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Exploring opportunities for reduced tillage systems in California rice

By

MIA GODBEY
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

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in the

OFFICE OF GRADUATE STUDIES

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DAVIS

Approved:

Bruce A. Linquist, Chair

Jeffrey Mitchell

Cameron M. Pittelkow

Committee in Charge

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Abstract

Rice production relies heavily on tillage for seedbed preparation, crop establishment, and residue management. However, reducing tillage may decrease production costs, conserve soil moisture, and provide greater flexibility in the timing of field operations. Despite these potential benefits, the effects of reduced tillage on rice productivity remain uncertain, particularly in flooded rice systems. This dissertation evaluated the agronomic effects of reduced tillage in rice at both global and regional scales and examined alternative tillage and establishment systems for California rice production.

The first study used a global meta-analysis of 115 studies and 579 paired observations to quantify rice yield responses to no-till (NT) relative to conventional tillage (CT) and identify conditions associated with improved NT performance. Across studies, NT reduced rice yield by 4.8%. Soil organic carbon, N fertilizer rate, soil pH, and clay content were among the most important factors associated with NT performance. Higher N rates and soils with greater organic carbon, moderate pH, and greater clay content reduced the NT yield penalty, although NT generally did not exceed CT yield.

The second study evaluated a summer stale seedbed (SSB) as an alternative approach for reducing spring tillage in California water-seeded rice. On-farm experiments conducted across four location-years and a replicated experiment at the Rice Experiment Station compared SSB, in which fields were prepared during a preceding summer fallow and planted the following spring without additional tillage, with conventional spring tillage. Grain yield and N response were similar between SSB and CT. SSB also conserved more preplant soil water, while crop establishment, disease severity, and seed midge abundance were generally similar between

tillage systems. These results demonstrate that shifting tillage from spring to the preceding summer can reduce spring soil disturbance without compromising productivity.

The third study expanded this work by comparing conventional tillage water-seeded rice (CT-WS) with summer stale seedbed drill-seeded rice (SSB-DS) and two continuous no-till drill-seeded systems (NTDS) differing in rice straw management. SSB-DS maintained similar or greater yield potential than CT-WS, whereas the NTDS systems had lower yield potential overall. Drill-seeded systems required greater N rates to reach maximum modeled yield than CT-WS. Differences in emergence and final stand density did not explain the contrasting yield responses among drill-seeded systems, and reduced tillage did not increase stem rot or aggregate sheath spot severity.

Collectively, these studies demonstrate that the agronomic effects of reducing tillage in rice depend on how reduced tillage is implemented. Continuous NT presents a greater risk of yield loss, whereas a summer SSB can substantially reduce spring tillage while maintaining rice productivity. In California, shifting seedbed preparation to fallow periods and combining summer SSB management with either water or drill seeding provides a promising approach for increasing flexibility in rice production while reducing reliance on conventional spring tillage.

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CHAPTER ONE

Title: No-till in rice systems: A global meta-analysis of key agronomic practices impacting yields

Authors: Mia Godbey^{a*}, Ignacio Macedo^b, Cameron M. Pittelkow^a, Bruce Linquist^a

^aDepartment of Plant Sciences, University of California, Davis CA, 95616

^bInstituto Nacional de Investigacion Agropecuaria, INIA – Uruguay, Ruta 8 km 281, Treinta y Tres 33000, Uruguay

*Corresponding author: Department of Plant Sciences, University of California, Davis, One Shields Ave., Davis CA 95616

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Highlights

- Global analysis of 579 paired observations (NT vs. CT) from 115 studies (1985 – 2025).
- No-till caused a 4.8% decrease in yields compared to conventional tillage.
- No-till yields improved in soils with fine texture, high carbon, and neutral soil pH.
- No-till systems improved at higher N rates but were still below CT yields.
- Rice establishment system, rotation, residues, and climate zone showed no effects.

