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Kwaku Onwona-Hwesofour Asante
asante.kwaku@gmail.com
CSIR–Crops Research Institute
Caleb Ocansey
CSIR–Crops Research Institute
Felix Frimpong
CSIR–Crops Research Institute
Sherrie Wang
Massachusetts Institute of Technology
Eric Owusu Danquah
CSIR–Crops Research Institute
Charles Afriyie Debrah
CSIR–Crops Research Institute
Harry Okyere
CSIR–Crops Research Institute
Clement Oppong Peprah
CSIR–Crops Research Institute
Jeanette Aduhene-Chinbuah
CSIR–Crops Research Institute
Reuben Nutefe Kuavedzi
Agroecology Circularity LBG

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Advancing Tier 2 Methane Flux Measurement in Smallholder Rice Systems: Operational Lessons from Five Agroecological Zones of Ghana

Kwaku Onwona-Hwesofour Asante[a,*], Caleb Melenya Ocansey[ae], Felix Frimpong[a,c], Sherrie Wang[d], Eric Owusu Danquah[a], Charles Afriyie-Debrah[a], Harry Okyere[a], Clement Oppong Peprah[a], Jeanette Aduhene-Chinbuah[a] and Reuben Nutefe Kuavedzi[b]

[a] *CSIR–Crops Research Institute, Fumesua, P.O. Box 3785, Kumasi, Ghana*

[b] *Environmental Quality Division, Agroecology Circularity LBG, P. O. Box KS 13804, Kumasi, Ghana.*

[c] *Department of Plant Resources Development, CSIR–College of Science and Technology, Kumasi, Ghana*

[d] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, United States*

[e] *Department of Soil Science, Institute of Environmental Science, Hungarian University of Agriculture and Life (MATE) Sciences, Gödöllő, Hungary*

** Corresponding author: asante.kwaku@gmail.com*

Abstract

Distributed closed-chamber networks are increasingly used to derive national methane emission factors for rice systems in sub-Saharan Africa. However, methodological guidance emphasizes statistical estimation while overlooking operational failures that can silently disconnect measurements from their plots, operators, instruments, or sampling dates, causing valid emissions to be discarded. Drawing on the establishment phase of a rice methane-monitoring network spanning five agroecological zones in Ghana, we identify twelve evidence-based design requirements for Tier 2 emission-factor development. Of 36 chamber closures evaluated at the first site, only two met all conventional quality criteria; the remaining 34 provided diagnostic evidence. Analyzer over-range represented data censoring rather than instrument failure: 96.9% of 2,836 flagged records from one unit exceeded an empirical clean-data ceiling of approximately 40,000 ppb, despite a nominal 100-ppm instrument range. Excluding the only modeled over-range closure reduced mean flux by 38% (from 20.34 to 12.56 mg CH_4 m^{-2} h^{-1}). Closures with R^2 below 0.5 contributed 20.4% of positive flux, while the broader low-fit class contributed 47.6%, demonstrating that poor fit alone does not establish measurement failure or ebullition. Using analyzer-cavity rather than ambient pressure underestimated flux by approximately 60%. Mid-morning fluxes cannot be treated as emission factors, particularly because one burst-dominated closure contributed 41% of cumulative flux. Water vapor also showed promise for distinguishing genuine zero flux from seal failure. The framework strengthens national inventories, mitigation accounting, and internationally comparable methane reporting under the Paris Agreement. It thereby supports credible national climate action and transparent global assessment of agricultural methane mitigation.

Keywords: closed chamber; methane flux; rice production systems; Tier 2 emission factors; greenhouse gas inventories

Introduction

Methane emissions from rice cultivation enter national greenhouse gas inventories as a baseline daily emission factor adjusted for water regime, pre-season conditions, and organic amendments (IPCC, 2006, 2019). Tier 1 inventories rely on default values derived largely from irrigated Asian systems. Tier 2 inventories require country-specific factors, and the 2019 Refinement encourages field measurements stratified by agroecological zone and water regime (IPCC, 2019). Such factors remain scarce across sub-Saharan Africa. Ghana therefore relies on defaults for national reporting and mitigation planning, including rice water-management activities implemented against an unmeasured baseline.

Because field measurements are costly and logistically demanding, national estimates often depend on inventory defaults or empirical models fitted to published studies. Nikolaisen et al. (2023), for example, used a generalized additive model and a global compilation of field measurements to identify soil texture, water regime, and organic amendment as major controls of paddy methane emissions. Their analysis also showed that dry-season rainfed and saturated fields emitted 70% and 56%, respectively, of the emissions from continuously flooded paddies. Country-level baselines can represent such differences only when pre-season and in-season water regimes are characterized where the factor will be applied. This is fundamentally a measurement requirement.

Developing Tier 2 factors for smallholder systems requires manual closed chambers deployed across agroecological zones, instruments, field teams, and farmer-managed plots. The statistical behavior of closed chambers under controlled conditions is well established. Headspace accumulation reduces the concentration gradient and can cause linear models to underestimate flux, whereas non-steady-state formulations can reduce this bias (Hutchinson & Mosier, 1981; Livingston et al., 2006; Pedersen et al., 2010; Venterea, 2010; Hüppi et al., 2018). Chamber design, enclosure duration, venting, detection limits, analytical uncertainty, and sampling time also affect the resulting estimates (Conen & Smith, 1998; Rochette & Eriksen-Hamel, 2008; Levy et al., 2011; Parkin et al., 2012; Minamikawa et al., 2012, 2015; Sander & Wassmann, 2014; Kandel et al., 2016).

The Integrated Carbon Observation System chamber protocol provides an important operational standard (Pavelka et al., 2018). It specifies collar equilibration, vent design, headspace mixing, measurement of ambient pressure and chamber temperature, retention of raw data, unique collar and chamber identifiers, and comparison of linear and nonlinear flux models. However, it was not designed for flooded tropical smallholder systems. The protocol specifies a methane analyzer range of at least 0-10 ppm, whereas concentrations in this study reached 288.6 ppm and the analyzers ceased returning diagnostically clean records near 40 ppm. It also does not fully address routine analyzer saturation, ebullition-dominated transport, or the need to bind each measurement to a farmer-managed field.

These differences have direct analytical consequences. A correctly fitted flux is unusable if it is assigned to the wrong farmer or field. Removing every poorly fitted closure can eliminate genuine ebullitive emissions. Analyzer saturation identifies a high-emitting closure rather than an instrument fault. Substituting analyzer cavity pressure for ambient pressure reduces the calculated flux by approximately 60% while allowing the result to pass ordinary internal checks.

We therefore specify twelve operational requirements for networks designed to produce Tier 2 rice methane emission factors and provide the diagnostic evidence for each requirement. Six requirements extend established practice, and six address conditions not covered by existing standards. The evidence comes from the network establishment phase. At the first site to begin routine measurements, only two of 36 closures met all conventional quality criteria without qualification. The other 34 closures revealed failures that an establishment phase should detect before calculating national emission factors.

We do not report emission factors. Instead, we identify the measurements, corrections, and quality controls still needed before defensible zonal and national factors can be derived.

Materials and Methods

Study Sites

Five sites span Ghana's principal rice agro-ecologies: Navrongo (Sudan Savannah), Tamale (Guinea Savannah), Kintampo (Forest–Savannah Transition), Donaso (Semi-Deciduous Forest) and Dawhenya (Coastal Savannah) (Fig. 1). The agro-ecological zone is the stratifying factor and the unit at which factors are to be reported. Each site includes fifteen participating farmer fields: eight instrumented for both methane and water level, and seven for water level alone. Each field carries three replicate plots, giving 225 water-level observation tubes nationally and 120 methane collars. A trained community farmer reads water level weekly; institute enumerators measure methane fortnightly, yielding 24 deployments per regional campaign, 120 nationally, and a design total of 960 deployments across a 16-week season.

Sites are farmer-managed. Participants retain agronomic control, and the measurement team does not administer water management at observation plots, which is appropriate for characterizing emissions under prevailing practice but has consequences addressed under Readiness. Evidence reported here is from Donaso, the first site to begin routine measurement, for campaigns in Weeks 1 and 2 (27 August and 4 September 2026); the second campaign re-measured the four farmers whose Week 1 chambers had been served by the second analyzer, giving 24 and 12 deployments, respectively. Detailed site characterization accompanies the emission factor report, not this specification.

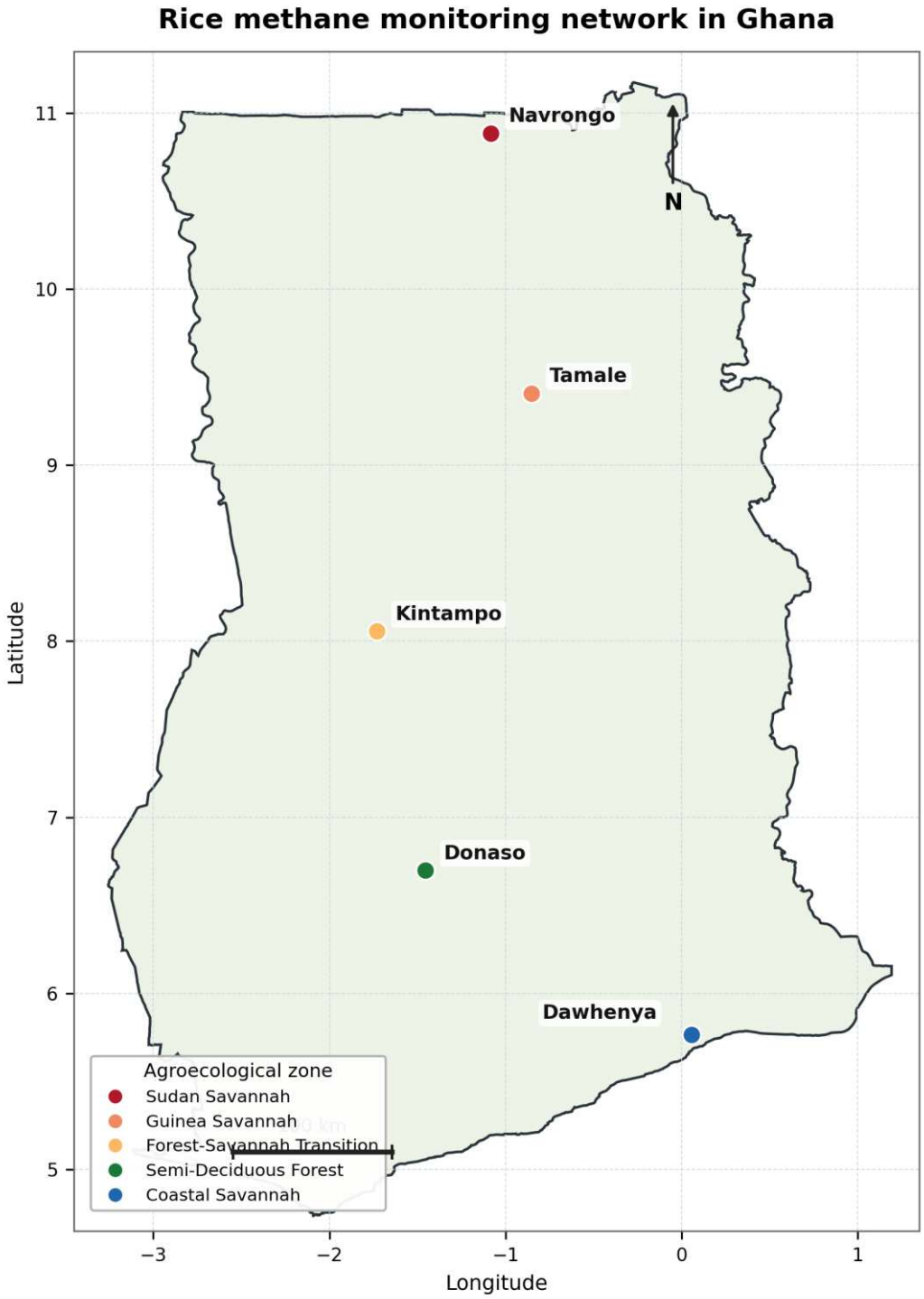


Fig. 1. A Map of Ghana showing the distribution of the five rice methane-monitoring sites across Ghanaian agroecological zones.

