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CAREER: Wet–Dry Cycles, Soil Redox, and the Methane–Nitrous Oxide Trade-off in Mid-South Rice

1. Career Vision and Overview

Rice growers in the Mid-South are being asked to do two things at once: draw less water from a declining aquifer and send less methane into the atmosphere. Alternate wetting and drying (AWD), in which a flooded field is allowed to drain and is then flooded again, promises both. Yet the same drained soil that stops making methane can start making nitrous oxide, a greenhouse gas with nearly three hundred times the warming effect of carbon dioxide over a century. Whether AWD is a climate solution or a trade of one gas for another depends on the details of each drain: how deep the water falls, how long the soil stays open to air, and when the field is flooded again. Growers cannot see those details. They see a water level in a pipe.

My long-term goal is to make water management in rice a measured practice rather than a rule of thumb: one in which a grower, a crop consultant, or a student can read what the soil is doing and decide when to bring the water back. My research program asks how the depth, duration and sequence of field drainage set the soil redox conditions that control the production and consumption of methane (CH_4) and nitrous oxide (N_2O). My education program uses the same low-cost instruments my laboratory builds for that research to bring environmental measurement into undergraduate engineering courses and into high school science classrooms in the rice-growing counties around our campus.

This CAREER project has three research objectives and three education objectives, designed to feed each other:

- **R1. Map the redox windows.** Measure, at plot scale and at sub-daily resolution, how the depth and duration of each drain move soil redox potential through the ranges that favor methanogenesis, methane oxidation, nitrification and denitrification, and how CH_4 and N_2O fluxes respond.
- **R2. Find who makes the pulse.** Link the abundance and expression of microbial functional genes (*mcrA*, *pmoA*, *amoA*, *nirK*, *nirS* and *nosZ*) to the timing and size of N_2O pulses after drainage and reflooding, including the effect of earlier drains on later ones.
- **R3. Turn redox into a decision.** Build and test a decision rule that schedules reflooding from soil redox measurements rather than from water depth alone, and validate it on a working farm.
- **E1. Measurement in the classroom.** Add a three-week sensor-building and calibration module to the department's environmental measurements course.
- **E2. A summer institute for teachers.** With the Harlow Bend School District, hold a one-week institute each summer in which science teachers build a field chamber, collect data at our research farm, and write lessons on the carbon and nitrogen cycles for their own classrooms.
- **E3. A pathway into research.** Recruit two undergraduate researchers each year, many from the course module and from the partner district, into a mentored research experience tied to R1 to R3.

The integration is direct. The chamber nodes students build in E1 are calibrated against the laboratory's gas chromatograph and, when they pass, are deployed in the R1 field plots; teachers in E2 collect real flux data that enter the R1 data set; and undergraduates in E3 analyze the gene and flux data of R2. The project will train one graduate student for five years and ten undergraduates, reach about forty engineering students a year through the course module, and support thirty-two teachers over four summers.

The timing matters. Growers in the region are adopting AWD and related practices now, encouraged by water savings and by emerging payments for methane reductions, and the rules they adopt in the next few years will be hard to change once equipment, habits and program requirements settle around them. A rule that accounts for N_2O, and an inexpensive way to apply it, are most useful before that happens.

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1.1 Career development plan

I joined Prairie Ridge State University in August 2023 as an assistant professor of biological and agricultural engineering, after a doctorate in environmental engineering and two years as a postdoctoral researcher in soil biogeochemistry. My appointment is 60% research and 40% teaching, and the department expects its faculty to build programs that serve the state's agriculture while contributing to the national science of water and greenhouse gases. This project is the plan for doing both.

Over the five years of the award I will (1) establish my laboratory as the regional group that measures soil redox and greenhouse gas fluxes together at the resolution that drainage events demand; (2) move from instrument development, the focus of my first award, to hypothesis-driven field science on the mechanisms of the methane–nitrous oxide trade-off; (3) learn and bring into the laboratory the molecular methods of R2, through a one-month visit in year 1 to a collaborating soil microbiology group and the campus genomics core's training program; and (4) build a teaching practice in which students learn measurement by doing it. Concrete milestones are the open release of the node in year 3, a tested reflooding rule by the end of year 4, and a graduating doctoral student and a sustained teacher network by the end of year 5. My department head and a senior colleague in crop, soil and environmental sciences mentor me under the department's early-career program; their role is described in the departmental letter.

2. Background and Significance

2.1 Water, rice and greenhouse gases in the Mid-South

The Mid-South, led by Arkansas, grows most of the nation's rice, and nearly all of it is irrigated from the Mississippi River Valley alluvial aquifer, whose water levels have fallen in much of the region. Field studies in the region have shown that AWD and related practices can save water without large yield penalties. Atwill and colleagues reported that AWD reduced aquifer withdrawal in Mississippi rice production systems across many sites and years [1], and Chlapecka and colleagues developed irrigation schedules for furrow-irrigated and intermittently flooded rice based on soil moisture thresholds [4]. Whole-system analyses in Arkansas have examined how conservation irrigation fits with other changes in rice production, from rice husk amendments to rotations [2, 14].

The climate side of the ledger is less settled. A recent synthesis of eleven meta-analyses found that, compared with continuous flooding, multiple-drainage practices such as AWD decreased CH_4 emissions by 31 to 62% but increased N_2O emissions by 37 to 445%; counting both gases, the global warming potential fell by 33.6 to 56.2%, and yields ranged from a 5.4% loss to an 11% gain [9]. The same synthesis notes that yields generally held when the water table fell no more than about 15 cm below the soil surface, the basis of the "safe AWD" recommendation [9]. The wide range for N_2O is the scientific problem at the center of this proposal. A twelve-fold spread in the N_2O response means that the practice itself does not determine the outcome; something about how each drain unfolds does.

Measurement is part of the difficulty. Static chambers resolve differences between plots but sample briefly and intermittently, while eddy covariance captures continuous whole-field fluxes but cannot separate treatments within a field; both approaches have been compared for CH_4 in Arkansas rice [13]. Seasonal CH_4 and N_2O budgets for furrow-irrigated rice with cover crops show that N_2O can rise when fields spend more time unsaturated [6]. Field-scale and national-scale models now simulate AWD [2, 7], but they represent drainage through water depth or soil moisture, not through the redox state that microorganisms actually experience. Longer-term questions remain as well, including whether drier management changes soil organic carbon and soil health over many seasons [8].