Abstract

While no-till (NT), one of the pillars of conservation agriculture, is widely practiced in upland crops, considerably less research has been conducted in rice systems. While adoption has been limited, numerous field experiments have evaluated NT rice across diverse regions and management contexts yet reported yield responses to key agronomic practices, soil properties, and climatic conditions remain inconsistent and poorly synthesized at a global scale. Our objective was to conduct a global meta-analysis comparing the effects of NT to conventional tillage (CT) on rice yields and to identify the agronomic practices, soil characteristics, and climate factors most strongly associated with yield changes under NT. We performed a global meta-analysis of 115 studies (579 paired observations) comparing rice yields under NT and CT. Yield response ratios (lnRR) were analyzed using mixed-effects meta-analysis to estimate overall effects. Meta-regression and Random Forest modeling were used to assess relative importance of soil properties, management practices, and climatic factors influencing NT performance. Overall, there was a 4.8% yield reduction under NT. The key factors influencing yield were soil organic carbon (SOC), nitrogen (N) application rate, soil pH, and soil clay content. Soil SOC levels above 18 kg ha⁻¹, N rates above 120 kg ha⁻¹, a pH range of 6 – 7, and clay content between 180 – 350 g kg⁻¹ were associated with improved NT yields. Residue retention and crop rotation – the other two key components of conservation agriculture along with minimum tillage – had limited influence on yield outcomes in flooded rice systems. This global meta-analysis provides the most up-to-date, and largest, global, quantitative framework for targeting NT. Results indicate that based on soil properties (higher SOC and clay content, moderate pH) coupled with sufficient N inputs, NT yields are highest. However, our analysis suggests that even under these more optimal conditions, NT yields might be similar to but not

exceed CT yields. That said, given other benefits of NT, it may be economical under certain conditions. We conducted the most comprehensive and up-to-date global meta-analysis on NT impacts in rice since 2013. This study evaluates how soil properties, agronomic management, and climatic conditions influence yield differences between NT and conventional tillage (CT) and identifies the key conditions under which NT may be agronomically viable.

Keywords: no-till, conservation agriculture, soil organic carbon, nitrogen, soil clay, soil pH

1. Introduction

In the pursuit for sustainable agricultural practices, which has intensified in recent years due to climate change, environmental degradation, and resource constraints, no-till (NT) has emerged as a promising option (Gangopadhyay et al., 2023). No-till is one of the three pillars of conservation agriculture, along with the retention of crop residues and implementation of crop rotations (Rai et al., 2011). Studies suggest there are numerous benefits to NT, including: reduced soil erosion, increased carbon sequestration, improved soil aggregation and structure, retention of soil moisture, and reduction of sediment runoff into water bodies (Crusciol et al., 2016; Nandan et al., 2019; Qi et al., 2022a; Somasundaram et al., 2020). However, many of these benefits have been demonstrated primarily in upland cropping systems and may manifest differently in rice environments due to flooded conditions along with the associated anaerobic soil conditions and different management practices. Economically, there is also potential for reduced costs (Watkins et al., 2008), with Jat et al. (2020) reporting a 25% increase in net economic returns across thousands of on-farm and on-station studies in South Asia.

Globally, it is estimated that NT is implemented on approximately 180 million hectares, representing around 14% of the world's total arable land (Jayaraman & Dalal, 2022). Since the mid- to late-1990s, NT has gained momentum due to advancements in herbicide application methods and NT technologies, along with economic incentives and its ability to mitigate soil erosion (Derpsch et al., 2010). While NT has been widely studied and adopted in upland cropping systems – including those rotationally linked with rice (Jat et al., 2009; Lal et al., 2004; Nawaz et al., 2019; Yao et al., 2013) – research examining the direct agronomic effects of NT on rice yields remains comparatively limited, fragmented, and geographically concentrated (Liu et al., 2024).

Rice, a major staple food crop globally, is grown on 11% of farmland and provides 21% of human calories (Yuan et al., 2021). It is the main source of food for over half of the global population and provides more than 75% of the calorie intake in some developing countries (Shi et al., 2023). Research to date has indicated that, as with other crops, rice yields under NT are variable (Chakraborty et al., 2017; Hashimi et al., 2023; Huang et al., 2015). Compared to other crops, NT may cause an overall greater yield reduction in rice (7.5%; Pittelkow et al., 2015b), but few studies have investigated the role of soil, climate, and management practices in explaining potential yield changes.

Some rice-focused studies suggest that NT reduces rice yields due to a reduction in plant density (Vitali et al., 2024) and greater soil compaction, which restricts root growth and limits nutrient uptake (Huang et al., 2015). Furthermore, the anaerobic environment of a flooded rice field impacts soil biogeochemistry, altering nutrient availability and C dynamics (Gatkal et al., 2024). Conversely, others have reported the potential for NT to enhance yields due to increase nitrogen, phosphorus, and carbon sequestration (Nandan et al., 2019; Yang et al., 2020) which leads to greater nutrient uptake compared to CT systems (Yang et al., 2020). These differences may explain why NT yield responses in rice often differ from those observed in upland cropping systems. Beyond these yield-related mechanisms, several practical constraints also limit the effectiveness of NT in flooded rice systems.