Chamber Design

Two chamber heights share a 59 × 41.5 cm footprint, enclosing 0.24485 m² and six rice hills at 24.5 hills m^{-2}, equivalent to 20.2 × 20.2 cm spacing. Because the footprint is common, area, hill count, and hill density are identical between configurations, and only headspace volume differs (Table 1). Chambers carry an internal mixing fan on an external battery and a pressure-equalization vent tube dimensioned to hold the headspace at ambient pressure during deployment (Xu et al., 2006), and are exchanged when the canopy reaches two-thirds of chamber height, based on growth stage rather than date, so that the volume step is not confounded with site.

Table 1. *Chamber specification and derived measurement properties.*

Property	Short chamber	Tall chamber
Height	60 cm	109 cm
Headspace volume	0.146910 m³	0.266887 m³
Volume ratio	1.000	1.817
Flux per ppb min⁻¹	0.02314 mg m⁻² h⁻¹	0.04204 mg m⁻² h⁻¹
Maximum flux quantifiable in a 4-minute closure	220 mg m⁻² h⁻¹	399 mg m⁻² h⁻¹
Detection limit, 2 × slope standard error: median (10th–90th percentile)	0.57 (0.015–5.9) mg m⁻² h⁻¹	1.04 (0.026–10.7) mg m⁻² h⁻¹, projected

The maximum quantifiable flux assumes linear accumulation from an ambient 2,000 ppb to the 40,000 ppb clean ceiling over the full 240-second window, at 30 °C and 101.0 kPa. The detection limit is twice the slope standard error across the 25 fitted closures, converted by the configuration factor; standard errors from ordinary least squares at 1 Hz are optimistic because residuals are autocorrelated, and a limit derived from analytical precision (Parkin et al., 2012) is the more conservative design quantity. No tall-chamber deployment has been made yet, so these values are projections. The taller configuration buys 1.8 times the dynamic range at the top of the distribution and costs 1.8 times at the bottom. For the fastest-rising closure observed, which exceeded the clean ceiling 28 seconds after its logged start, a constant accumulation rate would have extended that interval to about 51 seconds in the tall chamber, which is useful but not sufficient, so the ceiling protocol of Requirement 3 applies to both configurations.

Gas Analysis and Chamber Closure

Methane, carbon dioxide and water vapor are measured with two off-axis cavity-enhanced absorption analyzers (LI-7810, LI-COR Biosciences), logging at 1 Hz. Static chamber designs differ appreciably in their methane performance (Pihlatie et al., 2013), so the specification below is stated in full. Background methane, taken as the 5th percentile of diagnostically clean records, was 2,023 to 2,045 ppb. The gas path is non-recirculating: analyzer exhaust vents to atmosphere, and make-up air enters through the vent tube, which, over a four-minute closure, dilutes the accumulation slope by 0.34 percent; no correction is applied. Closures run for four minutes or until headspace methane reaches 35,000 ppb, whichever comes first. Both values are operational choices of this program rather than standards. Four minutes yields 241 observations at 1 Hz, limits exposure to saturation, and holds the dilution term well below 1 percent. The 35,000 ppb lift threshold lies below the lowest clean maximum recorded on either analyzer, 36,194 ppb, leaving margin for display lag and for concentration to continue rising while the chamber is lifted. Flux estimates are nevertheless window-dependent: refitting the twelve emitting closures on a 120-second window gives values a median 1.25 times those from 240 seconds, partly because the early segment carries placement disturbance, so window sensitivity is reported rather than assumed away. All closures fall between 09:00 and 12:30 local time, and each farmer is measured at approximately the same hour in every campaign.

Venting between chambers is mandatory: the chamber is held open to ambient for 60 to 90 seconds with the fan running and methane confirmed below 3,000 ppb before the next closure begins. The criterion and duration are program-specific: 3,000 ppb sits about 1,000 ppb above background, and 60 to 90 seconds is an operational estimate to be checked against observed decay times. The sequence is chamber one, vent, chamber two, vent, chamber three, vent, next farmer, at 7.5 minutes per chamber and 23 minutes per farmer. Two analyzers run in parallel on whole farmer blocks.

Ancillary Measurements

Floodwater chemistry is recorded per collar: electrical conductivity, total dissolved solids, temperature, pH, and oxidation–reduction potential, with a computed ratio of total dissolved solids to conductivity as a standing check expected between 0.5 and 0.7. Because standing water is frequently absent under alternate wetting and drying, 45.6% of readings across the sites recording water level to date, after correction of three copied entries, and 76.3% at Navrongo, a three-tier medium rule governs what is sampled: floodwater where water level is at or above the surface, water standing in the observation tube between 0 and 15 cm, and no aqueous sample below that. The medium is recorded as a factor, and tiers are never pooled, since tube porewater carries more solutes and pooling would generate an artifactual conductivity rise every time a field dried.

Soil redox electrodes were not available. Water-filled pore space, computed from calibrated probe moisture and measured bulk density, serves as the aeration variable. The two available aeration measures are complementary rather than redundant: water-filled pore space discriminates on the dry side but saturates once the soil is flooded, while water level resolves the wet side but is left-censored at −15 cm, where 22 percent of all readings and 45 percent of Navrongo readings sit.

Ambient barometric pressure is recorded once per site per day, in kPa, with the reading time.

Flux Calculation

Flux is computed as

$$F = (dC/dt) \cdot (V / A) \cdot (P / RT) \cdot M \qquad (1)$$

where V is the configuration-specific headspace volume, A = 0.24485 m², P is the measured ambient pressure, and T is the chamber air temperature. R is the universal gas constant, and M is the molar mass of methane. The right-hand side also includes constants that convert an accumulation rate expressed in ppb min^{-1} to a flux in mg CH_4 m^{-2} h^{-1}, as set out in Appendix A. We compute and retain three slope estimators for each closure: ordinary least squares over the full closure, ordinary least squares after a 30 s deadband excluding the initial mixing transient, and a quadratic non-steady-state fit evaluated at closure. Retaining all three shows how sensitive a reported value is to the estimator, rather than assuming it. Values reported in this paper are from full-window ordinary least squares; the window runs from the logged start to 240 seconds after it, inclusive of both endpoints, so a complete record contains 241 observations. We computed them with a placeholder pressure of 101.0 kPa and, in the processing run reported here, with soil temperature in place of chamber air temperature. Recomputing with measured site pressure and the mean of start and end chamber air temperatures would shift them by a few percent; the temperature correction alone lowers the mean by 1.4 percent, without altering any conclusion.

Data Architecture and Integration into Zone Emission Factors

Converting defensible chamber fluxes into a Tier 2 zone factor requires a further chain, specified here because it determines what the measurement system must deliver. Five estimands must be kept distinct: instantaneous chamber flux; diel-adjusted daily flux; collar-season cumulative emission; stratum or zone emission factor; and national inventory factor. Only the last two are comparable with IPCC factors, and every chamber value reported in this paper belongs to the first.

Records are held at five levels (Fig. 2): raw 1 Hz analyzer files retained unmodified; quality-flagged records with the diagnostic field decoded and every exclusion carrying a reason code; per-chamber flux with diagnostics and all three slope estimators; collar-season cumulative emission; and zone emission factors. Levels join on a deployment key encoding site, week, farmer, and chamber, assigned at field recording.

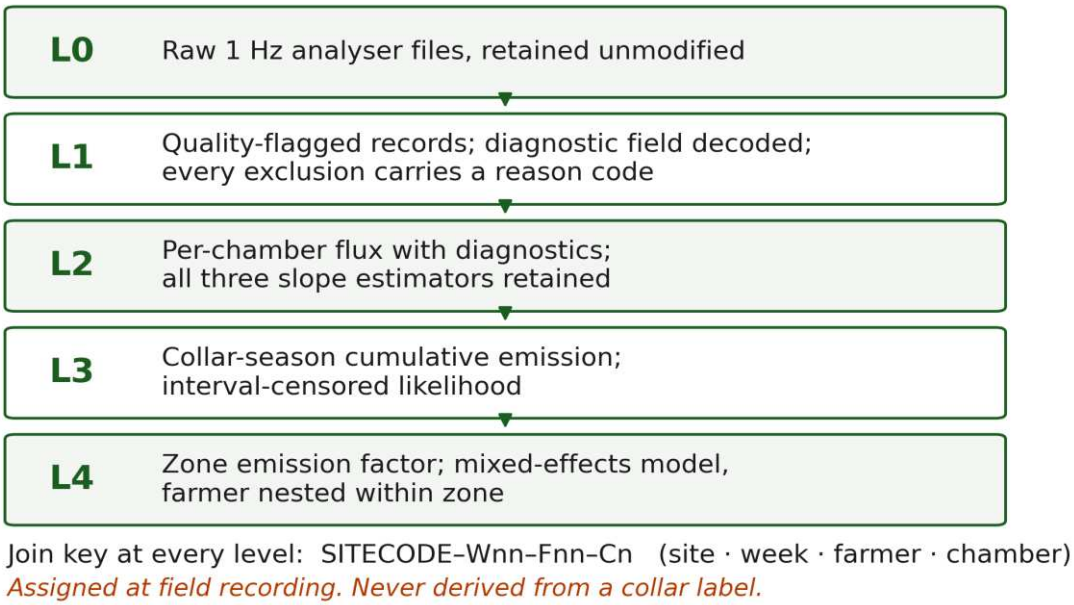


Fig. 2. Five-level data architecture. Retaining raw files unmodified, recording a reason code against every exclusion, and preserving all three slope estimators together allow a reported value to be traced to its raw record and its sensitivity to each analytical judgment to be demonstrated.

