savings; weed management burden	Moderate	(Chakravorty <i>et al.</i> , 2017; Mishra <i>et al.</i> , 2021; Tirol-Padre <i>et al.</i> , 2016)
Optimised nitrogen management	Positive	Positive through reduced nitrogen losses	Neutral	Positive for N ₂ O and yield-scaled GWP	Cost savings for farmers	Moderate to high	(Cui <i>et al.</i> , 2018; Islam <i>et al.</i> , 2018; Pittelkow <i>et al.</i> , 2014)
Rice-aquatic animal co-culture	Positive through diversified food	Neutral	Reduced pesticide use	Area-based CH ₄ may increase; SOC increases	Positive for diversified income and biodiversity	Moderate; metric-dependent	(Bhattacharyya <i>et al.</i> , 2013; Datta <i>et al.</i> , 2009; S. Li <i>et al.</i> , 2024; Xie <i>et al.</i> , 2011)

Note. SDG, Sustainable Development Goal; CH₄, methane; N₂O, nitrous oxide; GWP, global warming potential; SOC, soil organic carbon. Entries summarise the predominant direction of evidence reviewed in this article and are not exhaustive. "Neutral" indicates no consistent effect reported in the reviewed evidence

8.4 An Integrated Framework

The synthesis above suggests that the sustainability outcome of rice carbon farming depends on three interacting layers: the biophysical response of the paddy to management, the accounting rules through which that response is quantified and rewarded, and the institutional and socio-economic conditions that determine adoption and the distribution of benefits. Treating any layer in isolation risks either overstating mitigation or producing unintended social and ecological effects.

Table 6 assesses the direction and confidence of interactions between the principal practices and the SDGs most affected. Synergies with climate, food and water goals are supported by moderate to strong evidence, whereas interactions with health, biodiversity and equity are frequently conditional or under-studied. Fig. 1 then integrates these relationships into a conceptual framework that distinguishes relationships supported by field evidence from those that remain hypothesised.

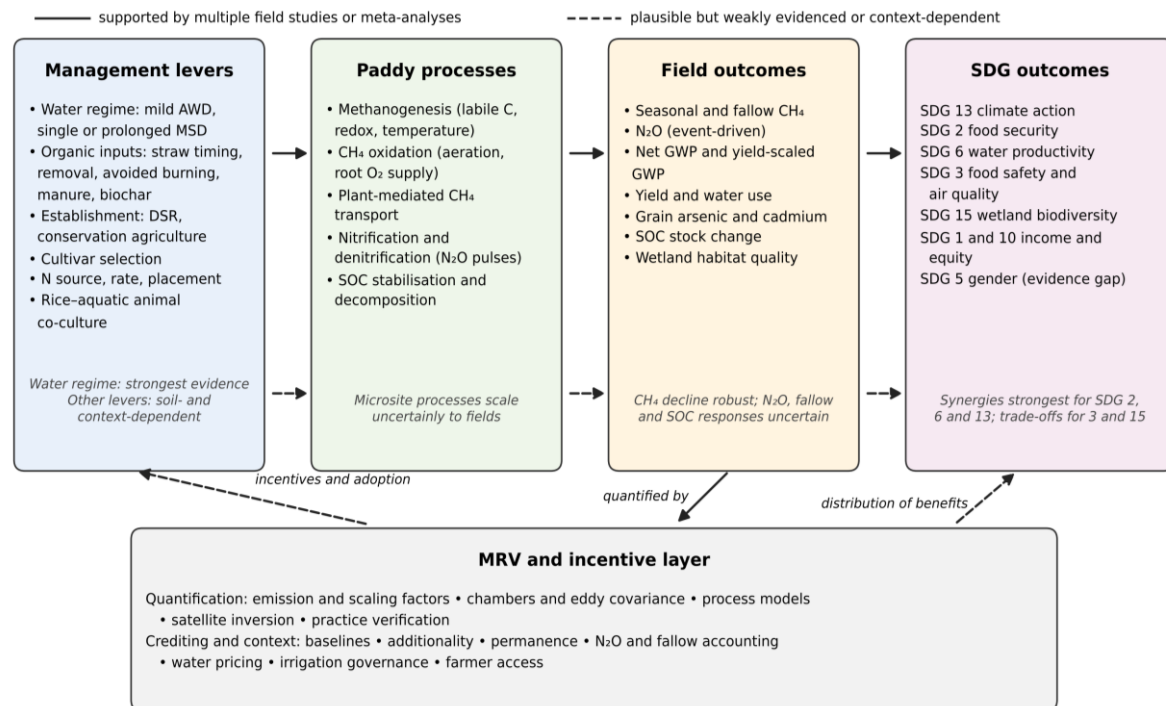


Fig. 1. Conceptual framework for carbon farming in rice cropping systems developed from the present synthesis. Management levers (left) act on paddy biogeochemical processes (centre-left), which determine field-level outcomes (centre-right); these outcomes are quantified through measurement, reporting and verification (MRV) and incentive mechanisms (bottom) and translated into Sustainable Development Goal (SDG) outcomes (right). Solid arrows denote relationships supported by multiple field studies or meta-analyses; dashed arrows denote relationships that are plausible but weakly evidenced or context-dependent. AWD, alternate wetting and drying; MSD, mid-season drainage; DSR, direct-seeded rice; N, nitrogen; CH₄, methane; N₂O, nitrous oxide; SOC, soil organic carbon; GWP, global warming potential. The framework is original and is not adapted from a previously published figure.