Nitrogen management ties the two gases together. Most rice in the region receives urea on dry soil just before the permanent flood, so that the flood moves the nitrogen into the soil, where it stays as ammonium while the soil is reduced. Every drain exposes that ammonium to nitrification. A drain early in the season, when the crop takes up little nitrogen, therefore has more substrate for N_2O production than a drain near panicle initiation, when crop uptake is fast. Growers already time drains around fertilizer applications for

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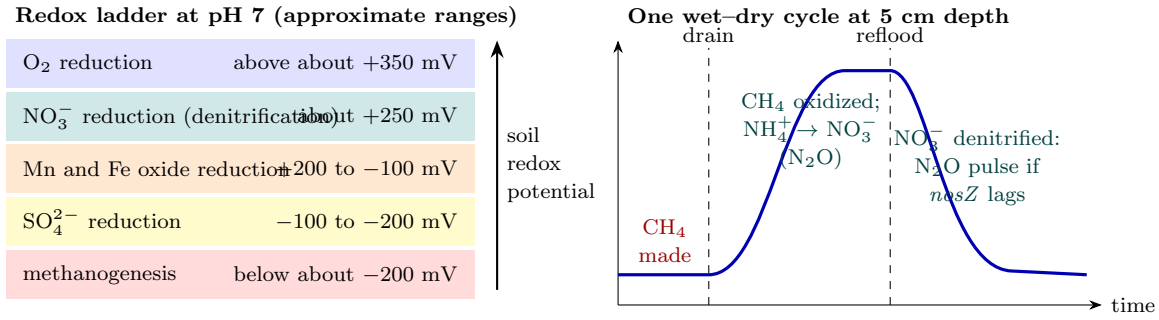


Figure 1: Conceptual model. Left: the sequence of electron acceptors in flooded soil, with approximate redox ranges. Right: during one drain and reflood, soil at 5 cm passes up and back down the ladder; the time spent in each range sets how much CH_4 is oxidized and how much nitrate is available for denitrification after reflooding.

agronomic reasons; this project asks how that timing shapes the greenhouse gas outcome, and the four regimes of R1 were chosen to cover drains at different points in the crop's nitrogen demand.

2.2 Why drainage can trade one gas for another

Flooded paddy soil is a layered redox system. When the soil is flooded, oxygen is consumed within millimeters of the surface, and microorganisms use, in turn, nitrate, manganese oxides, iron oxides and sulfate as electron acceptors. Only when these are depleted does methanogenesis dominate, at the lowest redox potentials. Draining the field reverses the sequence from the top down: oxygen enters, methane production stops, and methane-oxidizing bacteria consume much of the methane still in the soil. Ammonium that accumulated under flooding is nitrified to nitrate, with N_2O as a by-product. When the field is flooded again, the nitrate becomes the substrate for denitrification, which can release N_2O if the final step, the reduction of N_2O to N_2 by the enzyme encoded by *nosZ*, lags behind the earlier steps (Figure 1).

The microbial basis of that lag is known in outline. Many denitrifying organisms carry the genes for the reduction of nitrite (*nirK* or *nirS*) but not *nosZ*, and so end denitrification at N_2O; a second group of N_2O reducers, carrying the clade II form of *nosZ*, includes organisms that do not produce N_2O at all and act only as a sink. The balance of these groups, and how quickly each responds when oxygen disappears after reflooding, determines how much of the nitrate formed during a drain leaves the field as N_2O. Soil drying and rewetting are known to reshape these communities, but the timing in a rice field, measured in hours after a reflood, has rarely been sampled.

This framework suggests three gaps in what we know, each of which this project addresses:

- **G1. The duration of the oxidized window is not measured.** Recommendations specify a depth (for example, 15 cm) but not how long the soil spends at redox potentials that favor nitrification. Two drains to the same depth can differ several-fold in that time, depending on weather, soil texture and crop water use.
- **G2. The order of drains may matter.** Each drain-and-reflood cycle changes the nitrate pool and may change the microbial community that meets the next cycle. A legacy of earlier cycles could explain why later N_2O pulses are often larger, but this has not been tested with gene expression and flux measured together.
- **G3. Decision tools read water, not soil.** Growers schedule reflooding from field water tubes. A rule that reads soil redox directly could keep the CH_4 benefit of a drain while avoiding the conditions that produce the largest N_2O pulses, but no such rule has been tested in the field.

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2.3 How this project differs from related efforts

Three kinds of work sit close to this project. Field studies in the Mid-South have quantified water savings, yields and, in some cases, seasonal greenhouse gas budgets under AWD and furrow irrigation [1, 4, 6]; they tell us what happens over a season but not within the hours of a drain. Process models can simulate AWD at field and national scales [2, 7], but their drainage routines respond to water depth and soil moisture and cannot yet be tested against measured redox trajectories, because few data sets contain them. Studies of soil microbial communities in paddy soils describe the genes behind CH_4 and N_2O cycling but rarely follow them through repeated wet–dry cycles alongside fluxes. This project joins the three: it measures redox, fluxes and gene expression together through the events that matter, in a design that varies the property growers control, and it tests the resulting rule where growers work. The data set it produces is also what the models need to represent drainage through redox rather than water depth alone.

3. Preliminary Results

My laboratory's preliminary work, supported by an NSF Engineering Research Initiation award (Section 9) and by start-up funds, has produced the instruments and the first observations on which this proposal builds.

3.1 A low-cost chamber node

We designed a chamber node that costs about $180 in parts: a metal-oxide CH_4 sensor and a non-dispersive infrared CO_2 sensor in a vented, closed-path chamber, with temperature and humidity compensation, two platinum redox electrodes and a reference electrode at 5 and 15 cm depth, a capacitance soil moisture probe, and a pressure transducer in the field water tube. A microcontroller logs every ten seconds during each closure and stores data on a memory card with a cellular upload when coverage allows. In the 2024 and 2025 seasons we compared node fluxes with fluxes computed from syringe samples analyzed by gas chromatography during the same closures (Table 1). Agreement for CH_4 was good across the range of fluxes seen in the field, with a small positive bias at the lowest fluxes that we now correct with a humidity-dependent baseline. N_2O cannot yet be measured with low-cost sensors, so this project continues to measure it by syringe sampling and gas chromatography, timed by the redox electrodes.

Field robustness mattered as much as accuracy. In the first season, three of eight nodes failed within a month: two from condensation on the sensor board and one from a chewed cable. The second-generation node moved the electronics into a sealed enclosure above the chamber, vents the chamber through a capillary to equalize pressure, and runs its cables through conduit. Over the 2025 season, all eight second-generation nodes logged more than 95% of scheduled closures. Each node costs about four hours of student labor to assemble, which is what makes it suitable for the classroom module of E1.