Seasonal emission for a collar is the trapezoidal integral of campaign fluxes from transplanting to harvest. Because all closures fall between 09:00 and 12:30 while an emission factor is a 24-hour quantity, we apply a zone- and stage-specific diel ratio before integration, and we propagate its uncertainty into the factor. The 09:00 to 12:30 window is not arbitrary: mid-morning sampling is widely held to approximate the daily mean and is recommended on that basis (Darenova et al., 2014; Pavelka et al., 2018). In an irrigated Japanese paddy, weekly single measurements between 10:00 and 11:59 reproduced 93 to 106 percent of automated-chamber emissions (Minamikawa et al., 2012), but reversed, night-peaking diel patterns have been reported on most reproductive-stage days elsewhere (Li et al., 2024), and much of the general evidence comes from soil respiration and aerobic systems. In flooded rice, the diel signal is carried disproportionately by ebullition: Kajiura and Tokida (2024) report a maximum-to-minimum flux ratio of 3.5 for the bubbling component versus 1.4 for the plant-mediated component, with hysteresis against temperature and a pattern that is stage- and season-dependent. The window is therefore defensible as a starting assumption and insufficient as a basis for a national factor. Minamikawa et al. (2012) directly address the choice of sampling frequency and time of day for manual chambers and remain the appropriate reference for protocol design. One 24-hour campaign per zone per season, at mid-tillering and again at heading, supplies the ratio.

A closure that reaches the ceiling after enough in-range records is fitted on its pre-saturation segment and is an observed, window-truncated flux. Only a closure that saturates before a minimum fit length is censored; because only a lower bound on its flux is known, it is right-censored, and it enters the seasonal model through a censored (Tobit-type) likelihood so that it contributes its bound rather than being deleted or replaced. The bound must rest on steady accumulation: a closure whose saturation is driven by placement disturbance is a failed deployment, not a censored observation. Where non-detects are also treated as censored below the detection limit, the likelihood carries left-censored observations as well. Zone factors are obtained from a mixed-effects model with farmers nested within zones rather than by averaging collars directly, since the nesting is unbalanced and collar-level averaging would weight zones by the number of chambers that happened to return data. The response is collar-season emissions, with a log-normal or gamma family; random intercepts for farmer within zone and collars as replicates within farmer; zone as a fixed effect; equal collar weights unless collar losses are uneven; and uncertainty obtained via parametric bootstrap.

The resulting factor is expressed per unit area per season and, where yield and biomass are collected, per unit of production. Both forms are required: the areal factor supports inventory reporting, while the production-normalized factor is what a mitigation intervention is ultimately assessed against.

Use of AI Assisted Tools

Claude Opus 5 supported exploratory analysis, figure generation from the authors' dataset, reference verification against publisher records, and early drafting. The authors reviewed and verified all text, data, analyses, and figures and take full responsibility for the article. The tool is not listed as an author.

Results and Discussion

The establishment phase yielded twelve operational requirements. Each requirement is presented as a rule followed by the observation that motivated it. Figure 3 summarizes the outcomes of the 36 closures. We distinguish among the observed failure, its mechanistic interpretation, the operational response, and the likely transferability of that response because these statements carry different levels of certainty.

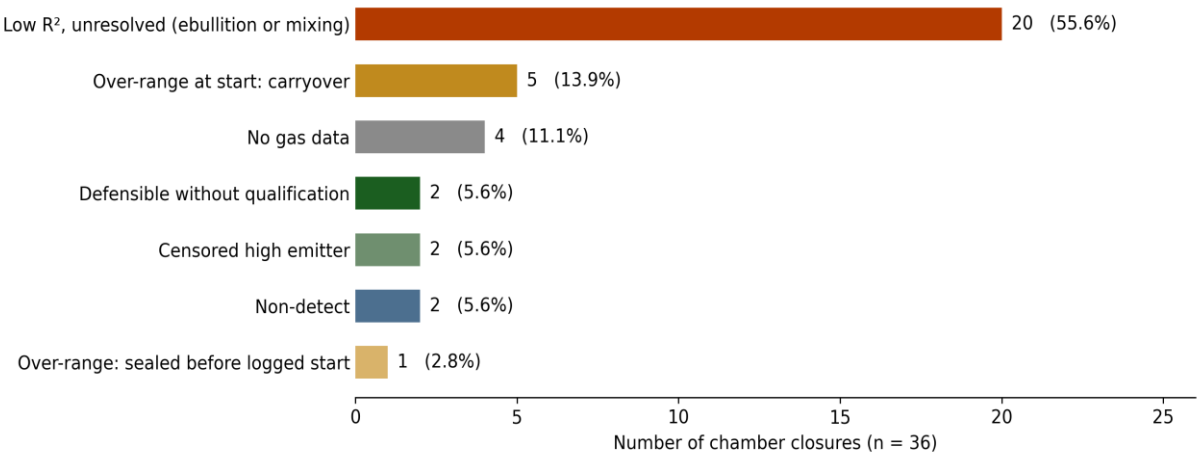


Fig. 3. Outcome of 36 chamber closures at Donaso, campaigns 1 and 2, graded by the standardized four-minute processing run. Two closures met conventional quality criteria without qualification.

Twenty-five closures yielded a numerical flux, spanning −7.55 to 207.05 mg CH_4 m^{-2} h^{-1} with a median of 0.76 and an arithmetic mean of 20.34. Eight of the twenty-five were negative. A conventional screen —adequate goodness of fit, no flagged records, non-negative flux—leaves nine closures of the thirty-six, of which only two carry no qualification at all. The set reconciles as follows: 36 closures attempted; 4 returned no gas data, leaving 32 with records; of these, 7 could not be fitted, leaving 25 with a numerical flux. The 25 comprise 2 graded defensible, 20 graded low goodness of fit, 2 non-detect, and 1 censored high emitter with sufficient in-range records to support a fit. That single censored closure supplies 41 percent of the summed flux of all 25 and alone accounts for the difference between the arithmetic mean and the screened mean reported below. Its trace is a series of discrete steps beginning about 70 seconds after the logged start, on a collar recorded as fully drained, and statistics that depend on it are reported with and without it.

Measured Flux Distribution and Tier 1 Scale Diagnostic

The IPCC Tier 1 baseline daily emission factor for continuously flooded rice without organic amendment is 1.3 kg CH_4 ha^{-1} day^{-1} in the 2006 Guidelines, equal to 5.42 mg CH_4 m^{-2} h^{-1}. The 2019 Refinement revised the global baseline to 1.19 kg CH_4 ha^{-1} day^{-1}, equal to 4.96 mg CH_4 m^{-2} h^{-1}. Both refer to continuously flooded fields. The Donaso fields are managed under alternate wetting and drying, for which the regime-matched Tier 1 value is the 2019 baseline for Africa, 1.19 kg CH_4 ha^{-1} day^{-1},

multiplied by the scaling factor for multiple drainage, 0.55 (95 percent range 0.41 to 0.72): 0.65 kg CH_4 ha^{-1} day^{-1}, equivalent to a daily-mean flux of 2.73 mg CH_4 m^{-2} h^{-1} (2.03 to 3.57) (IPCC, 2019). Fig. 4 places the measured closures against these values for scale only. This comparison is not an emission-factor comparison: the IPCC values are daily factors for a cultivation period, whereas the measured values are instantaneous mid-morning fluxes from one site on two dates, unadjusted for diel variation or seasonal integration.

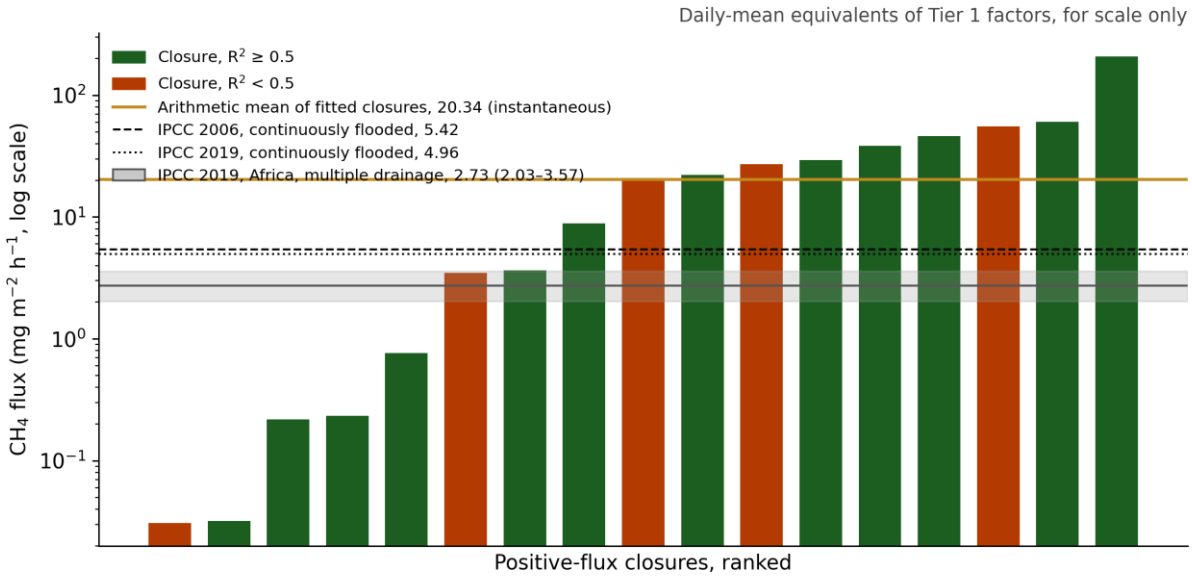


Fig. 4. Positive-flux closures ranked against the daily-mean equivalents of IPCC Tier 1 factors, shown for scale only. Bars are individual closures, colored by goodness of fit. The instantaneous fluxes are not emission factors and are not directly comparable with the Tier 1 values.

Two features of the distribution matter. The arithmetic mean of the fitted closures is 20.34 mg CH_4 m^{-2} h^{-1} (bootstrap 95 percent interval 7.0 to 39.7) and the median 0.76 mg CH_4 m^{-2} h^{-1} (−0.06 to 22.1). The distribution is extremely right-skewed, and one closure supplies 41 percent of the summed flux; without it the mean is 12.56.

An emission factor is an areal quantity. The arithmetic mean of equal-footprint chambers estimates the instantaneous areal mean flux of the sampled population, and it becomes an emission factor only after diel adjustment, seasonal integration, and area weighting by stratum. Summaries that discard part of the distribution do not estimate that quantity: the geometric mean, for example, is defined only for the 17 positive closures and excludes the eight negative fluxes by construction.