9. Future Directions

The most immediate priority is to establish the net, full-year climate effect of water management under farmer conditions. Existing meta-analyses agree on CH₄ reductions but rest largely on controlled experiments in which drying was imposed as designed, and on N₂O measurements of uneven temporal resolution. Multi-year, multi-site trials on farmers' fields across South and South-East Asia are needed, with high-frequency or automated N₂O measurement around fertilisation and re-flooding events, inclusion of fallow periods and direct monitoring of field water levels. Such trials should report CH₄, N₂O, yield, water use and grain arsenic and cadmium together, using common protocols so that results can be pooled. Paired eddy covariance sites at landscape scale would provide independent benchmarks for chamber and model estimates. This work would resolve whether the high N₂O emissions reported from parts of India are exceptional or widespread and would allow crediting methodologies to set evidence-based deductions.

A second immediate priority concerns verification. The divergence among inventory factors, process models and satellite inversions is of the same order as the reductions being credited. Research should test whether combinations of radar-based detection of field flooding, low-cost water-level sensors and calibrated process models can verify drainage at farm level with known error, and whether satellite inversions can detect programme-level emission changes. Independent validation datasets, withheld from model calibration, are essential. The outcome measures should be the error and bias of practice detection and of emission estimates at field, farm and programme scales, which would allow uncertainty discounting in crediting to be set rationally rather than arbitrarily.

A longer-term priority is to determine whether water-saving irrigation and straw removal reduce paddy SOC over decades. Current evidence rests on a small number of studies with carbon balances, and crediting periods are short relative to the time needed to detect SOC change. Long-term experiments, resampling of established monitoring sites and chronosequence approaches should quantify changes in SOC stocks to at least 30 cm depth on an equivalent soil mass basis under contrasting water and residue regimes. The results would determine whether SOC safeguards in crediting methodologies are adequate or need to be strengthened.

Breeding and cultivar evaluation offer a mitigation route that is easier to verify than water management. Multi-environment trials should test whether low-emission cultivar effects hold across soils of different carbon content and across water regimes, and whether they interact with AWD. Root traits, exudation and rhizosphere microbial communities should be measured alongside fluxes so that cultivar effects can be predicted rather than measured case by case. Research on biochar should move from short-term pot and plot studies to multi-year field trials with full lifecycle accounting, including feedstock alternatives, pyrolysis emissions and interactions with nitrogen inputs.

Social and institutional research is equally pressing. Randomised and quasi-experimental evaluations of carbon payment designs are needed to establish whether payments change behaviour, how they interact with water pricing and irrigation governance, and who participates. Evaluations should examine smallholders, tenants and women explicitly, and outcome measures should include participation, income, labour, and the distribution of payments, as well as verified emission reductions. Ecological studies should identify drying regimes and landscape configurations that reconcile CH₄ reduction with wetland biodiversity, for example by targeting drainage spatially or seasonally. Taken together, these research directions would allow rice carbon farming to be evaluated against the SDGs on the basis of measured rather than assumed co-impacts.

10. Conclusions

The evidence supports rice carbon farming as a meaningful but conditional contribution to climate change mitigation. Its strongest foundation is water management. Independent meta-analyses, multi-site field trials and production-scale flux measurements consistently show that alternate wetting and drying and mid-season drainage reduce methane emissions by around a half, with little average yield penalty when drying is mild. This is the most robust conclusion of the review, and it justifies continued investment in water management as a mitigation strategy.

Confidence declines when the question shifts from methane reduction to net climate benefit. Nitrous oxide usually offsets only a small part of the methane benefit, but large offsets have been reported under particular soils and management regimes, and the temporal resolution of nitrous oxide measurement in South Asia is insufficient to judge how common they are. Fallow-season emissions, pre-season water status and possible long-term losses of soil organic carbon further complicate accounting. Straw timing and removal, avoided burning, low-emission cultivars, direct seeding and optimised nitrogen management each have credible mechanisms and supportive field evidence, but their effects depend on soil, climate and the fate of residues. Biochar is the only lever capable of producing a durable carbon stock at scale, yet its field performance and lifecycle balance remain uncertain.

Verification is the main constraint on credible crediting. Inventory factors, process models and satellite estimates diverge by margins comparable to the reductions being claimed, farm-level confirmation of drainage remains costly, and additionality is difficult to establish where drainage already occurs for agronomic or hydrological reasons. Recent methodologies address some of these problems, but their effectiveness has not been evaluated empirically.

The relationship with the Sustainable Development Goals is predominantly synergistic for climate action, food security and water productivity, and conditional for health, through the opposing responses of arsenic and cadmium, and for biodiversity. Effects on livelihoods and equity depend on water pricing, irrigation governance and programme design, and evidence on gender is largely absent. Rice carbon farming should therefore be regarded neither as a ready-made offset opportunity nor as a marginal option, but as a set of practices whose climate and development value depends on full multi-gas accounting, conservative crediting, attention to co-impacts and institutional arrangements that allow smallholders to participate.

11. Limitations

As a narrative review, this article is subject to selection and interpretive bias despite the use of a documented search strategy and an explicit appraisal rubric. The selection of studies and the weight given to them reflect judgements that other reviewers might make differently. A narrative review does not require the procedural apparatus of a systematic review, such as screening and deduplication counts, independent duplicate screening or formal measures of reviewer agreement, and these were not undertaken. The conclusions are therefore qualitative syntheses of the strength and consistency of evidence rather than pooled estimates.