Flooded soils often remain soft and highly plastic, which reduces early root anchorage in NT fields (Saurabh et al., 2021). Rainfall and wet soils during harvest can create deep ruts that carry over into the next season without tillage to level the field surface (Jat et al., 2020). Transplanting seedlings into NT fields is more labor-intensive and often results in weaker seedling anchorage and delayed establishment (Farooq et al., 2011; Kumar & Ladha, 2011).

Finally, continuous rice systems produce high amounts of surface residues, which can interfere with seeding and germination and further promote anaerobic conditions that restrict early crop vigor (Gathala et al., 2011). Together, these agronomic and operational constraints likely contribute both to the yield penalties and may be why NT adoption in rice remains limited.

There are three main crop establishment methods in rice that may impact the success of NT practices (Chakraborty et al., 2017). Traditionally, rice is established by transplanting (TP) young seedlings into fields that have been tilled, flooded, and puddled. This method ensures uniform plant spacing and minimizes weed competition but requires significant amounts of labor and water (Chen et al., 2020). This practice is common throughout Asia where roughly 90% of the world's rice is grown (Rai et al., 2011). Rice can also be direct seeded. Broadly, there are two forms of direct seeding: dry seeding (DS) and wet seeding (WS). Dry seeding consists of planting seeds into soil using drill seeders or broadcast methods, similar to how upland crops are planted. In contrast, wet seeding involves broadcasting pre-germinated seeds into flooded fields. Dry seeding is more common in rice systems outside of Asia (Rao et al., 2007); however, given the labor demands of TP rice, direct seeded practices are becoming more common in Asia (Chaudhary et al., 2023). Both DS and WS rice with tillage have been found to have similar yields to TP; however, direct seeded NT yields were significantly reduced relative to conventionally tilled TP rice yields (Liang et al., 2016; Chakraborty et al., 2017).

The impact of NT on rice yields remains unclear, with previous reviews reporting substantial heterogeneity, ranging from significant yield declines to yields comparable to conventional tillage (CT) (Table 1.3). Although most reviews include rice within broader evaluations of NT, most do not explicitly examine how soil fertility, nutrient management, soil physical properties, and climate interact to impact yield responses under NT in flooded rice systems. As mentioned

above, it is likely that rice responds differently to NT than upland crops due to prolonged flooding, anaerobic soil conditions, and distinct residue and nutrient dynamics. To date, only one global review has evaluated moderating variables affecting NT performance in rice (Liang et al., 2016). However, that study was limited to publications available up to 2013, included a smaller number of observations, and did not evaluate several key soil and management variables that are now widely recognized as central to NT performance. Since 2013, a substantial number of field-based research publications have emerged across diverse agroecological regions. To address these limitations, this study provides the most up-to-date global meta-analysis of NT impacts on rice yields, while explicitly identifying the soil, nutrient, management, and climatic conditions under which NT yield penalties are minimized.

Here, we employ a global mixed-model meta-analysis to quantify (i) the effect of NT on rice yields compared to CT, and (ii) to assess the agronomic variables of importance that influence yield differences. By synthesizing data across diverse environments, this study aims to determine the conditions under which NT can be a viable strategy for sustainable rice production, identify factors that minimized yield penalties, and provide insights to optimize management practices for NT adoption in rice-based systems.

2. Methods

2.1 Data Collection

A literature search was conducted through August 2025 of peer-reviewed publications using the following Boolean search terms: “rice no till yield,” “rice no tillage yield,” “rice zero till yield,” “rice zero tillage yield,” “rice conservation till yield,” “rice conservation tillage yield” in the Web of Science Core Collection. All studies used in this analysis were written in English.

Titles and abstracts were screened, and data was extracted from full texts according to the procedure summarized below.

There were two main criteria required for selecting: (1) yield data from both CT and NT were obtained in a field study and, (2) it was a side-by-side comparison of NT and CT within the same crop establishment system with all other factors being the same. Various forms of minimum tillage or reduced tillage were not included in this analysis.

Literature screening was conducted in multiple stages. During title and abstract screening, studies were excluded if they were reviews, modeling studies, greenhouse or pot experiments, or did not include a direct NT – CT comparison in rice. Full-text screening was then used to confirm eligibility and data extractability. Studies were excluded at this stage if yield data were not reported or if NT and CT comparisons could not be clearly paired. However, all included studies met the predefined eligibility criteria above, and exclusion decisions were based on consistent and transparent rules.