This bears on screening. The closures that carry the upper tail of the distribution are those that conventional screening removes: the saturating high emitters and the stepped traces. A program that screens conventionally will obtain a lower mean and may conclude that a default is adequate for its system when the agreement is an artifact of the screening rather than a finding about the rice production system.

The implication extends beyond any single program. Both the IPCC defaults and the empirical models now being fitted to rice methane data, of which Nikolaisen et al. (2023) is the most comprehensive recent instance, are assembled from the published chamber literature. Where that literature has applied the screening conventions examined here, any resulting default or fitted model inherits the same truncation. We do not assert that it has. Establishing whether published studies retained saturating and ebullitive closures would require a systematic review of their quality-control statements, which is beyond this paper and which we recommend as a priority. We note only that the question is answerable, that it bears on the adequacy of the values national inventories currently use, and that the present dataset gives reason to ask it.

These figures are from one site over two campaigns, with no diel correction applied and only mid-morning sampling. They are not emission factors and must not be cited as such. They are sufficient to show that the question is open.

Identity and Attribution

Requirement 1. Bind every record to its participant through a verified crosswalk, established at installation and enforced in code. Never derive a participant from a collar label.

Collars are labeled in the methane sequence at installation; participants carry identifiers from enrolment. At Donaso, the sequences agree for five of eight farmers and diverge thereafter: Farmer 8 owns the collars labeled F6, Farmer 9 owns F7, Farmer 11 owns F8. A join on apparent numeric correspondence succeeds for every row, is correct for five farmers and wrong for three, and raises no error.

Partial correctness is the dangerous case. Site-level summaries are barely affected, internal consistency checks pass, and the fault surfaces only when a flux is compared against the water management history of the plot it supposedly describes — which is the comparison from which a water regime scaling factor is derived. Deployment sheets are therefore pre-printed with the verified key so that no identifier is constructed by hand in the field.

Requirement 2. Write the analyzer serial on every row at the moment of closure, read from the instrument face. Verify attribution empirically from the gas trace before analysis.

Two analyzers ran in parallel in Week 1, and the recorded attribution was transposed. The error arose from forward-filling a single instrument entry down a farmer block in the office rather than recording the serial per row in the field.

The gas traces revealed the transposition, as they carry instrument identity independently of what the log asserts. Three lines of evidence agreed: analyzer warm-up timing, which establishes when each unit entered service; alignment of the sequence of accumulation peaks against the physical route order; and an orphaned closure event present in one trace with no counterpart in the log for the unit to which it was attributed, but matching the other unit's route exactly. An undetected transposition applies instrument-specific corrections to the wrong records and introduces a spurious between-unit difference that can be mistaken for a site or treatment effect. The workbook retains logged and verified identifiers as separate columns, the first for audit and the second for analysis.

Upper Tail Censoring Rather Than Exclusion

Requirement 3. Treat analyzer over-range as a censoring condition. Lift the chamber at 35,000 ppb, annotate the time, and fit the closure on its pre-saturation segment where enough in-range records exist; otherwise retain it as right-censored with a known lower bound.

Requirement 4. Carry censored closures into the seasonal model through a censored (Tobit-type) likelihood. Never delete them and never substitute the censoring value.

One analyzer accumulated a large number of diagnostically flagged records in Week 1 and was quarantined on the assumption of a hardware fault. Of its 2,836 flagged records, 96.9 percent (2,748) were above 40,000 ppb rather than distributed across the measurement range, as a fault would produce. The unit correctly reported that headspace concentration exceeded the range it quantifies to specification, and the quarantine was reversed.

The concentrations are substantial. Over-range readings across the 36 closures reached 288,613 ppb, a factor of 7.2 above the ceiling of the diagnostically clean range (Fig. 5). That ceiling is not the nominal measurement range of the instrument, which the manufacturer specifies as 0 to 100 ppm, but the concentration above which these units cease to return diagnostically clean records. It is established empirically rather than assumed: across all raw records from the establishment phase, no record carrying a clean diagnostic flag exceeded 40,093 ppb, while flagged records extended to 288,613 ppb. The transition is a zone rather than a point: the over-range flag first appears near 30,000 ppb, and 99

percent of such records on the affected unit lie above 39,192 ppb. Three quantities must therefore be kept distinct: the manufacturer's nominal range, 0 to 100 ppm; the empirical clean ceiling, near 40,000 ppb; and the operational lift threshold, 35,000 ppb. Eight of the 32 closure-return records contained over-range records within the window. Six were over range from the first record, five were loaded by an unvented preceding closure, and one was sealed three minutes before its logged start, and two reached the ceiling during the closure, at 28 and 108 seconds. Seven of the eight left too few in-range records to support a fit.

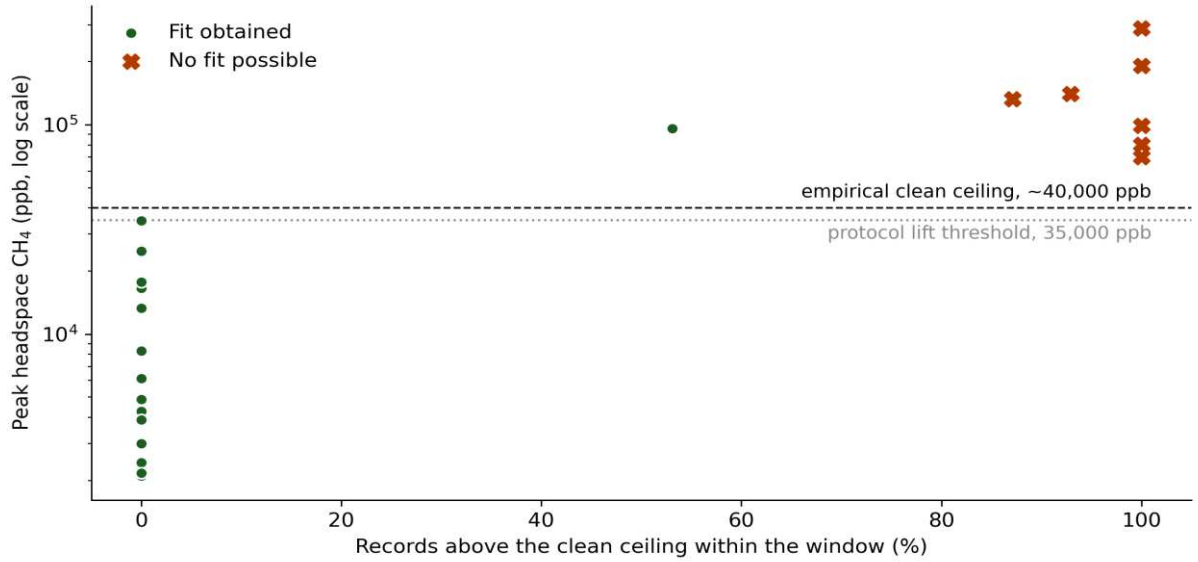


Fig. 5. Censoring structure across the closures returning records. Over-range readings reached 288,613 ppb, 7.2 times the empirically determined ceiling of the diagnostically clean range (40,093 ppb). Seven closures could not be fitted because too few records remained in range. The protocol lift threshold at 35,000 ppb converts an unusable saturated trace into a censored observation with a known lower bound.

Two cases must be separated. Over-range at the start of a closure usually indicates headspace already loaded when the chamber was sealed, a carryover artifact of the previous closure and not a property of the plot; these are excluded, but only after confirming that the same analyzer recorded elevated methane during the preceding vent interval, because one such closure proved instead to have been sealed three minutes before its logged start. Over-range reached during a closure indicates a genuine high emitter whose accumulation exceeded the range within the deployment; we retain these as right-censored observations.

Conflating them has a large, unidirectional effect. Excluding the one fitted closure that contains over-range records lowers the estimated mean flux by 38 percent, from 20.34 to 12.56 mg CH_4 m^{-2} h^{-1} (Fig. 6a). Under continuous flooding, these are the chambers that carry the areal mean, so excluding them discards precisely the emission that a baseline exists to capture. Each zone factor is reported under three treatments of censored closures (censored likelihood, censored values set at their lower bound, and censored closures excluded) together with the censored fraction, and is reported as a lower bound only if the censored-likelihood estimate is not identified or the first two treatments differ by more than the sampling uncertainty of the factor.

Transport Pathways Rather Than Measurement Failure

Requirement 5. Retain closures with low goodness of fit. Test magnitude against the detection limit before grading by goodness of fit, and attribute ebullition, a real transport pathway, only from discrete steps in the trace or from the field record; low goodness of fit alone also arises from incomplete mixing and from the absence of signal.

Requirement 6. Place chambers slowly and vertically. Annotate ebullition provoked by placement separately; it is not diffusive flux.

Twenty of the 36 closures (55.6 percent) were graded low goodness of fit, meaning a statistically significant slope with a coefficient of determination below 0.90. Methane leaves a flooded paddy by diffusion through the water layer, by plant-mediated transport through the aerenchyma, and by ebullition; bubble release produces a stepped, poorly linear pattern (Kajiura & Tokida, 2024; Komiya et al., 2015). In this dataset, coefficients of determination as low as 0.03 accompanied fluxes as high as 55.5 mg CH_4 m^{-2} h^{-1}. The class is heterogeneous. Four members have fluxes below 0.2 mg CH_4 m^{-2} h^{-1}, where a low coefficient of determination reflects the absence of signal, since a flat trace has a coefficient near zero by construction. A simple detector for discrete steps, counting one-second increments that exceed both ten times the robust noise level and 10 percent of the closure's range, finds none in either defensible closure and at least one in 7 of the 12 low-goodness-of-fit closures whose range exceeds 500 ppb. The detector is untuned and is reported as a preliminary attribution method, not a validated classifier.

The ebullitive share of total emission is large and varies strongly with growth stage. Komiya et al. (2015) attributed 95 to 97 percent of daily methane emission to bubbling, measured on the water surface between plant rows in a tropical paddy, so that plant-mediated transport was excluded by design; the figure is not a whole-system share. Kajiura and Tokida (2024) found ebullition accounted for 43 to 70 percent of total emissions at heading in a Japanese paddy, with a minor contribution at panicle formation. Reported diffusive shares elsewhere are far higher, so the quantity is evidently system-specific; ebullition can dominate.

Routine rejection on goodness of fit therefore removes a real and potentially dominant transport pathway. In this dataset, the nine closures with a coefficient of determination below 0.5 carry 20.4 percent of the measured positive flux, and the full class of twenty carries 47.6 percent (Fig. 6b). Because ebullition is episodic and high in magnitude, its removal biases the seasonal integral downward by an amount that is not estimable from the retained data. Retaining it adds variance and can also introduce bias when bursts are sampled non-randomly in time: ebullition is diurnally structured (Kajiura & Tokida, 2024), so a fixed sampling window can over- or under-represent it, and chamber placement can itself provoke a burst. The design implication is to replicate rather than exclude.