The search did not include subscription-only bibliographic databases, and some relevant studies indexed only in such sources may have been missed. Only English-language publications were included, which may under-represent research published in Chinese, Japanese, Korean, Vietnamese, Thai, Indonesian and other languages of major rice-producing countries, although the use of a regional platform partly mitigated this. The primary literature is concentrated in China, the United States and a limited number of South and South-East Asian sites, while rainfed systems, Africa and Latin America are under-represented. Studies differ in drying regimes, measurement periods, gas sampling frequency, climate metrics and reported outcomes, which limits comparability and precluded quantitative synthesis.

Several of the syntheses relied upon draw on overlapping sets of primary studies, so their agreement is not fully independent. Publication bias may favour reports of successful mitigation. Long-term evidence on soil carbon, cultivar performance and the

behavioural effects of carbon payments is scarce, and the field of rice carbon crediting is changing rapidly, so methodological and policy details discussed here may be superseded by subsequent revisions.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

- Adviento-Borbe, M. A., Pittelkow, C. M., Anders, M., van Kessel, C., Hill, J. E., McClung, A. M., Six, J., & Linquist, B. A. (2013). Optimal fertilizer nitrogen rates and yield-scaled global warming potential in drill seeded rice. *Journal of Environmental Quality*, 42(6), 1623–1634. <https://doi.org/10.2134/jeq2013.05.0167>
- Alauddin, M., Rashid Sarker, M. A., Islam, Z., & Tisdell, C. (2020). Adoption of alternate wetting and drying (AWD) irrigation as a water-saving technology in Bangladesh: Economic and environmental considerations. *Land Use Policy*, 91, Article 104430. <https://doi.org/10.1016/j.landusepol.2019.104430>
- Aulakh, M. S., Wassmann, R., & Rennenberg, H. (2001). Methane emissions from rice fields—Quantification, mechanisms, role of management, and mitigation options. *Advances in Agronomy*, 70, 193–260. [https://doi.org/10.1016/S0065-2113\(01\)70006-5](https://doi.org/10.1016/S0065-2113(01)70006-5)
- Baethge, C., Goldbeck-Wood, S., & Mertens, S. (2019). SANRA—A scale for the quality assessment of narrative review articles. *Research Integrity and Peer Review*, 4(1), Article 5. <https://doi.org/10.1186/s41073-019-0064-8>
- Bhatia, A., Jain, N., & Pathak, H. (2013). Methane and nitrous oxide emissions from Indian rice paddies, agricultural soils and crop residue burning. *Greenhouse Gases: Science and Technology*, 3(3), 196–211. <https://doi.org/10.1002/ghg.1339>
- Bhattacharyya, P., Sinhababu, D. P., Roy, K. S., Dash, P. K., Sahu, P. K., Dandapat, R., Neogi, S., & Mohanty, S. (2013). Effect of fish species on methane and nitrous oxide emission in relation to soil C, N pools and enzymatic activities in rainfed shallow lowland rice-fish farming system. *Agriculture, Ecosystems & Environment*, 176, 53–62. <https://doi.org/10.1016/j.agee.2013.05.015>
- Bo, Y., Wang, X., van Groenigen, K. J., Linquist, B. A., Müller, C., Li, T., Yang, J., Jägermeyr, J., Qin, Y., & Zhou, F. (2024). Improved alternate wetting and drying irrigation increases global water productivity. *Nature Food*, 5(12), 1005–1013. <https://doi.org/10.1038/s43016-024-01081-z>
- Cai, Y., Zheng, Y., Bodelier, P. L. E., Conrad, R., & Jia, Z. (2016). Conventional methanotrophs are responsible for atmospheric methane oxidation in paddy soils. *Nature Communications*, 7(1), Article 11728. <https://doi.org/10.1038/ncomms11728>
- Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, 203, 173–180. <https://doi.org/10.1016/j.fcr.2016.12.002>
- Chakraborty, D., Ladha, J. K., Rana, D. S., Jat, M. L., Gathala, M. K., Yadav, S., Rao, A. N., Ramesha, M. S., & Raman, A. (2017). A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports*, 7(1), Article 9342. <https://doi.org/10.1038/s41598-017-09742-9>
- Chakravorty, U., Dar, M. H., & Emerick, K. (2023). Inefficient water pricing and incentives for conservation. *American Economic Journal: Applied Economics*, 15(1), 319–350. <https://doi.org/10.1257/app.20210011>
- Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., . . . Zhang, F. (2014). Producing more grain with lower environmental costs. *Nature*, 514(7523), 486–489. <https://doi.org/10.1038/nature13609>
- Chen, Z., Lin, H., Balasus, N., Hardy, A., East, J. D., Zhang, Y., Runkle, B. R. K., Hancock, S. E., Taylor, C. A., Du, X., Sander, B. O., & Jacob, D. J. (2025). Global rice paddy inventory (GRPI): A high-resolution inventory of methane emissions from rice agriculture based on Landsat satellite inundation data. *Earth's Future*, 13(4), Article e2024EF005479. <https://doi.org/10.1029/2024EF005479>
- Conrad, R. (2020). Importance of hydrogenotrophic, acetoclastic and methylotrophic methanogenesis for methane production in terrestrial, aquatic and other anoxic environments: A mini review. *Pedosphere*, 30(1), 25–39. [https://doi.org/10.1016/S1002-0160\(18\)60052-9](https://doi.org/10.1016/S1002-0160(18)60052-9)
- Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mi, G., Miao, Y., Li, X., Gao, Q., Yang, J., Wang, Z., Ye, Y., Guo, S., Lu, J., Huang, J., Lv, S., Sun, Y., . . . Dou, Z. (2018). Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 555(7696), 363–366. <https://doi.org/10.1038/nature25785>
- Datta, A., Nayak, D. R., Sinhababu, D. P., & Adhya, T. K. (2009). Methane and nitrous oxide emissions from an integrated rainfed rice-fish farming system of Eastern India. *Agriculture, Ecosystems & Environment*, 129(1–3), 228–237. <https://doi.org/10.1016/j.agee.2008.09.003>
- Dobermann, A. (2004). A critical assessment of the system of rice intensification (SRI). *Agricultural Systems*, 79(3), 261–281. [https://doi.org/10.1016/S0308-521X\(03\)00087-8](https://doi.org/10.1016/S0308-521X(03)00087-8)
- Enriquez, Y., Yadav, S., Evangelista, G. K., Villanueva, D., Burac, M. A., & Pedre, V. (2021). Disentangling challenges to scaling alternate wetting and drying technology for rice cultivation: Distilling lessons from 20 years of experience in the Philippines. *Frontiers in Sustainable Food Systems*, 5, Article 675818. <https://doi.org/10.3389/fsufs.2021.675818>
- European Parliament, & Council of the European Union. (2024). Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming

- and carbon storage in products. *Official Journal of the European Union*, L series. <https://eur-lex.europa.eu/eli/reg/2024/3012/oj>
- Gadde, B., Bonnet, S., Menke, C., & Garivait, S. (2009). Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environmental Pollution*, 157(5), 1554–1558. <https://doi.org/10.1016/j.envpol.2009.01.004>
- Gaihre, Y. K., Singh, U., Islam, S. M. M., Huda, A., Islam, M. R., Satter, M. A., Sanabria, J., Islam, M. R., & Shah, A. L. (2015). Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. *Geoderma*, 259–260, 370–379. <https://doi.org/10.1016/j.geoderma.2015.06.001>
- Howell, K. R., Shrestha, P., & Dodd, I. C. (2015). Alternate wetting and drying irrigation maintained rice yields despite half the irrigation volume, but is currently unlikely to be adopted by smallholder lowland rice farmers in Nepal. *Food and Energy Security*, 4(2), 144–157. <https://doi.org/10.1002/fes3.58>
- Hu, Q., Li, J., Xie, H., Huang, Y., Canadell, J. G., Yuan, W., Wang, J., Zhang, W., Yu, L., Li, S., Lu, X., Li, T., & Qin, Z. (2024). Global methane emissions from rice paddies: CH4MOD model development and application. *iScience*, 27(11), Article 111237. <https://doi.org/10.1016/j.isci.2024.111237>
- Huang, W., Liu, X., Deng, Y., Zhao, D., Yuan, J., Shen, Q., & Xue, C. (2026). Mineral nitrogen input modulates the methane mitigation potential of biochar in rice systems: Based on meta-analysis and field experiment demonstration. *Biochar*, 8(1), Article 60. <https://doi.org/10.1007/s42773-025-00563-y>
- Intergovernmental Panel on Climate Change. (2019). *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: Volume 4. Agriculture, forestry and other land use*. <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html>
- Islam, S. M. M., Gaihre, Y. K., Biswas, J. C., Singh, U., Ahmed, M. N., Sanabria, J., & Saleque, M. A. (2018). Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea deep placement and alternate wetting and drying irrigation. *Scientific Reports*, 8(1), Article 17623. <https://doi.org/10.1038/s41598-018-35939-7>
- Itoh, M., Sudo, S., Mori, S., Saito, H., Yoshida, T., Shiratori, Y., Suga, S., Yoshikawa, N., Suzue, Y., Mizukami, H., Mochida, T., & Yagi, K. (2011). Mitigation of methane emissions from paddy fields by prolonging midseason drainage. *Agriculture, Ecosystems & Environment*, 141(3–4), 359–372. <https://doi.org/10.1016/j.agee.2011.03.019>
- Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry*, 101, 251–258. <https://doi.org/10.1016/j.soilbio.2016.07.021>
- Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., van Groenigen, K. J., & Linquist, B. (2019). Water management to mitigate the global warming potential of rice systems: A global meta-analysis. *Field Crops Research*, 234, 47–54. <https://doi.org/10.1016/j.fcr.2019.02.010>
- Jiang, Y., Qian, H., Huang, S., Zhang, X., Wang, L., Zhang, L., Shen, M., Xiao, X., Chen, F., Zhang, H., Lu, C., Li, C., Zhang, J., Deng, A., van Groenigen, K. J., & Zhang, W. (2019). Acclimation of methane emissions from rice paddy fields to straw addition. *Science Advances*, 5(1), Article eaau9038. <https://doi.org/10.1126/sciadv.aau9038>
- Jiang, Y., van Groenigen, K. J., Huang, S., Hungate, B. A., van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., Wang, L., Chen, J., Hang, X., Zhang, Y., Horwath, W. R., Ye, R., Linquist, B. A., Song, Z., Zheng, C., Deng, A., & Zhang, W. (2017). Higher yields and lower methane emissions with new rice cultivars. *Global Change Biology*, 23(11), 4728–4738. <https://doi.org/10.1111/gcb.13737>
- Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., & Schloter, M. (2010). Biogeochemistry of paddy soils. *Geoderma*, 157(1–2), 1–14. <https://doi.org/10.1016/j.geoderma.2010.03.009>
- Koyama, S., Katagiri, T., Minamikawa, K., Kato, M., & Hayashi, H. (2016). Effects of rice husk charcoal application on rice yield, methane emission, and soil carbon sequestration in Andosol paddy soil. *Japan Agricultural Research Quarterly*, 50(4), 319–327. <https://doi.org/10.6090/jarq.50.319>
- Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J., Adhya, T. K., Loecke, T., Esteves, T., Balireddygar, S., Dava, O., Ram, K., Abhilash, S. R., Madasamy, M., Dokka, R. V., Anandaraj, D., Athiyaman, D., Reddy, M., Ahuja, R., & Hamburg, S. P. (2018). High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. *Proceedings of the National Academy of Sciences of the United States of America*, 115(39), 9720–9725. <https://doi.org/10.1073/pnas.1809276115>
- Kumar, V., & Ladha, J. K. (2011). Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy*, 111, 297–413. <https://doi.org/10.1016/B978-0-12-387689-8.00001-1>
- Kumar, V., Jat, H. S., Sharma, P. C., Balwinder-Singh, Gathala, M. K., Malik, R. K., Kamboj, B. R., Yadav, A. K., Ladha, J. K., Raman, A., Sharma, D. K., & McDonald, A. (2018). Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agriculture, Ecosystems & Environment*, 252, 132–147. <https://doi.org/10.1016/j.agee.2017.10.006>
- LaHue, G. T., Chaney, R. L., Adviento-Borbe, M. A., & Linquist, B. A. (2016). Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. *Agriculture, Ecosystems & Environment*, 229, 30–39. <https://doi.org/10.1016/j.agee.2016.05.020>
- Lampayan, R. M., Rejesus, R. M., Singleton, G. R., & Bouman, B. A. M. (2015). Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, 170, 95–108. <https://doi.org/10.1016/j.fcr.2014.10.013>
- Li, C., Carrijo, D. R., Nakayama, Y., Linquist, B. A., Green, P. G., & Parikh, S. J. (2019). Impact of alternate wetting and drying irrigation on arsenic uptake and speciation in flooded rice systems. *Agriculture, Ecosystems & Environment*, 272, 188–198. <https://doi.org/10.1016/j.agee.2018.11.009>
- Li, C., Frolking, S., Xiao, X., Moore, B., Boles, S., Qiu, J., Huang, Y., Salas, W., & Sass, R. (2005). Modeling impacts of farming management alternatives on CO₂, CH₄, and N₂O emissions: A case study for water management of rice agriculture of China. *Global Biogeochemical Cycles*, 19(3), Article 2004GB002341. <https://doi.org/10.1029/2004GB002341>
- Li, L., Huang, Z., Mu, Y., Song, S., Zhang, Y., Tao, Y., & Nie, L. (2024). Alternate wetting and drying maintains rice yield and reduces global warming potential: A global meta-analysis. *Field Crops Research*, 318, Article 109603. <https://doi.org/10.1016/j.fcr.2024.109603>