For papers meeting these criteria, all relevant data were manually extracted from the selected papers, including mean yields (kg ha^{-1}), standard deviation (SD) or standard error (SE), sample size, and other ancillary data such as location, establishment system, crop rotation, residue management, climate, N management, and soil characteristics (Table 1.1; Table 1.2).

Table 1.1. Distribution of observations for each establishment system by country. TP – transplanting, DS – dry seeding, WS – water seeding.

	Studies (#)	Observations (#)	Establishment System (%)		
Country/region			TP	DS	WS
Asia					
China	46	275	68	17	11
India	43	198	29	71	-
Bangladesh	4	14	100	-	-
South Korea	3	15	47	53	-
Philippines	3	6	33	67	-
Japan	1	2	100	-	-
Indonesia	1	1	-	100	-
America					
Brazil	3	21	-	100	-
United States	3	8	-	37	63
Africa					
Nigeria	3	16	100	-	-
Benin	1	5	-	100	-
Cameroon	1	4	100	-	-
Europe					
Spain	2	9	-	100	-
Italy	1	5	-	100	-

Table 1.2. List of variables extracted from studies, including number of observations and method of categorization. When range is provided, these variables are treated as continuous variables.

Variable	Studies	Observations	Assumptions/Categorizations
Soil Properties			
Soil pH	97	475	Range: 4.3 – 8.5
Soil C (g/kg)	86	456	Range: 0.53 – 42.40
Soil Clay (g/kg)	95	460	Range: 32 – 600
N Rate (kg/ha)	101	526	Range: 0 – 230
Soil Texture			
Fine (Clayey)	7	36	Sandy clay, silty clay, clay
Moderately Fine (Loamy)	44	169	Clay loam, sandy clay loam, silty clay loam
Medium (Loamy)	16	84	Very fine sandy loam, loam, silt loam, silt
Moderately Coarse (Loamy)	31	173	Coarse sandy loam, sandy loam, fine sandy loam
Establishment System			
Transplanted	62	302	Hand or machine transplanted
Dry seeded	56	243	Dry seeding, usually using a drill-seeder
Water seeded	7	34	Broadcasting soaked and pregerminated seed into a flooded field. Includes practices such as thrown and grown, seedling throwing, manually thrown, manually broadcast
Climate Zone			
Subtropical	92	488	
Tropical	17	69	
Temperate	6	22	
Residue			
Yes	58	239	
No	42	163	
Rotated			
Yes	29	145	
No	44	221	
Previous Crop			
Brassica	13	62	Jute, mustard, oilseed rape, rapeseed
Legume	7	21	Chinese milk vetch, cover crop, mung bean, sesbania
Grass	36	215	Greengram, green-gram, maize, ryegrass, wheat, winter maize
Rice	48	243	Continuous rice, double-cropping rice, mono-rice paddy, ratoon rice, rice-ratoon rice, rice-rice

If SD or SE was not reported, variance was estimated using the average coefficient of variation (CV) derived from the full dataset, following the approach of (Nakagawa et al., 2023). Specifically, when only SE was reported, SD was calculated using:

$$SD = SE \times \sqrt{n}$$

If both SD and SE were missing, SD was approximated using the average CV and the reported mean values using:

$$SD = Yield \times CV_{mean}$$

Only 23% of cases reported SE; the remainder were imputed as described above.

In cases where data were only published graphically, we used WebPlotDigitizer (<https://apps.automeris.io/wpd4/>) to extract the values. One extreme outlier (Fangueiro et al., 2017) was excluded from the final dataset as its yield ratio of 1.7 was higher than 3 SD from the mean (1.34), which comprised 579 comparisons from 115 papers published between 1985 and 2025.

Soil carbon was prioritized over total soil N due to more frequent reporting. When soil carbon was not provided, but organic matter (%) was reported (Guo & Gifford, 2002), it was estimated as:

$$Soil\ C = Organic\ Matter \times 0.58$$

Alternatively, when total N (%) was reported but not C (USDA-NRCS), it was assumed:

$$Soil\ C = Total\ N \times 10$$

Assumptions were made for categorical variables with ambiguous reporting. For example, systems labeled as “thrown and grown,” “seedling throwing,” “manually thrown,” and “manually broadcast” were recorded as WS (Table 1.2). There were 26 observations from 5 papers, all originating from China, that used these terms. Soil textural classes were inferred using

the USDA Soil Texture Triangle (*Soil Survey Manual 2017*, n.d.), and median clay percentages were assigned accordingly when clay content was missing.