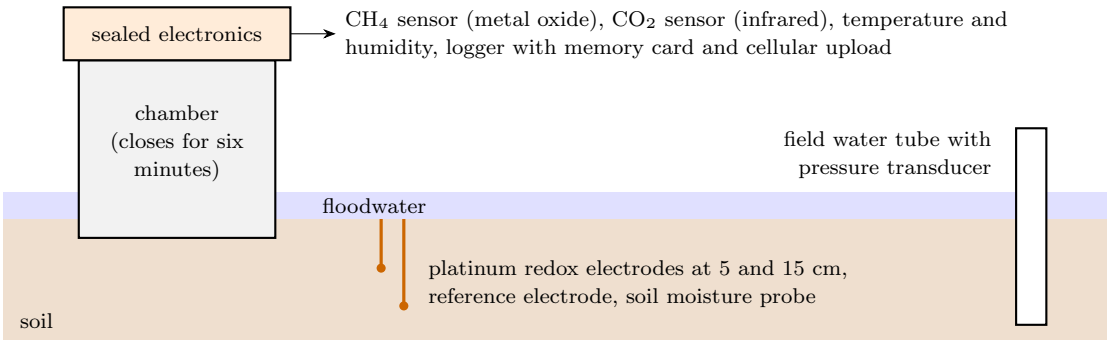


Figure 2: The second-generation chamber node (not to scale). One logger serves the chamber, the redox electrodes, the soil moisture probe and the water-tube transducer; about $180 in parts.

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Table 1: Validation of the chamber node against gas chromatography (2024 and 2025 seasons, research farm).

Quantity	n	R^2	Mean bias	RMSE
CH_4 flux, node vs. syringe samples and GC	212 closures	0.91	+4.8%	0.62 mg m^{-2} h^{-1}
CO_2 flux, node vs. reference analyzer	212 closures	0.95	−2.1%	18 mg m^{-2} h^{-1}
Redox electrode drift over 30 days	24 electrodes	—	+11 mV	9 mV

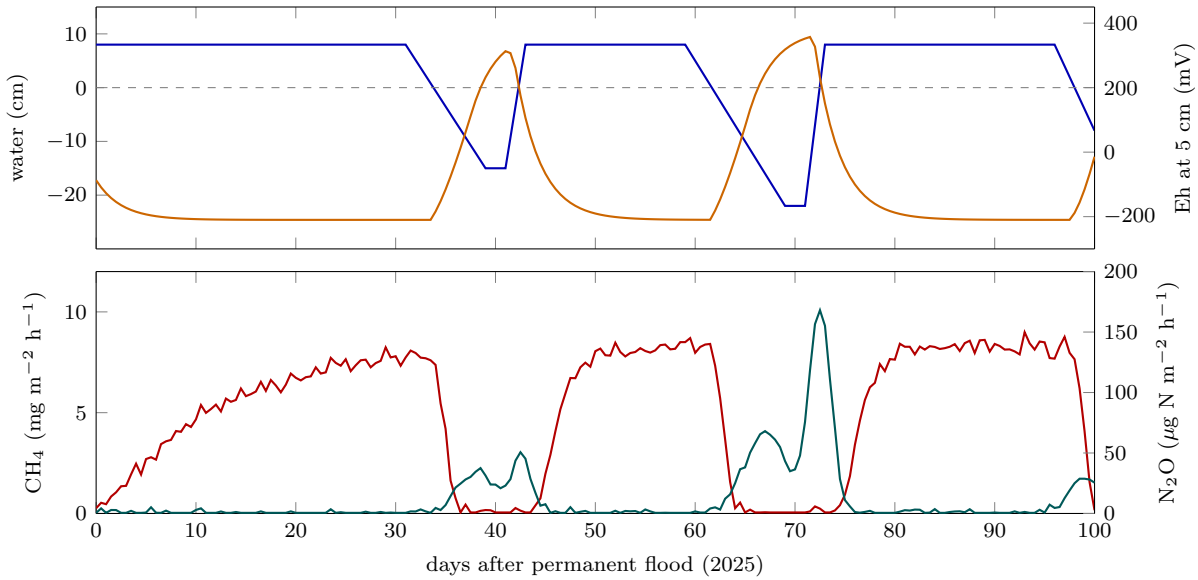


Figure 3: Pilot season, 2025 (one of two monitored plots). Top: field water level (blue, left axis) and redox potential at 5 cm (orange, right axis). Bottom: CH_4 flux from the chamber node (red, left axis) and N_2O flux from syringe samples (green, right axis). The reflood pulse of N_2O after the second, deeper drain was about three times the first.

3.2 The 2025 pilot season

In 2025 we monitored two plots at the university's rice research farm through a season with two drains and a final drain before harvest (Figure 3). Three observations shaped this proposal. First, CH_4 flux fell to near zero within about two days of the water table dropping below 10 cm, and recovered over two to three weeks after reflooding, so even a short drain removed a large part of the season's CH_4. Second, N_2O was emitted in two bursts in each cycle: a smaller one as the soil dried and a larger one within a day of reflooding. Third, the reflood pulse after the second, deeper drain was about three times larger than after the first. The second drain was deeper (22 cm against 15 cm) and longer (twelve days against ten), and the soil at 5 cm spent about 70 hours above +300 mV in the second cycle against about 28 hours in the first. We cannot tell from two plots and one season whether the depth, the duration, or the legacy of the first cycle drove the difference. That is precisely what R1 and R2 are designed to resolve.

Two seasons also taught us about logistics. Chamber collars must be installed before the permanent flood, when the soil can be walked on; redox electrodes need at least ten days to stabilize after installation; and syringe sampling around a reflood must be scheduled to the hour, because the pulse begins within hours of water reaching the soil. The R1 field calendar is built around these constraints, with installation in the two weeks before flooding and an on-call sampling rota for the 72 hours after each reflood.

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3.3 Laboratory incubations

Field data alone cannot separate the depth of a drain from its duration, because deeper drains also last longer. In 2025 we ran a first laboratory test with soil from the research farm: 36 intact cores were flooded for three weeks, then drained to one of two matric potentials (a shallow and a deep drain) for one of three durations (three, six or ten days), and then reflooded, with N_2O measured by headspace sampling for five days after reflooding. Two results matter here. The N_2O released after reflooding rose with drain duration at both drain depths, while the difference between depths at the same duration was small and not statistically distinguishable with six cores per cell. And in a second set of cores taken through three successive cycles of six days each, the reflood pulse grew from the first cycle to the third, consistent with the legacy effect we saw in the field (Table 2). These are small experiments with one soil, and the cores lack plants, which take up nitrate and supply carbon; the field experiment of R1 and the incubations proposed in R2 are designed to test whether the patterns hold under a crop.

Table 2: Cumulative N_2O over five days after reflooding in laboratory incubations (2025; mean ± standard error, μg N_2O-N per kg of dry soil; six cores per cell).