We note that retention is the minimum response, not the best available one. Kajiura and Tokida (2024) describe a partitioning scheme that separates plant-mediated from bubbling emission using high-time-resolution concentration data from closed chambers, identifying the plant-mediated component as the lowest-intensity local maximum in the flux frequency distribution. The scheme requires the 1 Hz record that portable cavity analyzers produce as a by-product, and applying it to networks of this kind is a clear next step rather than a novel proposal. Requirement 5 should therefore be read as a floor: retain these closures at minimum, and partition them where the data permit.

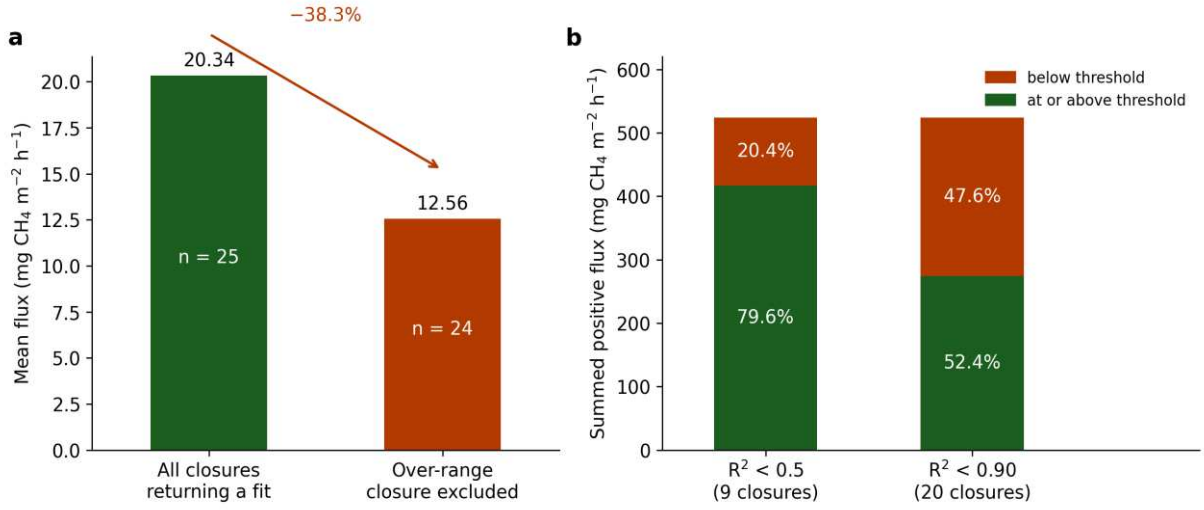


Fig. 6. Effect of conventional screening on the estimated flux. a Excluding the one fitted closure containing over-range records lowers the mean by 38 percent, from 20.34 to 12.56 mg CH_4 m^{-2} h^{-1}. b Closures with a coefficient of

determination below 0.5 carry 20.4 percent of the measured positive flux, and all twenty low-goodness-of-fit closures 47.6 percent; neither class is equivalent to confirmed ebullition.

Two operational distinctions support the interpretation. Ebullition provoked by placement is not diffusive flux and is annotated separately: one closure exceeded the clean ceiling within 28 seconds of its logged start, rising irregularly from 2,120 ppb, a pattern consistent with a placement-induced burst. A shallow drifting slope with low goodness of fit and no steps is the signature of a stationary or absent fan rather than ebullition, so Requirement 7 applies.

Requirement 7. Record fan state as an explicit value on every row. A blank field is not a record.

None of the twenty closures graded as low goodness of fit can be separated into ebullition and fan failure on the field record, because fan state was not recorded for any closure in Weeks 1 and 2. The step detector described above offers a partial substitute, but the flux shares reported above should be read as contributions of goodness-of-fit classes, not of confirmed ebullition. Where the field permits a blank, use a blank; the resulting closures are unrecoverable.

Lower Tail True Zeros and Carryover

Requirement 8. Use the water vapor channel to separate a true zero from a seal failure, fitting the rising portion of the trace rather than the full closure. A flat methane trace accompanied by a rising water vapor signal is a true zero and is retained; flat methane with no water vapor response is a seal failure and is excluded. Where the water vapor signal rises and then flattens within the closure, the plateau is not evidence of a failed seal.

Eight closures returned a negative fitted flux, and two were graded non-detect. This grading conflates three conditions: a genuinely non-emitting chamber, a chamber with a failed seal, and a chamber loaded by carryover whose concentration decayed through the closure.

Six transpiring hills sealed inside a chamber must drive a rising water vapor signal, at least initially, whether or not methane is produced. We applied the test to the raw 1 Hz record for every closure at Donaso, fitting water vapor and carbon dioxide over the same 240-second window used for methane.

The first result is that carbon dioxide cannot serve as the seal test in a chamber enclosing live plants. Of the 25 fitted closures, 14 showed declining carbon dioxide, and seven of those had a coefficient of determination above 0.5. The chambers admit light and the enclosed hills photosynthesize, so carbon dioxide may rise or fall depending on the balance of assimilation and respiration. Water vapor has no such ambiguity: transpiration adds water to the headspace regardless of how carbon dioxide moves. Fig. 7a shows the two channels side by side.

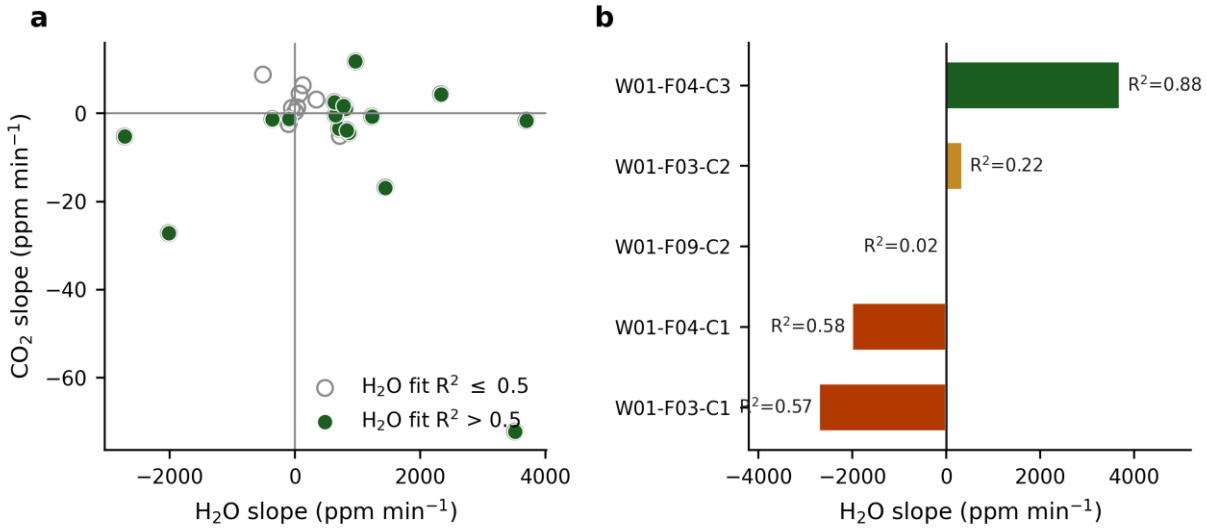


Fig. 7. Partitioning closures that show no methane accumulation. a Carbon dioxide slope against water vapor slope for all fitted closures; carbon dioxide is bidirectional because the enclosed hills photosynthesize, whereas water vapor is predominantly positive. b Water vapor slope for the five closures showing no methane accumulation, with the

coefficient of determination for each fit; green indicates a sealed transpiring headspace, orange a falling signal consistent with carryover of humid air from the preceding closure, gold an indeterminate result.

Applied to the five closures showing no methane accumulation, the test separates three conditions (Fig. 7b); on such a small set, this is a diagnostic demonstration, not a validated classifier. DON-W01-F04-C3 shows water vapor rising at 3,696 ppm min^{-1} with a coefficient of determination of 0.88: the chamber was sealed, and the enclosed plants were transpiring, so a flat methane trace is a true zero and is retained. DON-W01-F09-C2 shows no signal in any channel — water vapor, carbon dioxide, and methane all flat, with coefficients of determination of 0.02, 0.04, and 0.00 — which is the signature of a failed seal and is excluded. DON-W01-F03-C2 is indeterminate, with a weak positive water vapor trend at a coefficient of determination of 0.22.

The test requires one proviso, which the raw record makes explicit. Six transpiring hills enclosed in 0.147 m^3 of headspace raise humidity rapidly within four minutes of closure. At the chamber air temperatures recorded at these deployments, a median of 35 °C at the start of closure and up to 43 °C, the saturation mixing ratio at 101 kPa exceeds 55,000 ppm. The highest value observed within any closure, 44,089 ppm, was 85 percent of saturation at that closure's recorded temperature of 33.8 °C, and no closure exceeded 90 percent. Of the fourteen closures showing a clearly rising water vapor signal over the first half of the closure, ten flattened or reversed over the second. Saturation of the headspace air does not explain that flattening; condensation on chamber surfaces cooler than the air, or declining transpiration as the vapor-pressure deficit collapses, is more likely. Either way, fitting water vapor across the full window would misgrade a sealed chamber whose signal had flattened. Requirement 8 states the rule accordingly: the diagnostic is a rising first portion, not a positive full-window slope, and a plateau following a rising first portion is consistent with enclosure rather than evidence against it.

Applying the rule in that form leaves the true zero at DON-W01-F04-C3 secure, since its water vapor signal rises at 4,294 ppm min^{-1} over the first half and 2,659 ppm min^{-1} over the second. The seal failure at DON-W01-F09-C2 is less secure than the full-window fit implied: its first-half slope is 316 ppm min^{-1}, weak but not zero, and at a peak of 30,622 ppm it had not flattened. We therefore report it as a probable, rather than confirmed, seal failure. The carryover attribution for DON-W01-F03-C1 and DON-W01-F04-C1 is unaffected, because it rests on elevated carbon dioxide at the moment of closure (441 and 468 ppm against a set mean of 420), independent of the water vapor evidence.

The remaining two closures, DON-W01-F03-C1 and DON-W01-F04-C1, show water vapor falling steeply, at −2,716 and −2,012 ppm min^{-1}. Both opened at a water vapor concentration near 42,000 ppm against a set mean of 34,100, and both at the highest starting carbon dioxide concentrations in the set, 441 and 468 ppm against a mean of 420. The chamber was closed on air left over from the preceding closure, and the headspace cleared during the measurement as ambient air entered through the vent. This is carryover, and it is invisible in the methane channel: both closures were graded low goodness of fit by the methane-only pipeline because their methane traces are merely flat.