Residue management was classified as retained (yes) or removed (no). Because the term “stubble” was inconsistently defined, it was excluded from consideration. Crop rotations were categorized as “rotated” or “not rotated.” Systems such as continuous rice, double-cropping rice, mono-rice paddy, ratoon rice, rice-ratoon rice, and rice-rice were designated as not rotated, while rice with all other crops listed in the NT database under crop rotation were considered rotated. Additionally, in studies that included ratoon rice, only main season crop yields were reported. Rotated systems were categorized into broad classes of previous crops: brassicas, legumes, and grasses (Table 1.2).

Soil textural classes were categorized following Chakraborty et al. (2017) and using the Soil Survey Manual (2017) into four classes: fine, moderately fine, medium, and coarse. Establishment systems were classified as transplanted (TP), dry seeded (DS), or water seeded (WS). Climate was delineated into three zones: temperate, tropical, and subtropical.

2.2 Data analysis

We used the natural logarithm of the response ratio (lnRR) to quantify and compare the yield performance of NT (Y_{NT}) against CT (Y_{CT}) in rice systems (Hedges et al., 1999):

$$\ln RR = \ln \left(\frac{Y_{NT}}{Y_{CT}} \right)$$

The corresponding sampling variance (v_i) was calculated as:

$$v_i = \left(\frac{SE_{NT}^2}{Y_{NT}^2} \right) + \left(\frac{SE_{CT}^2}{Y_{CT}^2} \right)$$

where SE_{NT} and SE_{CT} represent the standard errors of the NT and CT treatment yields.

A mixed-effects meta-analysis was conducted using the '*rma.mv*' function in the '*metafor*' package (Viechtbauer, 2010) in R. We treated each unique study and observation nested within studies as random effects to account for study-level clustering and within-study dependence. The overall mean lnRR was back transformed to express the percent yield change under NT as:

$$\text{Percent Change} = (e^{\ln RR} - 1) \times 100$$

To assess potential publication bias, we conducted Egger's regression test ('*regtest*') (Viechtbauer, 2010).

Separate mixed-effects meta-regression models were then fitted for each moderator. Fitting all moderators in a single model would have substantially reduced sample size, so this approach is consistent with recommendations for sparse datasets using complete cases of each moderator (Viechtbauer, 2010). Meta-regression models were fitted using '*rma.mv*' with REML estimation (Lenth, 2009). Effect sizes (lnRR) were converted to percent change and presented as forest plots grouped by variable level using '*ggplot2*' (Wickham 2020). Observations per level were labeled by the number of contributing studies.

To explore non-linear relationships and identify the most important variables influencing yield response to NT, we used Random Forest (RF) models (Breiman, 2001). Random Forest is a non-parametric ensemble modeling approach that constructs multiple decision trees and combines their results to improve prediction accuracy (Tseng et al., 2021). It has become increasingly popular in agricultural and ecological studies because it can handle multicollinearity, accommodate missing values, and model nonlinear relationships among variables (Tseng et al., 2021). In this study, the model was implemented using the '*ranger*' package (Wright & Ziegler, 2017) in R with *ntree* = 1000 and *mtry* = 3, meaning the model included 1000 trees and considered 3 randomly selected variables at each split. This choice

follows common heuristics for random forest regression, where $mtry$ is typically set to the square root of the total number of predictors to reduce correlation among trees and minimize prediction error (Breiman, 2001). Given that our model included ten predictor variables, $\sqrt{10} \approx 3.2$, we therefore selected $mtry = 3$. Preliminary checks using alternative $mtry$ values (including the default regression setting) produced qualitatively similar variable importance rankings and effect patterns, indicating that model results were robust to reasonable changes in this parameter. As a result, we did not pursue extensive hyperparameter tuning.

Missing values for RF modeling were imputed using the ‘*missRanger*’ package (Mayer 2025). Variables included were both continuous (e.g., pH, soil clay, soil C, N rate) and categorical (e.g., soil texture, establishment system, previous crop class, climate zone, residue retention, and crop rotation). To interpret model behavior and quantify marginal effects, we used the ‘*iml*’ package (Molnar et al. 2018) in R. Variable importance was assessed by permuting each predictor and measuring the resulting increase mean squared error (MSE). We then visualized the effect of key predictors using Accumulated Local Effects plots via the ‘*DALEXtra*’ package (Maksymiuk et al. 2020), highlighting non-linear responses of yield ratio to continuous variables.