- Li, S., Li, W., Ding, K., Shi, X., Kalkhajeh, Y. K., Wei, Z., Zhang, Z., & Ma, C. (2024). Co-culture of rice and aquatic animals enhances soil organic carbon: A meta-analysis. *Science of the Total Environment*, 955, Article 176819. <https://doi.org/10.1016/j.scitotenv.2024.176819>
- Li, Y., Zhang, L., Li, H., Crippa, M., & Zheng, B. (2025). Co-benefits of water-saving irrigation for mitigating CH₄ emissions from rice cultivation in China: Insights from the past seven decades. *Environmental Science & Technology*, 59(44), 23949–23961. <https://doi.org/10.1021/acs.est.5c06837>
- Liang, R., Zhang, Y., Hu, Q., Li, T., Li, S., Yuan, W., Xu, J., Zhao, Y., Zhang, P., Chen, W., Zhuang, M., Shen, G., & Chen, Z. (2024). Satellite-based monitoring of methane emissions from China's rice hub. *Environmental Science & Technology*, 58(52), 23127–23137. <https://doi.org/10.1021/acs.est.4c09822>
- Liang, X. Q., Li, H., Wang, S. X., Ye, Y. S., Ji, Y. J., Tian, G. M., van Kessel, C., & Linquist, B. A. (2013). Nitrogen management to reduce yield-scaled global warming potential in rice. *Field Crops Research*, 146, 66–74. <https://doi.org/10.1016/j.fcr.2013.03.002>
- Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., & van Groenigen, K. J. (2012). Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135, 10–21. <https://doi.org/10.1016/j.fcr.2012.06.007>
- Linquist, B. A., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., da Rosa, E. F. F., & van Kessel, C. (2015). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, 21(1), 407–417. <https://doi.org/10.1111/gcb.12701>
- Livsey, J., Kätterer, T., Vico, G., Lyon, S. W., Lindborg, R., Scaini, A., Da, C. T., & Manzoni, S. (2019). Do alternative irrigation strategies for rice cultivation decrease water footprints at the cost of long-term soil health? *Environmental Research Letters*, 14(7), Article 074011. <https://doi.org/10.1088/1748-9326/ab2108>
- Loaiza, S., Verchot, L., Valencia, D., Guzmán, P., Amezcuita, N., Garcés, G., Puentes, O., Trujillo, C., Chirinda, N., & Pittelkow, C. M. (2024). Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production. *Agriculture, Ecosystems & Environment*, 360, Article 108787. <https://doi.org/10.1016/j.agee.2023.108787>
- Lynch, J., Cain, M., Pierrehumbert, R., & Allen, M. (2020). Demonstrating GWP*: A means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters*, 15(4), Article 044023. <https://doi.org/10.1088/1748-9326/ab6d7e>
- Ma, J., Ma, E., Xu, H., Yagi, K., & Cai, Z. (2009). Wheat straw management affects CH₄ and N₂O emissions from rice fields. *Soil Biology and Biochemistry*, 41(5), 1022–1028. <https://doi.org/10.1016/j.soilbio.2009.01.024>
- Milne, S., Beaver, S., Baljak, C., Cox, A., & Howden, M. (2024). Carbon farming co-benefits: A review of concepts, policy and potential in Australian landscapes. *The Rangeland Journal*, 46(3), Article RJ24015. <https://doi.org/10.1071/RJ24015>
- Mishra, J. S., Poonia, S. P., Kumar, R., Dubey, R., Kumar, V., Mondal, S., Dwivedi, S. K., Rao, K. K., Kumar, R., Tamta, M., Verma, M., Saurabh, K., Kumar, S., Bhatt, B. P., Malik, R. K., McDonald, A., & Bhaskar, S. (2021). An impact of agronomic practices of sustainable rice-wheat crop intensification on food security, economic adaptability, and environmental mitigation in eastern Indo-Gangetic Plains. *Field Crops Research*, 267, Article 108164. <https://doi.org/10.1016/j.fcr.2021.108164>