	3-day drain	6-day drain	10-day drain
Shallow drain (matric potential −10 kPa)	41 ± 7	88 ± 12	139 ± 19
Deep drain (matric potential −30 kPa)	47 ± 9	97 ± 15	151 ± 22
Successive 6-day cycles (shallow drain)	cycle 1: 85 ± 11	cycle 2: 124 ± 16	cycle 3: 171 ± 20

3.4 What the pilot implies

The pilot leads to three hypotheses, one for each research objective:

- **H1 (R1).** The size of the N_2O pulse after reflooding scales with the time the surface soil spends above the redox range of nitrification during the drain, more than with the depth the water table reaches.
- **H2 (R2).** Each drain-and-reflood cycle shifts the ratio of nitrite-reductase genes (*nirK* and *nirS*) to N_2O-reductase genes (*nosZ*) toward incomplete denitrification, so later cycles produce larger pulses for the same oxidized time.
- **H3 (R3).** A reflooding rule based on redox time at 5 cm keeps at least 80% of the CH_4 reduction of a safe-AWD drain while cutting the reflood N_2O pulse by half or more, without a yield penalty.

4. Research Plan

4.1 Sites and design

The field work takes place at two sites. The Prairie Ridge State University Rice Research Farm has a silt loam soil typical of the region's rice land, sixteen leveled and independently irrigated plots of 0.1 ha each, flow meters on every inlet, and a field laboratory with power and a gas chromatograph within ten minutes of the plots. Teal Slough Farms, a commercial operation of about 1,100 ha that grows rice in rotation with soybean, will host the farm-scale validation of R3 in years 4 and 5 in two production fields of about 16 ha each, one managed by the cooperator's usual AWD practice and one by the redox-based rule. The collaboration is documented in the cooperator's letter and described in the Facilities, Equipment and Other Resources section.

At the research farm, four water regimes will be compared in a randomized complete block design with four blocks (Figure 4): continuous flooding (CF); safe AWD, in which the water table is allowed to fall to 15 cm below the soil surface before reflooding (AWD15); deep AWD, to 30 cm (AWD30); and a single early-season drain at mid-tillering followed by flooding (ED). The same cultivar, seeding rate, fertilizer program (urea preflood, with a midseason application timed by the farm's standard practice) and pest management will be used in all plots. The experiment will run for two seasons (years 2 and 3), which lets us test the legacy

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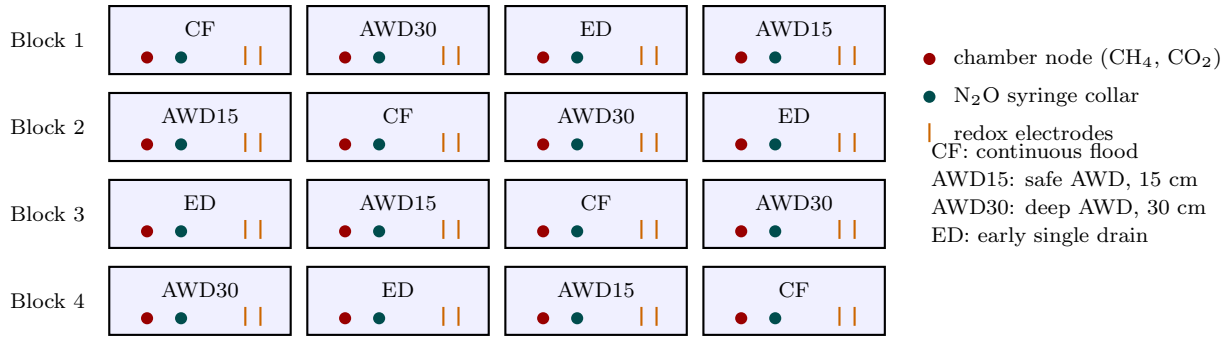


Figure 4: Research farm layout for R1 and R2: four water regimes in four randomized blocks (sixteen 0.1-ha plots). Each plot carries one automated chamber node, one collar for manual N_2O sampling, and paired redox electrodes at 5 and 15 cm.

hypothesis H2 within a season (successive cycles) and between seasons (the same plots under the same regime).

4.2 Objective R1: map the redox windows

Rationale. H1 predicts that the oxidized time of the surface soil, not the water depth, controls the N_2O pulse. Testing it requires redox and flux measured together, often enough to resolve the hours after each drain and reflood, in plots that differ in drain depth and therefore in oxidized time.

Measurements. Each plot receives one automated chamber node on a permanent collar, closing for six minutes every two hours, day and night, from flooding to the final drain (Table 3). Paired platinum electrodes at 5 and 15 cm log redox potential every fifteen minutes; the readings are corrected to the standard hydrogen electrode and to pH 7 using weekly porewater pH. Field water tubes with pressure transducers record the water table. N_2O is sampled by syringe from a second collar in each plot, once a day under flood and four times a day for three days after each drain begins and after each reflood, the windows in which the pilot saw the pulses. Porewater nitrate, ammonium and dissolved organic carbon are sampled with suction cups at 5 and 15 cm at the same times. Yield, grain quality and irrigation volume are measured in every plot at the end of each season.

Table 3: Measurements in R1 and R2 at the research farm (years 2 and 3), by plot.

Variable	Method	Frequency	Objective
CH_4 and CO_2 flux	automated chamber node, six-minute closures	every 2 h	R1, R3
N_2O flux	manual syringe samples, gas chromatography	daily; 4 per day near events	R1, R2, R3
Redox potential, 5 and 15 cm	platinum electrodes, logged	every 15 min	R1, R3
Water table	pressure transducer in field water tube	every 15 min	R1, R3
Soil moisture, 5 cm	capacitance probe	every 15 min	R1
Nitrate, ammonium, DOC	suction cups, colorimetry and combustion	with N_2O near events	R1, R2
Functional genes and transcripts	soil cores, DNA and RNA, qPCR and RT-qPCR	12 times per cycle	R2
Yield, grain quality, irrigation	harvest; flow meters	per season	R1, R3

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Analysis. For every drain we will compute the hours the 5-cm electrode spends in each redox range (Figure 1), the maximum depth of the water table, the length of the drain, and the cumulative N_2O and CH_4 fluxes over the drain and over the five days after reflooding. Cumulative fluxes will be computed by linear interpolation between sampling times with bootstrapped uncertainty. H1 will be tested with linear mixed models of the cumulative reflood N_2O flux with redox time and drain depth as competing predictors, block and plot as random effects, and cycle number as a covariate; the hypothesis is supported if redox time explains more of the variance than depth when both are in the model. With four blocks, three drains per AWD plot and two seasons, the design gives 48 drain events in the AWD treatments. Using the pilot's variance, a simulation-based power analysis gives 0.8 power to detect a standardized effect of 0.45 for redox time at $\alpha = 0.05$.