That is the substantive finding of this requirement. Elevated water vapor and carbon dioxide at the moment of closure indicate carryover that leaves no methane signature, and identifying it costs nothing because both channels are recorded as a by-product. We recommend screening starting water vapor and carbon dioxide concentrations against the session distribution as a routine carryover check, in addition to the venting protocol of Requirement 9.

Retaining true zeros matters for the same reason as retaining censored high emitters: saturation truncates the upper tail of the flux distribution, and discarding true zeros truncates the lower; truncating both tails distorts the shape of the distribution as well as its mean, and neither distortion can be recovered by a correction applied afterward.

Requirement 9. Vent to below 3,000 ppb between every closure. Treat a cleanly fitted negative slope with an elevated opening concentration as carryover unless independent evidence supports net uptake.

Of the eight negative fluxes, three opened at elevated methane, 4,280, 8,126 and 3,091 ppb, and declined through the closure: chambers that began loaded and were cleared during measurement. The steepest, −7.55 mg CH_4 m^{-2} h^{-1} with a coefficient of determination of 0.89, exceeds plausible uptake by one to two orders of magnitude, since net soil uptake of atmospheric methane is typically of order 0.01 to 0.1 mg m^{-2} h^{-1}. The other five opened at ambient concentration, with fluxes of −0.06 to −1.80 mg CH_4 m^{-2} h^{-1}, and are retained as near-zero observations rather than attributed to carryover. Separately, five chambers were lost because the preceding chamber had not been vented, opening at 46,078 to 181,417 ppb.

Computation inputs that are invisible when wrong

Requirement 10. Record ambient barometric pressure per site per day. Never take pressure from the analyzer cavity, and range-check every entry against the instrument's stated operating envelope.

Equation 1 requires ambient pressure at the chamber, and flux scales linearly with it. The analyzer reports a cavity pressure, an internal setpoint near 40 kPa maintained for spectroscopic stability, bearing no relationship to ambient conditions. At the logged setpoint of 40.9 kPa against a true ambient near 99 kPa at these sites, substitution understates every flux by roughly 60 percent. Because the setpoint is constant, the error is constant in proportion, so replicates agree, the series is well behaved, and the entire dataset is simply scaled.

The instrument's own specification supplies the diagnostic. The analyzer is specified to operate over an ambient range of 70 to 110 kPa. Any value in an ambient pressure field falling outside that range cannot be an ambient measurement, and a value near 40 kPa is definitionally the cavity setpoint. A range check therefore detects the substitution with certainty and costs nothing to implement. The diagnostic generalizes to any flux program using an instrument with a published operating envelope.

A second and smaller error follows from using a single national placeholder. Ghana's rice-growing sites lie below approximately 400 m, giving ambient pressures of roughly 96.5 to 101 kPa under the standard atmosphere, before synoptic variation of about ±1 kPa, so a placeholder overstates flux by a few percent in a direction that varies systematically with site elevation and could be mistaken for an agro-ecological gradient.

Requirement 11. Record chamber height on every deployment. Height is not a site property.

The two configurations differ in headspace volume by a factor of 1.817, so a deployment processed with the wrong height overstates the flux by 82 percent where a short chamber is processed as tall, and understates it by 45 percent in the reverse case, with no signature in the data other than an unexplained step between weeks.

Ancillary records and coverage

Requirement 12. Subject ancillary records to structural checks, and confirm before leaving a site that the analyzer file extends past the last logged closure.

Spreadsheet-assembled records fail structurally rather than randomly, producing values that are individually plausible and jointly impossible. Four distinct instances were identified. Adjacent-row copying produced an apparent 26 cm difference between the water-level log and the chamber log for the same observation tube and day, which was a fill applied to the wrong row rather than a drainage event; an automated check now flags any two adjacent farmers sharing an identical water-level triplet. Carry-down produced Week 2 soil temperatures identical to Week 1 across a set of rows. Adjacent-column fill produced two records with conductivity and total dissolved solids both equal to 37,000, the value in the neighboring light-sensor column rather than a floodwater measurement; the standing expectation that conductivity falls between 470 and 1,410 µS cm^{-1} would have caught this at the collar. Forward-filling produced the instrument transposition of Requirement 2.

Coverage is lost at the end of the file rather than the start. Four of the 36 deployments returned no gas data because the analyzer file ended before the last logged closure: one unit stopped at 11:37 with

three chambers remaining, and the other ended at 11:45:00 against a closure logged for 11:45 to 11:55. A thirty-second check that the file extended past the last logged closure would have caught the truncation while the team was still on site; these same four deployments are unrecoverable because the team had dispersed by the time the gap was found.

Replication required for a zonal factor

Because ebullition adds variance, and can add bias where it is sampled non-randomly, the practical question for any adopting program is how many chamber observations a zone factor requires. The establishment-phase set gives a preliminary planning estimate.

Across the 25 fitted closures, the standard deviation is 43.56 mg CH_4 m^{-2} h^{-1} against a mean of 20.34, a coefficient of variation of 2.14. A bootstrap over the observed distribution, which makes no normality assumption, gives the number of chamber observations at which a sample mean lands within a stated tolerance of the full-set mean on 95 percent of draws: about 70 observations for ±50 percent, 185 to 190 for ±30 percent and 420 for ±20 percent, from 10,000 resamples. A normal approximation, $n = (1.96 \times CV / \text{tolerance})^2$, returns 71, 196 and 441 from the observed coefficient of variation of 2.14, so a reader can check the claim in one line, and the two agree closely despite the skew. Both rest heavily on the single burst-dominated closure: without it the coefficient of variation is 1.59 and the normal approximation returns 39, 109 and 244.

Set against the network as designed — eight paired fields per region, three collars each, and fortnightly campaigns through a 16-week season — a zone yields roughly 192 chamber observations per season. At that sample size, the bootstrap gives a 95 percent probability of landing within ±30 percent and an 80 percent probability of landing within ±20 percent. The design therefore supports a zonal factor at approximately ±30 percent, and does not support ±20 percent. Comparable analyses in aerobic soils report tighter bounds from fewer chambers (Davidson et al., 2002), which would be consistent with ebullition being an additional variance source here. That is a useful and previously unstated property of the design, and it is the number an adopting program needs before it sizes its own network.

A decomposition of that variance into within-farmer and between-farmer components is not identifiable from these data. Estimates from the 25 fluxes change rank with the grouping used, the estimator, and the inclusion of the single burst-dominated closure: the ratio of within- to between-farmer variance ranges from 0.48 to 36 across restricted maximum likelihood specifications, and farmer is confounded with analyzer and date in Week 1. Whether additional collars or additional farmers buy more precision will be answered from the seasonal dataset.

These are therefore preliminary planning figures, not established replication requirements for Ghanaian rice systems. They derive from 25 observations at one site early in a season, one of which dominates the distribution, and seasonal averaging will reduce the effective coefficient of variation. And the distribution is strongly skewed, so a normal approximation is a planning guide rather than a precise requirement; a log-scale or bootstrap treatment should replace it once a full season is available. The order of magnitude is unlikely to fall to tens, but it should be re-estimated from the seasonal data before a second season is sized.

Summary of requirements

The twelve requirements are collected here for reference. Fig. 8 sets out the order in which the tests are applied to a completed closure, and Table 2 lists each requirement with its diagnostic and the direction of the emission-factor bias that follows when it is not met.

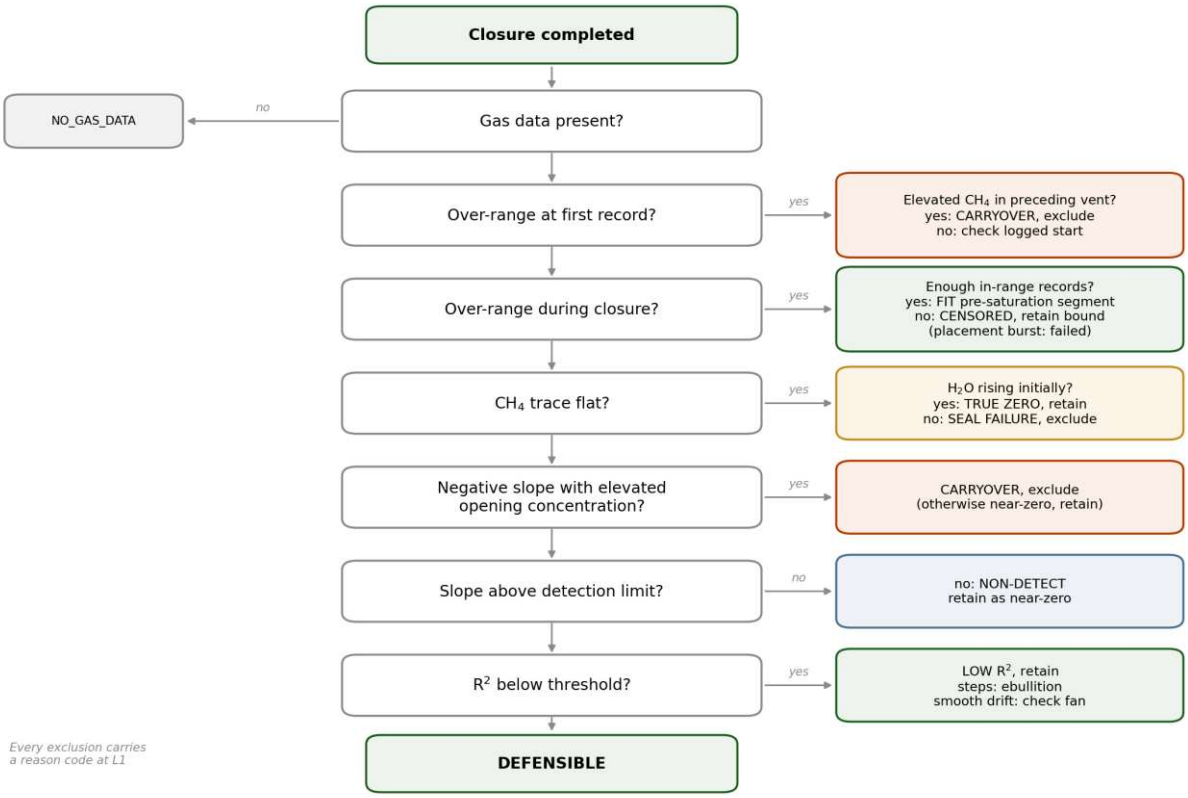


Fig. 8. Disposition of a completed closure. Tests are applied in the order shown, because an earlier condition changes the meaning of a later one: a trace that is over-range at its first record is not graded on goodness of fit, and is attributed to carryover only where the preceding vent interval shows elevated methane.