3. Results

3.1. Data overview and global yield trends

A total of 579 paired yield observations from 115 studies published between 1985 and 2025 were included in this meta-analysis. This represents a significant increase in scope compared to earlier syntheses (Table 1.3), enabling a more comprehensive evaluation of NT systems in rice production.

Table 1.3. General results from this current and previous reviews compared on the impact of NT on yields in rice systems. ns – not significant

Study	Scope	Number of rice observations	Yield impact of NT relative to CT	Important variables (when NT had lower yields)
Current study (2025)	Global; only rice; yield focus	579	- 4.76%	Soil pH > 6.0 and < 7.0; soil clay content > 18% and < 35%; soil organic carbon > 14 g kg ⁻¹ ; Nitrogen rate > 125 kg ha ⁻¹
Liang et al. (2016)	Global; only rice; yield focus	381	-3.83%	Soil pH (< 6.5); soil texture (sandy soils); establishment method (direct seeding); N rate < 120 kg ha ⁻¹ ; duration < 3 years)
Huang et al. (2015)	China; only rice; yield focus	265	ns	Soil pH (< 6.0); low fertility; no rotation
Hashimi et al. (2022)	Asia; major agronomic crops; soil properties focus and yield	64	ns	No examination of moderating variables within cropping systems
Liao et al. (2021)	Global; only rice; GHG focus	52	ns	No examination of moderating variables
Su et al. (2021)	Global; major agronomic crops; yield focus	195	ns	No examination of moderating variables
Zhao et al. (2019)	Global; only rice; GHG focus	22	ns	No examination of moderating variables
Huang et al. (2018)	Global; major agronomic crops; GHG focus	52	ns	No examination of moderating variables
Pittelkow et al. (2015b)	Global; major agronomic crops; yield focus	154	-7.5%	No examination of moderating variables

The majority of studies were conducted in China ($n = 46$) and India ($n = 43$), together accounting for over 77% of the dataset. Most rice systems evaluated used either TP or DS methods; only 6% involved WS rice. Climatically, 80% of observations were from subtropical environments, followed by tropical (15%) and temperate (5%) zones (Figure 1.1).