Data processing and quality control. Chamber fluxes will be computed from the slope of concentration against time over each closure, choosing between linear and exponential fits by information criterion, and closures with a poor fit (for example, from ebullition, a sudden release of bubbles that is common in flooded rice) will be flagged rather than discarded, because ebullition is part of the CH_4 flux; flagged closures will be analyzed with and without the bubble events. Redox readings will be screened for electrode failure by comparing the two electrodes at each depth and by weekly checks against a portable reference electrode. All processing will be scripted, version controlled and run from the raw logger files, so that every figure can be regenerated from the archived data.

Weather and water balance. A weather station at the research farm records rainfall, air temperature, humidity, wind and solar radiation every fifteen minutes, and the inlet flow meters record every irrigation. Together with the water-tube transducers, these let us close a simple water balance for each plot and estimate how fast each drain proceeds by evapotranspiration and seepage. The water balance matters for H1: it explains why two drains to the same depth take different times, and it lets the R3 rule anticipate how long a drain will last from the weather forecast.

4.3 Objective R2: find who makes the pulse

Rationale. If H2 holds, the same oxidized time produces a larger N_2O pulse in later cycles because the denitrifying community shifts toward organisms that lack *nosZ*, or because *nosZ* expression lags. Gene abundance alone cannot distinguish these; transcripts measured through the reflood window can.

Sampling and assays. In two blocks, we will take soil cores (0 to 5 and 5 to 15 cm) from every plot at twelve times across each cycle: before the drain, at three points during it, and at eight points in the first 72 hours after reflooding, when transcript levels change fastest. DNA and RNA will be extracted with commercial kits; RNA will be reverse-transcribed after DNase treatment. Quantitative PCR will target *mcrA* (methanogens), *pmoA* (methanotrophs), archaeal and bacterial *amoA* (ammonia oxidizers), *nirK* and *nirS* (nitrite reductases) and both clades of *nosZ* (N_2O reductases), with established primer sets, standard curves from synthetic gene fragments, and inhibition checks by dilution. The campus genomics core runs the assays on a fee-for-service basis.

Analysis. For each core we will compute the ratio of (*nirK* + *nirS*) to *nosZ* for both genes and transcripts. H2 predicts that this ratio rises from the first cycle to the third within a season, and from the first season to the second in the same plots, and that the transcript ratio in the first 24 hours after reflooding predicts the size of the pulse after accounting for redox time. We will fit hierarchical models with cycle and season as fixed effects and plot as a random effect, and use the transcript ratio as an added predictor in the R1 model to ask whether it explains variance that redox time does not.

Expected patterns. From the pilot and the incubations, we expect the transcript ratio of nitrite reductases to *nosZ* to peak within 12 to 24 hours of reflooding, before the N_2O pulse reaches its maximum, and to be higher in the third cycle of a season than in the first. If, instead, the ratio does not change across cycles while the pulses grow, the legacy effect must lie in the nitrogen pool rather than in the community, and the porewater nitrate data of R1 will show it; the R3 rule would then need to account for fertilizer timing rather

than cycle number.

Community composition. At four of the twelve time points in each cycle, we will also sequence the 16S rRNA gene and the *nosZ* clade II gene from the same extracts. These data will tell us whether a rising (*nirK* + *nirS*) to *nosZ* ratio reflects a change in which organisms are present or a change in what the same organisms express, a distinction that matters for management: a shift in community composition may persist from one season to the next, while a lag in expression may not. Sequencing will be done by the campus genomics core, and reads will be processed with an open, scripted pipeline and deposited in a public archive at publication.

Controlled incubations. To separate depth, duration and legacy under conditions we control, the graduate student will run three incubation experiments in years 2 to 4 with intact cores taken from the CF plots before planting. Each uses a full factorial design: drain depth (two matric potentials) by drain duration (three, six and ten days) by cycle (one to three), with six cores per cell and rice seedlings grown in half of the cores, to test whether plant uptake changes the response. Headspace N_2O and CO_2 will be measured daily, and cores will be destructively sampled for genes and transcripts at the end of each cycle. The incubations answer the question the field cannot: whether duration matters at a fixed depth, and depth at a fixed duration. Their results also give the R3 model priors for the redox-time effect before the field data are complete.

4.4 Objective R3: turn redox into a decision

Rationale. A rule a grower can use must be simple, must rest on a measurement that can be made in a field, and must be shown to work outside a research plot. The chamber node and its redox electrodes cost little enough to be used on farms, and the logic of Figure 1 suggests a rule of the form: reflood when the soil at 5 cm has spent a set number of hours above a set redox potential, or when the water table reaches 15 cm, whichever comes first.

Building the rule. Using the R1 data from year 2, we will fit the relationship between redox time and the reflood N_2O pulse, and between redox time and the CH_4 saved by the drain, and choose the threshold that maximizes the reduction in combined global warming potential subject to keeping at least 80% of the CH_4 reduction of the AWD15 treatment. The rule will be fixed before year 3 and tested at the research farm in year 3 as a fifth regime in two of the blocks, managed in real time from the nodes' cellular uploads.

Farm validation. In years 4 and 5, the rule will be tested at Teal Slough Farms in a paired-field design: one field managed by the cooperator's usual AWD practice and one by the rule, with four chamber nodes and two redox stations in each field, weekly N_2O sampling with event sampling around drains, and the farm's own yield monitor data. The cooperator decides when to irrigate in both fields; in the rule field, we send a text message when the rule says to reflood, and the cooperator records when the pump was started. This design tests the rule as a grower would use it, including the lag between advice and action.

Model structure. The rule rests on a simple statistical model fitted to the R1 data. For drain i in plot j, let T_{ij} be the hours the 5-cm electrode spends above a redox threshold E^*, and N_{ij} the cumulative N_2O flux over the five days after reflooding. We fit

$$\log N_{ij} = \beta_0 + \beta_1 \log(1 + T_{ij}) + \beta_2 c_{ij} + u_j + \varepsilon_{ij},$$

where c_{ij} is the cycle number within the season (the legacy effect of H2), u_j is a plot effect and ε_{ij} is the residual, and a parallel model for the CH_4 saved by the drain. The threshold E^* and the allowed time T^* are chosen by cross-validation over the year-2 data, leaving out one block at a time. The rule's predictions for year 3 will be stated in writing before the season begins, so that the year-3 test at the research farm is a genuine test and not a refit (Figure 5).

What success looks like. H3 is supported if the rule field keeps at least 80% of the CH_4 reduction of the practice field and its reflood N_2O pulses are at least 50% smaller, with no yield difference beyond the field-to-field variation measured in the year before the test.