- Nalley, L., Linquist, B., Kovacs, K., & Anders, M. (2015). The economic viability of alternative wetting and drying irrigation in Arkansas rice production. *Agronomy Journal*, 107(2), 579–587. <https://doi.org/10.2134/agronj14.0468>
- Nikolaissen, M., Cornulier, T., Hillier, J., Smith, P., Albanito, F., & Nayak, D. (2023). Methane emissions from rice paddies globally: A quantitative statistical review of controlling variables and modelling of emission factors. *Journal of Cleaner Production*, 409, Article 137245. <https://doi.org/10.1016/j.jclepro.2023.137245>
- Nilsson, M., Griggs, D., & Visbeck, M. (2016). Policy: Map the interactions between Sustainable Development Goals. *Nature*, 534(7607), 320–322. <https://doi.org/10.1038/534320a>
- Oldfield, E. E., Eagle, A. J., Rubin, R. L., Rudek, J., Sanderman, J., & Gordon, D. R. (2022). Crediting agricultural soil carbon sequestration. *Science*, 375(6586), 1222–1225. <https://doi.org/10.1126/science.abl7991>
- Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., Weigl, S., Wiesmeier, M., Wolf, A., & Helming, K. (2023). Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation? *Journal of Environmental Management*, 330, Article 117142. <https://doi.org/10.1016/j.jenvman.2022.117142>
- Pearson, K. A., Millar, G. M., Norton, G. J., & Price, A. H. (2018). Alternate wetting and drying in Bangladesh: Water-saving farming practice and the socioeconomic barriers to its adoption. *Food and Energy Security*, 7(4), Article e00149. <https://doi.org/10.1002/fes3.149>
- Pérez-Méndez, N., Echeverría-Progulakis, S., Katayama, N., Amano, T., Smith, P., Cambero-Conejero, G., Mensch, E. L., Karp, D. S., & Martínez-Eixarch, M. (2026). Climate change mitigation in rice farming should account for biodiversity. *Global Change Biology*, 32(2), Article e70754. <https://doi.org/10.1111/gcb.70754>
- Perry, H., Carrijo, D., & Linquist, B. (2022). Single midseason drainage events decrease global warming potential without sacrificing grain yield in flooded rice systems. *Field Crops Research*, 276, Article 108312. <https://doi.org/10.1016/j.fcr.2021.108312>
- Pittelkow, C. M., Adviento-Borbe, M. A., van Kessel, C., Hill, J. E., & Linquist, B. A. (2014). Optimizing rice yields while minimizing yield-scaled global warming potential. *Global Change Biology*, 20(5), 1382–1393. <https://doi.org/10.1111/gcb.12413>
- Qian, H., Zhu, X., Huang, S., Linquist, B., Kuzyakov, Y., Wassmann, R., Minamikawa, K., Martinez-Eixarch, M., Yan, X., Zhou, F., Sander, B. O., Zhang, W., Shang, Z., Zou, J., Zheng, X., Li, G., Liu, Z., Wang, S., Ding, Y., . . . Jiang, Y. (2023). Greenhouse gas emissions and mitigation in rice agriculture. *Nature Reviews Earth & Environment*, 4(10), 716–732. <https://doi.org/10.1038/s43017-023-00482-1>
- Rajendran, S., Park, H., Kim, J., Park, S. J., Shin, D., Lee, J.-H., Song, Y. H., Paek, N.-C., & Kim, C. M. (2024). Methane emission from rice fields: Necessity for molecular approach for mitigation. *Rice Science*, 31(2), 159–178. <https://doi.org/10.1016/j.rsci.2023.10.003>