Table 2. *The twelve requirements, their diagnostics, and the direction of the emission-factor bias when a requirement is not met.*

No.	Requirement	Diagnostic	Bias if unmet	Magnitude
1	Verified participant crosswalk	Installation mapping against label sequence	Severs flux–practice link	Invalidating
2	Per-row serial; empirical verification	Warm-up timing; peak alignment; orphaned closures	Misapplied corrections	Unquantified
3	Lift and annotate at 35,000 ppb	Records above the clean ceiling	Downward	See Requirement 4
4	Censored (Tobit-type) likelihood	Censored fraction per zone	Downward	−38.3% in mean
5	Retain low-R^2 closures	Discrete steps in trace, above detection limit	Downward	20.4–47.6% of positive flux
6	Slow vertical placement	Rapid rise within seconds of sealing	Upward	Ceiling exceeded within 28 s
7	Fan state as explicit value	Shallow drift without steps	Unclassifiable	20 closures

No.	Requirement	Diagnostic	Bias if unmet	Magnitude
8	Water vapor test for true zeros	Flat CH_4 against H_2O rise	Upward	5 closures partitioned
9	Vent below 3,000 ppb	Clean negative slope; high opening value	Downward	5 chambers lost
10	Ambient pressure; range check	Value outside 70–110 kPa envelope	Downward	≈60%
11	Chamber height per deployment	Unexplained step between weeks	Either	+82% or −45%
12	Structural checks; file-end check	Row fill, carry-down, adjacent-column fill; file end time	Spurious signal; loss	4 deployments

Seven Requirements That Prevent Downward Bias

3. Lift and annotate at the analyzer ceiling rather than allowing a closure to saturate.

4. Carry censored closures into the seasonal model as bounds; never delete them or substitute the ceiling value.

5. Retain closures with low goodness of fit; low goodness of fit is not evidence of measurement failure.

8. Use the water vapor channel to retain true zeros and exclude only genuine seal failures.

9. Vent between closures; a negative slope with an elevated opening concentration is carryover, not uptake.

10. Use measured ambient pressure, range-checked against the analyzer operating envelope.

12. Verify the analyzer file extends past the last logged closure before leaving the site.

If a program can implement only part of this specification, these seven determine whether the resulting emission factor is biased low. Each addresses a mechanism by which conventional practice removes real emission from the record. Requirements 1, 2, 6, 7 and 11 address attribution, upward bias and unclassifiable records. They are not optional, but a program short of resources should secure the seven above first.

Relationship to Existing Standardization

Table 3 compares the twelve requirements against the ICOS chamber standardization protocol (Pavelka et al., 2018), the most developed existing standard for chamber flux measurement. This comparison shows what a program already working to that standard would need to add to support a flooded tropical smallholder system.

Table 3. *The twelve requirements set against the ICOS chamber standardization protocol.*

No.	Requirement	Status in ICOS standard	What the present system adds
1	Verified participant crosswalk	Unique collar and chamber identifiers specified	Binding to a farmer participant, where collar and participant sequences diverge

No.	Requirement	Status in ICOS standard	What the present system adds
2	Per-row serial; empirical verification	Not addressed	Verification of instrument attribution from the gas trace itself
3	Lift and annotate at ceiling	Analyzer range specified as 0–10 ppm CH_4	Over-range readings to 288.6 ppm; a ceiling protocol is required, not an exception
4	Censored (Tobit-type) likelihood	Not addressed	Censored closures carried as bounds rather than deleted
5	Retain low-R^2 closures	Linear and non-linear fits both recommended	Low R^2 not read as failure; ebullition attributed from trace shape; retention rule
6	Careful placement	Placement effects on CH_4 documented (Christiansen et al., 2011)	Annotation of placement-provoked ebullition as a separate class
7	Fan state as explicit value	Mixing requirements specified in detail	Per-closure recording, to separate fan failure from ebullition
8	Water vapor test for true zeros	Not addressed	Per-closure discrimination of true zero from seal failure using transpiration
9	Vent below threshold between closures	Chamber vents specified for pressure equilibrium	Venting between sequential closures to clear headspace carryover
10	Ambient pressure; range check	Ambient pressure mandatory; single fixed value identified as a risk	Range check against the analyzer operating envelope to detect cavity-pressure substitution
11	Chamber height per deployment	Height error propagates linearly to flux	Two-configuration design where misassignment carries an 82 percent error
12	Structural checks; file-end check	Raw data retention for recalculation specified	Structural checks on ancillary records; end-of-file verification before leaving site

Six requirements extend established practice into a new context; six address conditions the existing standard does not reach. The concentration of the novel requirements is not random. They cluster around saturation, ebullition and carryover, which are the three behaviors that distinguish a flooded organic-rich paddy from the aerobic mineral soils for which chamber standardization was principally

developed, and around participant identity, which distinguishes a farmer-managed network from a research infrastructure.

Direction of Bias Under Conventional Screening

Seven of the twelve requirements prevent downward bias, and two prevent upward bias. The asymmetry is not accidental. Conventional quality screening is designed to remove implausible values, and in a flooded rice system the implausible values are disproportionately the real extremes: the chamber that saturated the analyzer, the trace that stepped rather than rose smoothly, the flat trace from a genuinely non-emitting plot. Screening removes the tails, and because the upper tail carries more mass than the lower, the net effect is downward. For three of them, censoring, goodness-of-fit screening, and pressure substitution, the effect is demonstrated or calculated in these data; for the others, the direction is expected from the mechanism rather than measured.

The two quantified cases in this dataset are consistent in direction and large in magnitude. Excluding the over-range closure lowers the mean by 38 percent. Excluding closures with a coefficient of determination below 0.5 removes a fifth of the measured positive flux, and excluding the full low-goodness-of-fit class nearly half. Applied together to a seasonal dataset, these would produce a Tier 2 factor materially below the true value, derived by a procedure that would appear methodologically conventional at every step.

Where such a factor sets a baseline against which an intervention is credited, downward bias is not conservative. It misstates the emission avoided by alternate wetting and drying, and the error is not detectable from the screened dataset.

Diagnostic Value of the Establishment Phase

A 5.6 percent conventional yield would ordinarily be reported, if at all, as a failure of execution. We suggest the opposite reading. We discovered each of the twelve requirements because a closure behaved in a way we could not initially explain, and we now close each with a rule traceable to an observed event rather than to abstract precaution. A program achieving a high first-pass yield would have learned none of them and would have carried them into the seasonal dataset, where they become uncorrectable.

The distribution in Fig. 3 is itself informative about the system. The low-goodness-of-fit class accounts for the largest single category. Ebullition is one cause, consistent with a continuously or near-continuously flooded, organic-rich paddy, and the class indicates that variance is a principal statistical problem and that replication is part of the response. Saturation in 8.3 percent of closures, two during the closure and one sealed before its logged start, shows that this site emits at rates that require the ceiling protocol as standard, not as an exception. Neither conclusion is available from a dataset that has been screened before it has been understood.

Readiness

A specification is incomplete without stating what it does not yet satisfy. Table 4 gives the position at the close of the establishment phase.

Table 4. *Preconditions for a defensible zonal emission factor, with status at the close of the establishment phase.*

Requirement	Status	Consequence if unmet
All five sites measuring on the fortnightly methane schedule	Two not started	Zone missing entirely; no substitute exists
At least 6 of 8 methane campaigns per site	Donaso at 2	Integration unreliable; gaps require interpolation

Requirement	Status	Consequence if unmet
Diel correction	Not begun	Unquantified bias of unknown sign
Bulk density, both season ends	Pre-season cores collected at all sites; triplicate, 0–10 and 10–20 cm; post-season pending	Water-filled pore space not computable until both ends are available
Soil moisture probe calibration	Gravimetric samples taken alongside probe readings; calibration not yet fitted	Water-filled pore space not computable
Ambient pressure per site-day	Specified; in force from Week 3	Systematic error of a few percent
Chamber height per deployment	Specified; in force from Week 3	82% error where the tall chamber is used
Censored observations retained	Implemented	Downward, non-random bias
Continuously flooded control	Not established	Factor reportable but not comparable
Yield and biomass	Not begun	No production-normalized factor

Two entries govern the timetable. The diel correction is the largest remaining methodological gap and can be obtained within a single season at modest cost. The continuously flooded control cannot be obtained opportunistically: an attempt to identify a naturally flooded field failed when the strongest candidate proved affected by a data-entry error, and two others drained in their third week. A field that happens to remain wet is confounded, since whatever keeps it flooded is a soil or landscape property that independently affects methanogenesis. A control must be established as a treatment, at one farmer and three collars per site, and measured on the same schedule.

Without that control, the network can produce an areal emission factor under prevailing practice, which, once the preconditions in Table 4 are met, is a legitimate Tier 2 contribution to national inventory reporting. It cannot derive a country-specific water regime scaling factor, which the 2019 Refinement allows from comparative field data and which is the quantity a mitigation intervention is credited against; inventory compilers can still combine a prevailing-practice factor with the default scaling factor. The distinction is worth stating plainly, because the two are frequently conflated.

Transferability to Other National Programs

The requirements set out here were derived in Ghana, but almost none of them is specific to Ghana. They arise from network structure rather than from place. Wherever measurement is distributed across several sites, several instruments and rotating field teams, identity bindings between records and participants can break silently, instrument attribution can be transposed, analyzer over-range can be mistaken for hardware fault, and conventional screening can remove both the ebullitive and the zero tails of the flux distribution. A program in any country beginning Tier 2 development with portable analyzers and manual chambers will encounter the same twelve problems, and the resulting bias will be the same even where the emission factors are not.

What does not transfer are the numbers. The proportion of closures that saturate, the ebullitive share of total emission, and the diel ratio are properties of the system being measured. They must be established locally, and importing them from another country would reproduce precisely the substitution of foreign defaults for national measurement that Tier 2 development exists to end. What we expect to transfer is the specification, the diagnostics that detect each failure, and the data architecture that makes a reported value traceable to its raw record. All three can be adopted before a first campaign, at no cost beyond attention.

The practical implication for national programs is that the binding constraint is rarely the instrument. Analyzers and chambers can be purchased, and increasingly are. What cannot be purchased is the operational discipline that determines whether the resulting dataset means anything, and that discipline is acquired through an establishment phase whose immediate yield resembles failure. We therefore suggest that such a phase be designed, resourced and reported as a distinct stage of any national emission factor program; that its intended output be protocol revisions rather than emission factors; and that the resulting protocol be published alongside the factors it eventually supports, so that the evidence for each rule travels with the rule. A country that adopts a specification of this kind at the outset inherits the corrections without making the errors, which is the shortest available route from Tier 1 defaults to a defensible national factor.

Sources of Uncertainty

An adopting program has to decide where to spend effort. The establishment phase separates the principal sources of uncertainty and error by statistical type (Table 5). Random components are compared only within a category and in variance units. Systematic errors are stated conditionally, as the bias that arises if the error occurs, and are eliminated by recording rules rather than reduced by replication. Sensitivity diagnostics show how far a screening choice moves the estimate.