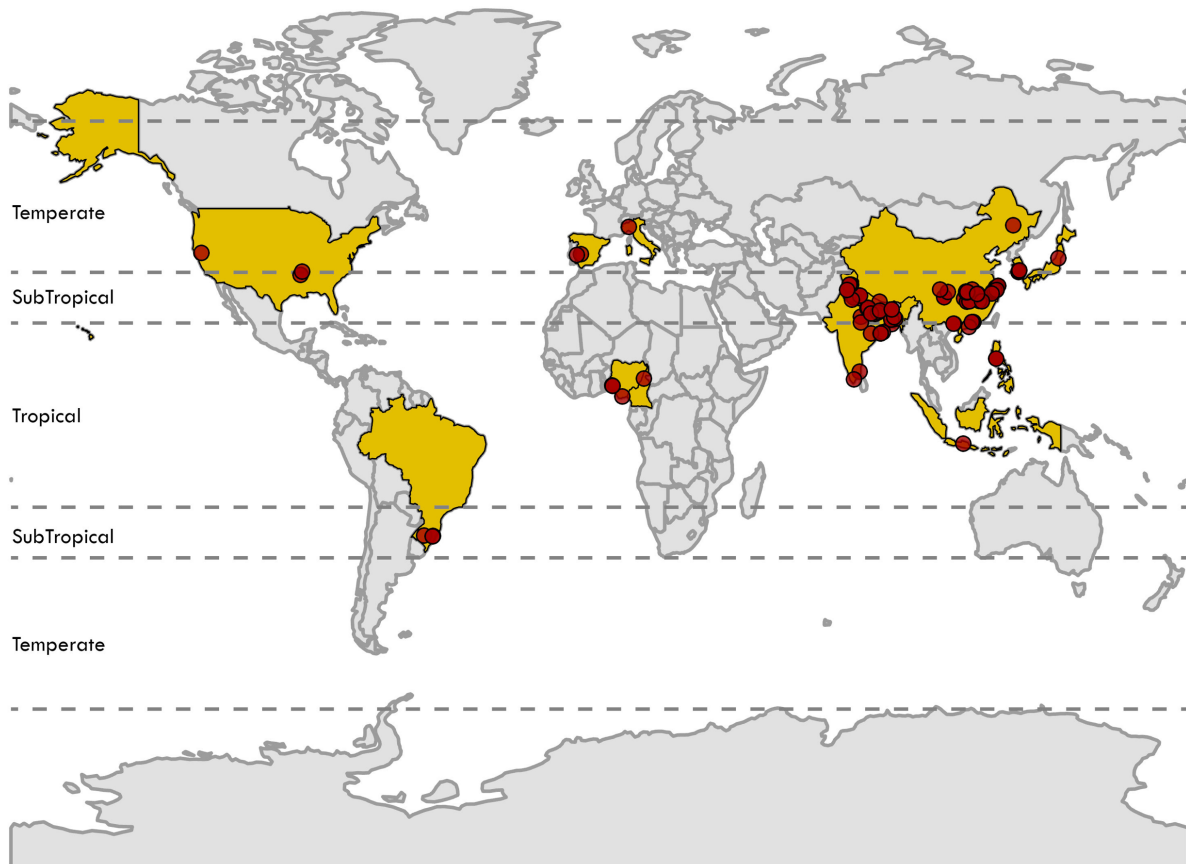


Figure 1.1. Map of study sites from all 115 papers. The red dots represent the coordinates of the study sites in each paper, and the yellow shading represents the countries in which the studies were conducted. The climate delineations – temperate (22 observations, 4 papers), subtropical (488 observations, 95 papers), tropical (69 observations, 16 papers) – are shown between the horizontal lines.

The log-transformed yield response ratio (lnRR) under NT was negatively skewed, indicating that most comparisons reported lower yields under NT relative to CT systems (Figure 1.2). Across all paired observations, 30.4% showed yield increases under NT, 67.6% showed yield reductions, and 2% showed no difference. A random-effects meta-analysis supported this pattern, revealing a significant mean yield reduction of 4.8% under NT relative to CT ($\lnRR = -0.0476$; $p < 0.001$). Substantial heterogeneity was observed among studies ($p < 0.0001$), indicating considerable variability in yield responses to NT across regions, management practices, and environmental conditions. The high degree of heterogeneity justified the use of mixed-effects models and further exploration of moderating variables. Assessment of publication bias using Egger's regression test did not indicate significant asymmetry in effect sizes ($p = 0.57$), suggesting that the results were not strongly influenced by publication bias.

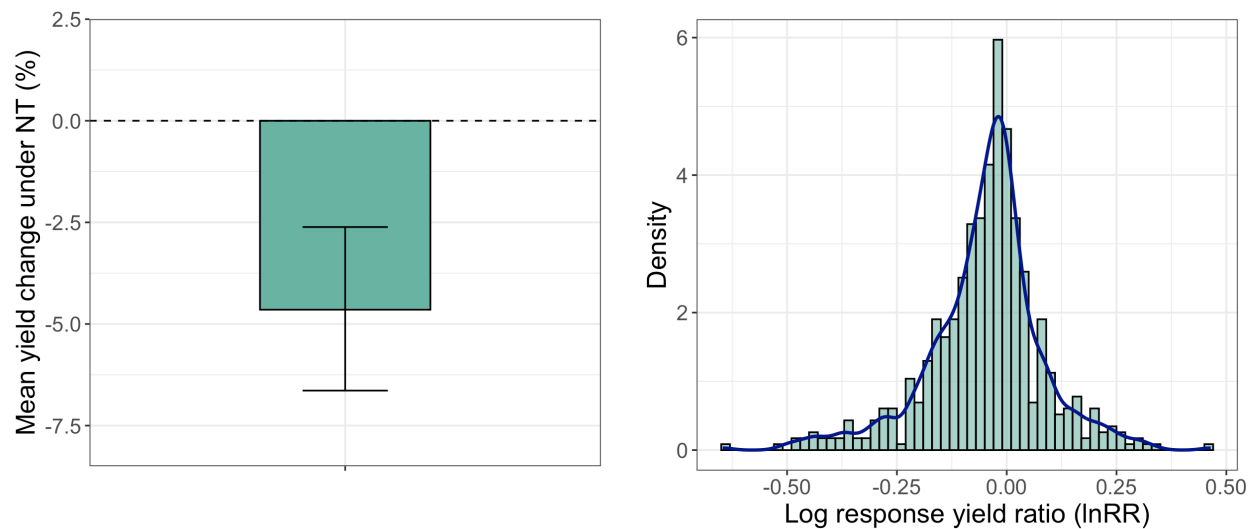


Figure 1.2. Effect of no-till on rice yield. Error bars refer to 95% confidence intervals (CIs) (left). Distribution of log-transformed response ratios of rice yield (lnRR) to NT/CT (right).