Costs to the grower. A rule is only useful if it pays for itself or costs little. Using the farm's pumping records, energy use per acre-inch and labor logs, we will compare the practice and rule fields for irrigation volume,

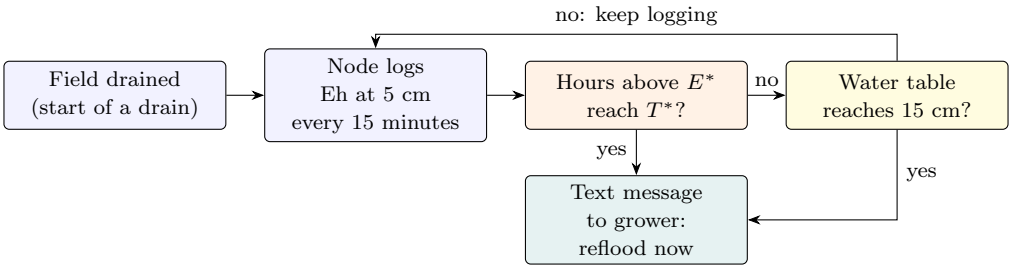


Figure 5: The reflooding rule tested in R3. Whichever comes first, the redox criterion or the safe-AWD depth, triggers a reflood message; the thresholds E^* and T^* are fixed from year-2 data before the year-3 test.

pumping energy and the number of irrigation decisions per season. The node and redox station cost about $400 per field, and the cellular plan about $5 a month during the season. We will report the cost per field and per tonne of CO_2 equivalent avoided, so that growers, consultants and incentive programs can judge the rule on their own terms.

Alternative rules. The redox rule will be compared, using the R1 and R3 data, with three simpler alternatives a grower could apply without electrodes: the safe-AWD depth rule alone; a fixed number of days after the water leaves the soil surface; and a soil moisture threshold read from a capacitance probe, which is cheaper and more robust than a redox electrode. If a moisture or day-count rule performs nearly as well, we will recommend it, because simplicity matters more to adoption than a small gain in performance. The comparison is part of the analysis plan fixed before year 3.

4.5 Expected results, risks and alternatives

We expect R1 to show that redox time is a better predictor of N_2O than drain depth, R2 to show that the transcript ratio of nitrite to N_2O reductases rises across cycles, and R3 to deliver a rule that halves reflood N_2O at little cost in CH_4. Each result is useful even if the others are not: a null result for H1 would tell growers that depth-based safe AWD is already the right tool, and a null result for H2 would simplify the rule by removing the need to count cycles.

The main risks are practical. Redox electrodes drift and can fail in clay pockets; we install them in pairs, check them weekly against a portable reference, and replace any that drift more than 30 mV. A dry spring can force early irrigation decisions; two seasons at the research farm and two at the commercial farm spread the weather risk. Low-cost CH_4 sensors respond to humidity; the 2025 correction and weekly chromatograph comparisons keep the bias below 5%. If RNA yields are low in drained soil, we will pool replicate cores within a plot and time point, which costs replication but keeps the time series intact.

4.6 Reproducibility, permissions and safety

All analysis code will be kept in a version-controlled repository from the first season, with the processing of each data product scripted from raw files; the statistical models of R1 to R3 will be specified in a written analysis plan before the year-3 season, and any later change to that plan will be recorded with its reason. Field work at Teal Slough Farms is covered by a written access agreement that sets the cooperator's control over the timing of farm operations, the confidentiality of the farm's yield and financial records, and the return of all equipment. Students working in the field complete the university's field safety and heat illness training before their first day, work in pairs, and follow a written protocol for the gas cylinders and the chromatograph. The teacher institute and its assessment have been reviewed by the university's institutional review board as exempt research, and teachers consent to the use of their survey responses.

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4.7 What the project will establish

If the hypotheses hold, the project will show that the N_2O cost of AWD is set mainly by how long the surface soil stays oxidized, not by how deep the water falls; that repeated cycles shift the denitrifying community toward incomplete denitrification, so that the order of drains matters; and that a field-tested rule based on redox time can keep most of the CH_4 benefit while avoiding most of the N_2O cost. If they do not hold, the project will still deliver the first high-resolution record of redox, fluxes and gene expression through repeated drains in a working rice system, an open and validated instrument, and a direct test of whether depth-based safe AWD is already sufficient. Each outcome changes what growers and programs should do, and each gives the models of rice systems the measured redox trajectories they now lack.

5. Education Plan

My education goal is to make environmental measurement something students do with their own hands, from a ninth-grade classroom to a graduate laboratory, using the same instruments and the same data that the research uses. The plan builds on two observations from my first three years at Prairie Ridge State University. Students in our environmental measurements course could compute a flux from a textbook example but had never built or calibrated the instrument behind one; and the science teachers I met through the university's field day wanted local, real data for the carbon and nitrogen cycles, which the state's science standards emphasize but which their textbooks illustrate with examples from far away.

5.1 E1: measurement in the classroom

I will replace three weeks of lecture in BAE 3413, Environmental Measurements (about 40 students a year, required for the department's environmental and water resources track), with a module in which teams of three build a chamber node from a kit, write the calibration code, and test their node against the laboratory's chromatograph using standard gases. Each team then deploys its node for one week at the research farm in early fall, when the fields are drained for harvest, and writes a short report on its node's bias and noise. The module uses the active-learning structure that a large meta-analysis found improves student performance in science, engineering and mathematics courses [5]: short framing lectures, structured team problems, and frequent low-stakes checks. Nodes that meet the project's calibration standard (Table 1) join the R1 field network the following season, with the team named in the data set's documentation. Over five years, about 200 students will take the module.

Table 4: The E1 module in BAE 3413, week by week.

Week	In class	Team deliverable
1	How a chamber measures a flux; sensor physics; soldering and enclosure assembly	a working node that logs in the lab
2	Calibration with standard gases; humidity correction; uncertainty	calibration code and a bias and noise report
3	Field deployment at the research farm; comparing nodes; writing a data note	a one-page data note and the node's record

We will know the module works if students' scores on a short concept test about measurement uncertainty and calibration rise from the first to the last week, if teams' nodes meet the calibration standard, and if students who took the module choose measurement-heavy senior design projects more often than students before it. The concept test, the calibration records and the senior design choices are all collected as part of the course and analyzed with the Office of Assessment.

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5.2 E2: a summer institute for teachers

With the Harlow Bend School District, a rural district in the rice-growing region near campus whose science coordinator has worked with my laboratory since 2024, I will hold a one-week summer institute each year from year 2 to year 5 for eight middle and high school science teachers from the district and neighboring districts. Teachers spend two days building and calibrating a simplified chamber node, two days at the research farm measuring fluxes and redox potential alongside the graduate student and undergraduates, and one day writing lessons with a curriculum specialist from the College of Education. The lessons are aligned with the practices and crosscutting concepts of the Framework for K-12 Science Education [11] and the Next Generation Science Standards [12]: students plan an investigation, analyze real data, and construct an explanation of how water management changes the carbon and nitrogen cycles. Each teacher receives a stipend and a classroom kit with two nodes, and brings students to the research farm's fall field day. The institute is budgeted as participant support.