Table 5. *Sources of uncertainty and error in a zonal emission factor, grouped by statistical type, with the action that addresses each. Quantities in different categories are not commensurable and are not ranked against one another.*

Term	Type	Magnitude in these data	Action that addresses it
Slope fit	Measurement uncertainty: relative standard error of the fitted slope	Median 5.4 percent, interquartile range 3.2 to 11.8; optimistic at 1 Hz because residuals are autocorrelated	Report per closure
Variability between chambers	Sampling variability: coefficient of variation	2.14; 1.59 without the single burst-dominated closure	More collars within fields; more campaigns
Diel ratio	Temporal-integration uncertainty	Unmeasured here; late-morning sampling reproduced 93 to 106 percent of daily emission in one irrigated paddy (Minamikawa et al., 2012), and reversed diel patterns occur at reproductive stages elsewhere (Li et al., 2024)	One 24-hour campaign per zone per season, at mid-tillering and heading
Seasonal interpolation	Temporal-integration uncertainty	Not yet estimable from two campaigns	Complete the fortnightly schedule
Censoring treatment	Sensitivity diagnostic: change in the mean	−38.3 percent when the single over-range closure is excluded	Censored likelihood; lift-and-annotate protocol; report under three treatments
Goodness-of-fit screening	Sensitivity diagnostic: share of positive flux	20.4 percent (R^2 below 0.5) to 47.6 percent (R^2 below 0.90)	Retain low-R^2 closures; partition ebullition where the 1 Hz record permits
Cavity-pressure substitution	Systematic error, conditional on occurrence	About −60 percent	Per-site-day barometry with a range check

Term	Type	Magnitude in these data	Action that addresses it
Placeholder pressure	Systematic error	A few percent, varying with elevation	Per-site-day barometry
Chamber height misassignment	Systematic error, conditional on occurrence	+81.7 or −45.0 percent	Record height on every deployment
Participant or instrument misattribution	Systematic error, conditional on occurrence	Invalidating where it occurs	Verified crosswalk; trace-based instrument verification

Two practical conclusions follow within the random components. The slope-fit uncertainty of a single closure, a median of 5.4 percent, is small relative to the variability among closures, so replication rather than instrument precision limits a zonal factor. And the diel ratio, currently unmeasured anywhere in this network, is the largest temporal-integration term that can be removed within a season. The systematic errors are of a different kind: each is large where it occurs, and each is eliminated by a recording rule at negligible cost.

Verification

Where measured factors support crediting under Article 6 of the Paris Agreement or a voluntary standard, the dataset becomes subject to independent verification of internationally transferred mitigation outcomes (ITMOs), which asks whether each reported figure traces to a raw record, whether every exclusion is documented, and whether a third party can reproduce the chain. The architecture in Fig. 2 was adopted with that in mind and serves scientific and verification purposes without modification; we make no claim about the eligibility of any resulting factor under a particular crediting standard.

Provenance cannot be reconstructed retrospectively. An establishment phase is the only point at which the cost of building it is low, and a program intending to support crediting should adopt such an architecture before its first campaign rather than after its first audit.

Limitations

Every quantitative estimate of bias reported here is site- and stage-specific. The 38 percent reduction from excluding the over-range closure, the 20.4 and 47.6 percent of positive flux carried by closures below the two goodness-of-fit thresholds, and the coefficient of variation of 2.14 are properties of one site in the early part of one season, measured under the water regime prevailing at that time. The direction of each effect should generalize because it follows from the structure of the method; the magnitudes, however, should not be transferred to other systems, zones or growth stages without local measurement. Several of them depend heavily on a single closure whose field record for that campaign is being verified.

The evidence is from a single site and two campaigns. The phase establishes what the requirements are; it does not estimate how often each condition arises, and the proportions in Fig. 3 should not be read as expectations for other zones; Navrongo in particular is substantially drier, with 76.3 percent of chemistry readings taken where no floodwater exists. The water vapor test of Requirement 8 has been applied to the five closures showing no methane accumulation, but only at a single site and on a small set; its discrimination should be confirmed across the full network. Similarly, the ebullition partitioning scheme described by Kajiura and Tokida (2024) is applicable to the 1 Hz record held by this program but has not yet been implemented; until it is, the low-goodness-of-fit closures are retained whole rather than resolved into their component pathways.

Soil redox potential is not measured. Redox is the proximate control on methanogenesis, and its absence limits interpretation to correlative association with water level and water-filled pore space. A partial deployment of permanent electrodes at one farmer per site would allow water-filled pore space to be calibrated against redox and that relationship applied across the full dataset, which is a substantially stronger position than either variable alone.

Bulk density, porosity and gravimetric moisture are determined at every site from triplicate cores at two depths, and water-filled pore space is computed from them. Particle-size distribution is not among the determinations. Soil texture is one of the strongest controls on rice paddy methane emission in global synthesis (Nikolaisen et al., 2023), so its absence will limit interpretation of between-zone differences, and the authors should add particle-size analysis to the existing soil physical suite before reporting zonal factors.

Nitrous oxide is not measured. Drainage under alternate wetting and drying lowers methane while raising nitrous oxide, and a methane-only account of the practice is incomplete.

Conclusions

Distributed chamber networks can support Tier 2 methane emission factors for rice in sub-Saharan Africa only when their operational controls are as rigorous as their statistical models. This study defines twelve requirements and links each to diagnostic evidence from the establishment phase of a five-agroecology network in Ghana.

Four findings have broad methodological relevance. Analyzer over-range should be treated as censoring rather than instrument failure; excluding the single over-range closure that could be fitted reduced mean flux by 38%. Low goodness of fit did not establish measurement failure, because closures below conventional thresholds contributed 20.4-47.6% of measured positive flux and could include genuine ebullition. Substituting analyzer cavity pressure for ambient pressure underestimated flux by approximately 60%. Finally, verified crosswalks and code-enforced identifiers were essential because partially correct data joins could silently assign fluxes to the wrong farmers or fields.

Seven requirements specifically prevent downward bias, which can overstate credited mitigation when measured factors define baselines. Applying this framework will strengthen Ghana's greenhouse gas inventory, improve the integrity of methane mitigation and carbon-crediting programs, and support evidence-based water management in rice systems. Wider adoption would also improve the transparency and comparability of national methane estimates, helping countries report progress credibly under the Paris Agreement and informing global efforts to reduce agricultural methane emissions.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

Not applicable. This study did not involve human participants, human data, human tissue or animals. Farmers consented to the installation of equipment on their land; no personal data were collected, and the study therefore did not require review by a human research ethics committee. We measured soil and crop surfaces in farmer-managed rice fields.

Consent to participate

Participating farmers gave informed consent to install measurement collars in their fields, allow access for weekly measurements, and use the associated field records in this research.

Consent to publish

This article includes no identifying information relating to any individual. Participants are referred to only by anonymized identifiers.

Data availability

The datasets generated and analyzed during the current study, comprising raw analyzer records and all derived flux levels, will be deposited in a publicly available repository with a persistent identifier on publication. They are not yet publicly deposited because the establishment-phase records reported here form part of an ongoing seasonal series that is not yet complete. The minimal dataset necessary to interpret and replicate every figure and table in this article is available from the corresponding author on reasonable request.

Code availability

The flux processing code and the field working protocol are available from the corresponding author on reasonable request and will be deposited alongside the datasets on publication.

Author contribution

Kwaku Onwona-Hwesofour Asante: Conceptualization; Methodology; Software; Formal analysis; Investigation; Data curation; Writing – original draft; Writing – review and editing; Visualization; Supervision; Project administration. **Caleb Ocansey:** Methodology; Investigation; Data curation; Writing – review and editing. **Felix Frimpong:** Methodology; Validation; Investigation; Writing – review and editing. **Eric Owusu Danquah:** Methodology; Investigation; Writing – review and editing. **Charles Afriyie-Debrah:** Investigation; Resources; Writing – review and editing. **Harry Okyere:** Investigation; Data curation; Writing – review and editing. **Clement Oppong Peprah:** Investigation; Writing – review and editing. **Jeanette Aduhene-Chinbuah:** Investigation; Writing – review and editing. **Reuben Nutefe Kuavedzi:** Conceptualization; Writing – review and editing. All authors read and approved the final manuscript.

Ethical responsibilities of authors

All authors have read, understood, and have complied, as applicable, with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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Appendix A. Worked example: one closure from raw trace to flux

Deployment DON-W01-F01-C1, Donaso, campaign 1, 27 August 2026, graded defensible. Table A1 gives the measured and derived inputs to Eq. 1 for this closure, together with the resulting flux.

Table A1. *Inputs and result for a single closure*

Quantity	Value	Source
Chamber configuration	Short, 60 cm	Recorded per deployment
Enclosed area, A	0.24485 m²	Chamber specification
Headspace volume, V	0.146910 m³	Chamber specification
V / A	0.600 m	Derived; equals chamber height
Clean records in window	241 (100 percent)	L1, diagnostic-clean, 240 s at 1 Hz, both endpoints included
Slope, dC/dt	1,274.64 ± 13.27 ppb min^{-1}	L2, full-window ordinary least squares
Coefficient of determination	0.975	L2
Ambient pressure, P	101.0 kPa	Placeholder; per-site-day barometry supersedes
Chamber air temperature, T	308.1 K (34.9 °C)	Chamber air, mean of start (33.0 °C) and end (36.8 °C) readings
Molar mass, M	16.04 g mol^{-1}	Constant
Molar density, P/RT	39.44 mol m^{-3}	Derived
Flux, F	29.03 ± 0.30 mg CH_4 m^{-2} h^{-1}	Recomputed; the processing run with soil temperature gave 29.39

Substituting into Eq. 1:

$$F = 1{,}274.64 \times 10^{-9} \times 0.600 \times 39.44 \times 16.04 \times 60 \times 10^{3} = 29.03 \text{ mg m}^{-2} \text{ h}^{-1}$$

where the factor of 60 converts from minutes to hours, the factor of 10^{-9} converts from ppb to a mole fraction, and the factor of 10^{3} converts from grams to milligrams. The processing run behind the results in this paper applied the soil temperature recorded for this farmer, 31.1 °C, in place of chamber air temperature and returned 29.39 mg m^{-2} h^{-1}; the difference, 1.2 percent, is of the size expected across the dataset. Three checks follow. The ratio V/A equals the chamber height exactly, because the two configurations share a footprint; any departure indicates a geometry error. The molar density must lie between roughly 37 and 41 mol m^{-3} for field conditions in this network; a value near 16 would indicate that the analyzer cavity pressure had been substituted for ambient. And the relative standard error on the flux, here 1.0 percent, is a property of the fit alone and should not be mistaken for the uncertainty on a zonal factor, which is two orders of magnitude larger.

Seasonal emission for this collar is the trapezoidal integral of its campaign fluxes, multiplied by the zone- and stage-specific diel ratio before integration. A zone factor is then obtained from the mixed-effects model described under Data architecture, not by averaging collars directly.