- Reavis, C. W., Reba, M. L., Shults, D. D., & Runkle, B. R. K. (2023). Assessing the methane mitigation potential of innovative management in US rice production. *Environmental Research Letters*, 18(12), Article 124020. <https://doi.org/10.1088/1748-9326/ad0925>
- Rejesus, R. M., Palis, F. G., Rodriguez, D. G. P., Lampayan, R. M., & Bouman, B. A. M. (2011). Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. *Food Policy*, 36(2), 280–288. <https://doi.org/10.1016/j.foodpol.2010.11.026>
- Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., . . . Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, 27(23), 6025–6058. <https://doi.org/10.1111/gcb.15873>
- Romasanta, R. R., Sander, B. O., Gaihre, Y. K., Alberto, M. C., Gummert, M., Quilty, J., Nguyen, V. H., Castalone, A. G., Balingbing, C., Sandro, J., Correa, T., & Wassmann, R. (2017). How does burning of rice straw affect CH₄ and N₂O emissions? A comparative experiment of different on-field straw management practices. *Agriculture, Ecosystems & Environment*, 239, 143–153. <https://doi.org/10.1016/j.agee.2016.12.042>
- Runkle, B. R. K., Suvočarev, K., Reba, M. L., Reavis, C. W., Smith, S. F., Chiu, Y.-L., & Fong, B. (2019). Methane emission reductions from the alternate wetting and drying of rice fields detected using the eddy covariance method. *Environmental Science & Technology*, 53(2), 671–681. <https://doi.org/10.1021/acs.est.8b05535>
- Sander, B. O., & Wassmann, R. (2014). Common practices for manual greenhouse gas sampling in rice production: A literature study on sampling modalities of the closed chamber method. *Greenhouse Gas Measurement and Management*, 4(1), 1–13. <https://doi.org/10.1080/20430779.2014.892807>
- Sander, B. O., Samson, M., & Buresh, R. J. (2014). Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma*, 235–236, 355–362. <https://doi.org/10.1016/j.geoderma.2014.07.020>
- Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P. A., Regnier, P., Canadell, J. G., Jackson, R. B., Patra, P. K., Bousquet, P., Ciais, P., Dlugokencky, E. J., Lan, X., Allen, G. H., Bastviken, D., Beerling, D. J., Belikov, D. A., Blake, D. R., Castaldi, S., . . . Zhuang, Q. (2025). Global methane budget 2000–2020. *Earth System Science Data*, 17(5), 1873–1958. <https://doi.org/10.5194/essd-17-1873-2025>
- Sheehy, J. E., Peng, S., Dobermann, A., Mitchell, P. L., Ferrer, A., Yang, J., Zou, Y., Zhong, X., & Huang, J. (2004). Fantastic yields in the system of rice intensification: Fact or fallacy? *Field Crops Research*, 88(1), 1–8. <https://doi.org/10.1016/j.fcr.2003.12.006>
- Shyamsundar, P., Springer, N. P., Tallis, H., Polasky, S., Jat, M. L., Sidhu, H. S., Krishnapriya, P. P., Skiba, N., Ginn, W., Ahuja, V., Cummins, J., Datta, I., Dholakia, H. H., Dixon, J., Gerard, B., Gupta, R., Hellmann, J., Jadhav, A., Jat, H. S., . . . Somanathan, R. (2019). Fields on fire: Alternatives to crop residue burning in India. *Science*, 365(6453), 536–538. <https://doi.org/10.1126/science.aaw4085>
- Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M. A., Manning, F. C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., . . . Arneeth, A. (2020). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology*, 26(3), 1532–1575. <https://doi.org/10.1111/gcb.14878>
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 789–813. <https://doi.org/10.1098/rstb.2007.2184>
- Souza, R., Yin, J., & Calabrese, S. (2021). Optimal drainage timing for mitigating methane emissions from rice paddy fields. *Geoderma*, 394, Article 114986. <https://doi.org/10.1016/j.geoderma.2021.114986>
- Stuart, A. M., Pame, A. R. P., Vithoonjit, D., Viriyangkura, L., Pithuncharurnlap, J., Meesang, N., Suksiri, P., Singleton, G. R., & Lampayan, R. M. (2018). The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. *Field Crops Research*, 220, 78–87. <https://doi.org/10.1016/j.fcr.2017.02.005>
- Su, J., Hu, C., Yan, X., Jin, Y., Chen, Z., Guan, Q., Wang, Y., Zhong, D., Jansson, C., Wang, F., Schnürer, A., & Sun, C. (2015). Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. *Nature*, 523(7562), 602–606. <https://doi.org/10.1038/nature14673>
- Thai, V. T., Checco, J., Mitchell, J., Garba, I. I., Akber, M. A., & Abdul Aziz, A. (2026). Producing more rice with fewer emissions: A global meta-analysis. *npj Sustainable Agriculture*, 4, Article 27. <https://doi.org/10.1038/s44264-026-00136-x>
- Tirol-Padre, A., Minamikawa, K., Tokida, T., Wassmann, R., & Yagi, K. (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: A synthesis. *Soil Science and Plant Nutrition*, 64(1), 2–13. <https://doi.org/10.1080/00380768.2017.1409602>
- Tirol-Padre, A., Rai, M., Kumar, V., Gathala, M., Sharma, P. C., Sharma, S., Nagar, R. K., Deshwal, S., Singh, L. K., Jat, H. S., Sharma, D. K., Wassmann, R., & Ladha, J. (2016). Quantifying changes to the global warming potential of rice wheat systems with the adoption of conservation agriculture in northwestern India. *Agriculture, Ecosystems & Environment*, 219, 125–137. <https://doi.org/10.1016/j.agee.2015.12.020>
- United Nations Environment Programme, & Climate and Clean Air Coalition. (2021). Global methane assessment: Benefits and costs of mitigating methane emissions. *United Nations Environment Programme*. <https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions>
- United Nations General Assembly. (2015). Transforming our world: *The 2030 Agenda for Sustainable Development* (A/RES/70/1). <https://sdgs.un.org/2030agenda>
- van Groenigen, K. J., van Kessel, C., & Hungate, B. A. (2013). Increased greenhouse-gas intensity of rice production under future atmospheric conditions. *Nature Climate Change*, 3(3), 288–291. <https://doi.org/10.1038/nclimate1712>