The week is organized as follows:

- **Days 1 and 2, on campus:** how a chamber measures a gas flux; assembling and calibrating a classroom node; the carbon and nitrogen cycles in a flooded field.
- **Days 3 and 4, at the research farm:** measuring fluxes and redox potential in the R1 plots with the graduate student and undergraduates; comparing the teachers' nodes with the laboratory's.
- **Day 5, on campus:** writing or adapting a lesson with the curriculum specialist, and planning the fall classroom visit.

Recruitment is through the district's science coordinator and the regional education service cooperative, with priority for teachers in schools where most students qualify for free or reduced-price meals. Support continues after the week: the graduate student visits each teacher's classroom once in the fall to help with the first use of the kit, teachers meet online twice during the school year to share what worked, and a returning teacher from the previous cohort serves as a lead teacher at the next institute. Lessons are revised after each school year from the teachers' logs and the observation notes, and the final versions are released with the node's build guide.

An example shows what the lessons ask of students. In "Does a rice field breathe?", a ninth-grade class receives a week of real chamber data from the research farm, one table from a flooded plot and one from a drained plot, with the dates of the drain. Students first predict which plot releases more methane and why, then plot the data, find the day the methane fell, and compare it with the water level. In a second session they receive the N_2O data for the same days and must explain why draining the field changed one gas in one direction and the other gas in the other. The lesson ends with a question growers face: when would you flood the field again, and what would you want to measure before you decide?

5.3 E3: a pathway into research

Each year two undergraduates will join the laboratory for a summer of full-time research and continue part time during the academic year. Recruitment draws on E1, where students show what they can do with an instrument, and on E2, through which teachers refer graduates of their schools who enroll at Prairie Ridge State University. Many students in both groups are the first in their families to attend college. Each undergraduate owns a defined piece of R1 or R2 (for example, the redox electrode quality checks or the qPCR standard curves), is co-mentored by the graduate student, presents at the university's undergraduate research symposium, and is offered authorship when the work is published. The design follows the elements that a National Academies consensus study associates with effective undergraduate research experiences, including ownership of a project, mentoring, and communication of results [10].

Mentoring follows a written structure. Each undergraduate meets weekly with the graduate student and every other week with me, keeps an electronic laboratory notebook that I review, and writes an individual development plan at the start of the summer that we revisit at its end. The laboratory holds a weekly meeting at which undergraduates present their progress in turn, and each summer ends with a short written

report in the format of a journal article. Students are paid for their time at the university's undergraduate research rate, so that research is open to students who must work during the summer.

5.4 Assessment

The College of Education's Office of Assessment will help design the instruments and will analyze the survey data each year at no cost to the project (Table 5). Results will be used to revise each activity the following year.

5.5 Reaching rural and first-generation students

Most of the region's rice-growing counties are rural, and many of their students would be the first in their families to attend college. The plan reaches them at three points: in their own classrooms through the teachers of E2, at the research farm's field day, which many of their families already attend, and on campus through the paid research positions of E3. The pathway is designed so that a student can move from one to the next: a high school student who builds a node in class with an E2 teacher can meet the laboratory at the field day, enroll at Prairie Ridge State University, take BAE 3413, and join the laboratory as an undergraduate researcher. We will track how many students take each step, with consent, as part of the assessment.

5.6 Sustaining the activities after the award

The E1 module will become a permanent part of BAE 3413; the department has agreed to keep the course's laboratory fee at a level that pays for replacement node kits. The teacher network will continue through the lead-teacher model, with the lessons and the kit design freely available, and the district has indicated that it will fund kits for new teachers from its science budget after year 5. The open-hardware release lets other universities and extension programs adopt the node without the laboratory's involvement.

Table 5: Education objectives, measures and targets.

Activity	Outcome	Measure	Target
E1 course module	measurement and calibration skills	pre/post concept test; graded node report	+25% mean gain
E1 course module	student-built nodes in research	nodes passing calibration	6 nodes per year
E2 teacher institute	lessons taught with local data	classroom observation; teacher logs	6 of 8 teachers
E2 teacher institute	students reached	enrollment in participating classes	600 students over 4 years
E3 undergraduate research	persistence in STEM	enrollment and degree records	80% complete a STEM degree
E3 undergraduate research	communication	symposium talks; co-authored papers	10 talks; 3 papers

6. Integration of Research and Education

The research and education objectives share instruments, data and people. The chamber node is the common object: designed in the laboratory, rebuilt and calibrated by students in E1, simplified for teachers in E2, and deployed in the R1 and R3 field networks. The data flow both ways: the R1 data set supplies the course and the institute with local measurements, and the course and the institute add measurements to it, each with its calibration record. The graduate student leads the field work of R1 and R2 and serves as a teaching assistant for the E1 module in years 2 and 4, which gives the student both research and teaching experience,

a combination my department values in its graduates. The undergraduates of E3 come largely from E1 and E2 and return to them as peer mentors, so each cohort teaches the next.

The graduate student's development is part of the integration. Besides leading the field work, the student co-teaches the E1 module twice, assists at the teacher institute each summer, and mentors the undergraduates of E3, under an individual development plan reviewed each year. By the end of the project the student will have designed and taught laboratory material, mentored at least four undergraduates, and presented the research to growers, teachers and scientists, a preparation for academic, agency and industry careers alike.

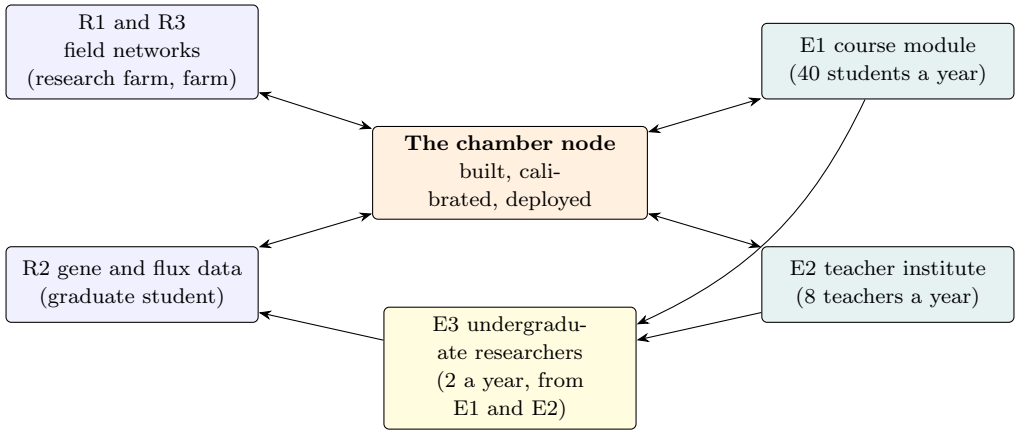


Figure 6: How research and education meet. The node and its data move between the field networks, the course and the institute; undergraduates recruited through E1 and E2 work on the data of R2.