- Verra. (2025). VM0051 improved management in paddy rice production systems (Version 1.0). *Verified Carbon Standard*. <https://verra.org/methodologies/improved-management-in-rice-production-systems>
- Vitali, A., Moretti, B., Bertora, C., Miniotti, E. F., Tenni, D., Romani, M., Facchi, A., Martin, M., Fogliatto, S., Vidotto, F., Celi, L., & Said-Pullicino, D. (2024). The environmental and agronomic benefits and trade-offs linked with the adoption alternate wetting and drying in temperate rice paddies. *Field Crops Research*, 317, Article 109550. <https://doi.org/10.1016/j.fcr.2024.109550>
- Wang, J., Akiyama, H., Yagi, K., & Yan, X. (2018). Controlling variables and emission factors of methane from global rice fields. *Atmospheric Chemistry and Physics*, 18(14), 10419–10431. <https://doi.org/10.5194/acp-18-10419-2018>
- Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8(3), 512–523. <https://doi.org/10.1111/gcbb.12266>
- Wissing, L., Kölbl, A., Schäd, P., Bräuer, T., Cao, Z.-H., & Kögel-Knabner, I. (2014). Organic carbon accumulation on soil mineral surfaces in paddy soils derived from tidal wetlands. *Geoderma*, 228–229, 90–103. <https://doi.org/10.1016/j.geoderma.2013.12.012>
- Woelf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(1), Article 56. <https://doi.org/10.1038/ncomms1053>
- Xie, J., Hu, L., Tang, J., Wu, X., Li, N., Yuan, Y., Yang, H., Zhang, J., Luo, S., & Chen, X. (2011). Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. *Proceedings of the National Academy of Sciences of the United States of America*, 108(50), E1381–E1387. <https://doi.org/10.1073/pnas.1111043108>
- Xuan, T. D., Minh, T. T. N., Rayee, R., Dong, N. D., & Chien, N. X. (2025). Advances in mitigating methane emissions from rice cultivation: Past, present, and future strategies. *Environmental Science and Pollution Research*, 32(34), 20232–20247. <https://doi.org/10.1007/s11356-025-36776-8>
- Yamaguchi, T., Luu, M. T., Minamikawa, K., & Yokoyama, S. (2017). Compatibility of alternate wetting and drying irrigation with local agriculture in An Giang Province, Mekong Delta, Vietnam. *Tropical Agriculture and Development*, 61(3), 117–127. <https://doi.org/10.11248/jsta.61.117>
- 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), Article 2008GB003299. <https://doi.org/10.1029/2008GB003299>
- Yan, X., Yagi, K., Akiyama, H., & Akimoto, H. (2005). Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology*, 11(7), 1131–1141. <https://doi.org/10.1111/j.1365-2486.2005.00976.x>
- Yang, X., Song, Z., Van Zwieten, L., Guo, L., Chen, J., Luo, Z., Wang, Y., Luo, Y., Wang, Z., Wang, W., Wang, J., Wang, Y., Liu, C.-Q., & Wang, H. (2024). Significant accrual of soil organic carbon through long-term rice cultivation in paddy fields in China. *Global Change Biology*, 30(3), Article e17213. <https://doi.org/10.1111/gcb.17213>
- Yin, M., Zhang, X., Li, F., Yan, X., Zhou, X., Ran, Q., Jiang, K., Borch, T., & Fang, L. (2024). Multitask deep learning enabling a synergy for cadmium and methane mitigation with biochar amendments in paddy soils. *Environmental Science & Technology*, 58(3), 1771–1782. <https://doi.org/10.1021/acs.est.3c07568>
- Zeng, Z.-C., Byrne, B., Gong, F.-Y., He, Z., & Lei, L. (2021). Correlation between paddy rice growth and satellite-observed methane column abundance does not imply causation. *Nature Communications*, 12(1), Article 1163. <https://doi.org/10.1038/s41467-021-21434-7>
- Zhang, G., Xiao, X., Dong, J., Xin, F., Zhang, Y., Qin, Y., Doughty, R. B., & Moore, B. (2020). Fingerprint of rice paddies in spatial–temporal dynamics of atmospheric methane concentration in monsoon Asia. *Nature Communications*, 11(1), Article 554. <https://doi.org/10.1038/s41467-019-14155-5>
- Zhang, J., Tian, H., Liang, X.-Z., Canadell, J. G., Ciais, P., Jackson, R. B., Ouyang, Z., Zhang, J., & Pan, S. (2026). Global rice paddy greenhouse gas emissions have doubled over the past six decades driven by area expansion and intensified residue incorporation. *Nature Food*, 7(5), 474–487. <https://doi.org/10.1038/s43016-026-01355-8>
- Zhao, C., Qiu, R., Zhang, T., Luo, Y., & Agathokleous, E. (2024). Effects of alternate wetting and drying irrigation on methane and nitrous oxide emissions from rice fields: A meta-analysis. *Global Change Biology*, 30(12), Article e17581. <https://doi.org/10.1111/gcb.17581>
- Zou, J., Huang, Y., Jiang, J., Zheng, X., & Sass, R. L. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles*, 19(2), Article 2004GB002401. <https://doi.org/10.1029/2004GB002401>

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