7. Benefits to Society

The Broader Impacts of this project reach farmers, teachers and students across the Mid-South, and they follow from the research rather than sitting beside it. For growers and the crop consultants who advise them, R3 will produce a tested reflooding rule and a low-cost way to apply it. We will present the rule and the farm validation results at the research farm's annual field day, where several hundred growers and consultants attend each year, and in a two-page grower guide written with the cooperating farmer. For the scientific community, R1 and R2 will produce the first data set in which CH_4 flux, N_2O flux, redox potential and functional gene expression are measured together through repeated drain and reflood cycles; it will be shared as described in the Data Management and Sharing Plan.

The chamber node itself is a contribution. Its design, firmware and calibration procedure will be released under open licenses so that other laboratories, extension programs and classrooms can build it. Build guides, calibration code and the teacher lessons from E2 will be posted on the project website at https://awd-lab.prsu.example/build and updated as the design improves. For the region's schools, the institute will give at least thirty-two teachers and several hundred students direct experience with environmental measurement in the setting where their families work. For the workforce, the project will train one doctoral student and about ten undergraduates in field instrumentation, molecular methods and data analysis, skills in demand in agricultural technology, environmental consulting and public agencies.

The results also bear on decisions beyond the farm. Programs that pay growers for reducing methane through water management need measurements they can trust, and they generally count CH_4 more carefully than N_2O; a rule that manages both, and a node that measures redox cheaply, give such programs a way to check that a practice change does not simply shift emissions from one gas to the other. We will share the results with the state's conservation and extension agencies through the field day and the grower guide, and with the scientific community through peer-reviewed publications, presentations at national meetings of the soil and agricultural engineering societies, and the open data set. For the public, the laboratory will run a

hands-on station on how rice fields breathe at the county fair and the university's science open house each year, staffed by the undergraduates of E3.

The project is also designed to widen who does this science. Field research in agriculture can be hard to enter for students without farm connections, transportation or summer income. The paid positions of E3, transportation to the research farm for all field activities, and recruitment through the region's own schools remove those barriers for the students the project serves, and the teacher institute brings the field to students who would not otherwise see it.

Finally, the project contributes to better measurement in a field where measurement is expensive. Static chambers and eddy covariance are well established, and comparisons between them are available for rice [13]; low-cost sensors are newer, and their limits are less well documented. By publishing the node's validation against gas chromatography, its failure modes and its correction for humidity, together with the redox electrode protocol, the project gives other groups a documented, inexpensive option for the plot-level measurements that drainage studies need.

8. Timeline and Management

The PI directs the project, supervises the graduate student and undergraduates, teaches the E1 module, and leads the E2 institute with the district's science coordinator. The graduate student leads field operations and the R2 assays from year 2. The cooperating farmer manages the farm-scale fields in years 4 and 5. The department head, who mentors the PI under the department's mentoring program for early-career faculty, meets with the PI each semester to review progress against the timeline (Table 6).

Two risks to the education plan are planned for. If teacher recruitment falls short in a given year, the institute will open to pre-service teachers from the College of Education, who take the same week and use the kits in their student teaching. If a cohort of undergraduates is smaller than planned, the summer positions will be offered through the university's existing summer research program, which recruits statewide. The graduate student will be recruited in year 1 from the department's applicant pool and from the master's students trained under the prior award, and will begin field work in the spring of year 2.

The project team meets weekly during the field season and every two weeks otherwise. The cooperating farmer and the district's science coordinator join a planning meeting each winter, at which the season's field schedule and the summer institute are set. Progress is reported each year in NSF's annual report, and the department head's semester reviews check the education milestones alongside the research milestones.

Table 6: Timeline by project year (each mark is one half year).

Activity	Year 1		Year 2		Year 3		Year 4		Year 5	
Node revision, electrode tests, field installation	•	•								
R1 field experiment, research farm			•	•	•	•				
R2 sampling and qPCR			•	•	•	•		•		
R3 rule built (year 2 data), tested at the farm				•	•					
R3 farm validation, Teal Slough Farms							•	•	•	•
E1 course module (fall)		•		•		•		•		•
E2 summer teacher institute			•		•		•		•	
E3 undergraduate researchers (two a year)	•	•	•	•	•	•	•	•	•	•
Grower guide, open hardware release, field days						•		•		•

9. Results from Prior NSF Support

Award ENG-0000000 (fictional), $199,876, September 1, 2023 to August 31, 2025, "ERI: Low-Cost Chamber Sensors for Field Methane Flux in Flooded Rice" (PI: Wren Castellano). The project set out to design a

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chamber sensor for CH_4 flux cheap enough to be deployed in every plot of a field experiment, and to test it against gas chromatography. It produced the node described in Section 3: a closed-path chamber with a metal-oxide CH_4 sensor and an infrared CO_2 sensor, temperature and humidity compensation, and redox electrodes, at about $180 in parts. Across 212 closures in two seasons the node's CH_4 fluxes agreed with chromatograph fluxes with $R^2 = 0.91$, and the project found and corrected a humidity bias that affects metal-oxide sensors at low fluxes, a correction that other groups using such sensors can apply. The award supported one graduate student, who completed a master's thesis on the sensor's calibration in 2025 and now works for an environmental monitoring firm, and three undergraduates, two of whom are now in graduate programs. The node was used in a pilot module in BAE 3413 in fall 2024 and in two classroom visits in the Harlow Bend School District, the origin of objectives E1 and E2.

The project also tested three chamber geometries and two closure times. Taller chambers reduced the disturbance of the rice canopy late in the season but increased the time needed to detect low fluxes; the final design uses an extension collar added at panicle initiation, which keeps the detection limit below 0.1 mg CH_4 m^{-2} h^{-1} through the season. A comparison of six-minute and twelve-minute closures showed no difference in flux for closures without ebullition, so the shorter closure, which allows more closures per day, was adopted. These results, together with the redox electrode installation protocol, are the technical basis of R1. In its outreach, the project brought the node to the research farm's field day in 2024 and 2025, where growers asked whether the node could tell them when to reflood, the question at the center of R3.

No publications were produced under this award. A manuscript describing the node and its humidity correction is in review. The node's design files, firmware and the 2024 and 2025 validation data are available in the university's institutional repository [3]. The master's thesis supported by the award, on the calibration of metal-oxide sensors under field humidity, is available through the university library, and the calibration code is included with the design files. The data set includes every closure, its raw concentrations and the computed fluxes, so that others can test their own flux calculations against the chromatograph values.