3.2. Key predictors of NT yield performance

The Random Forest analysis explored potential drivers of variation in yield response. This model explained approximately 34% of the variance in yield ratio. Among the 10 candidate variables, four emerged as primary predictors of yield under NT: soil organic carbon, nitrogen application rate, soil pH, and clay content, (Figure 1.3). Accumulated Local Effects plots (Figure 1.4) revealed that NT systems performed best when SOC was above 18 g kg⁻¹, soil pH was between 6 and 7, clay content between 180 – 350 g kg⁻¹, and N rates were above 120 kg N ha⁻¹.

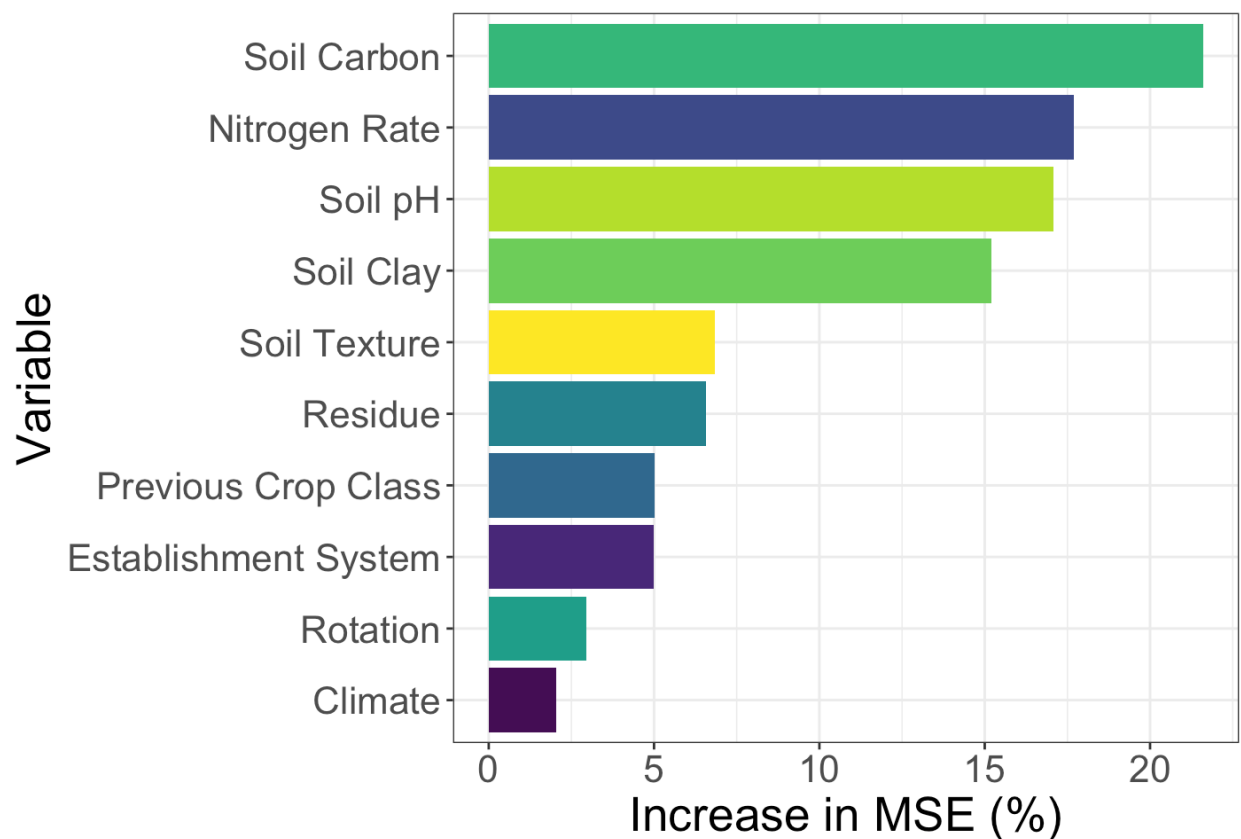


Figure 1.3. Variable importance in a Random Forest model explaining rice yield ratios under no-till systems. Importance is measured as the increase in mean squared error (MSE) when each variable is permuted, with higher values indicating greater influence on yield outcomes.

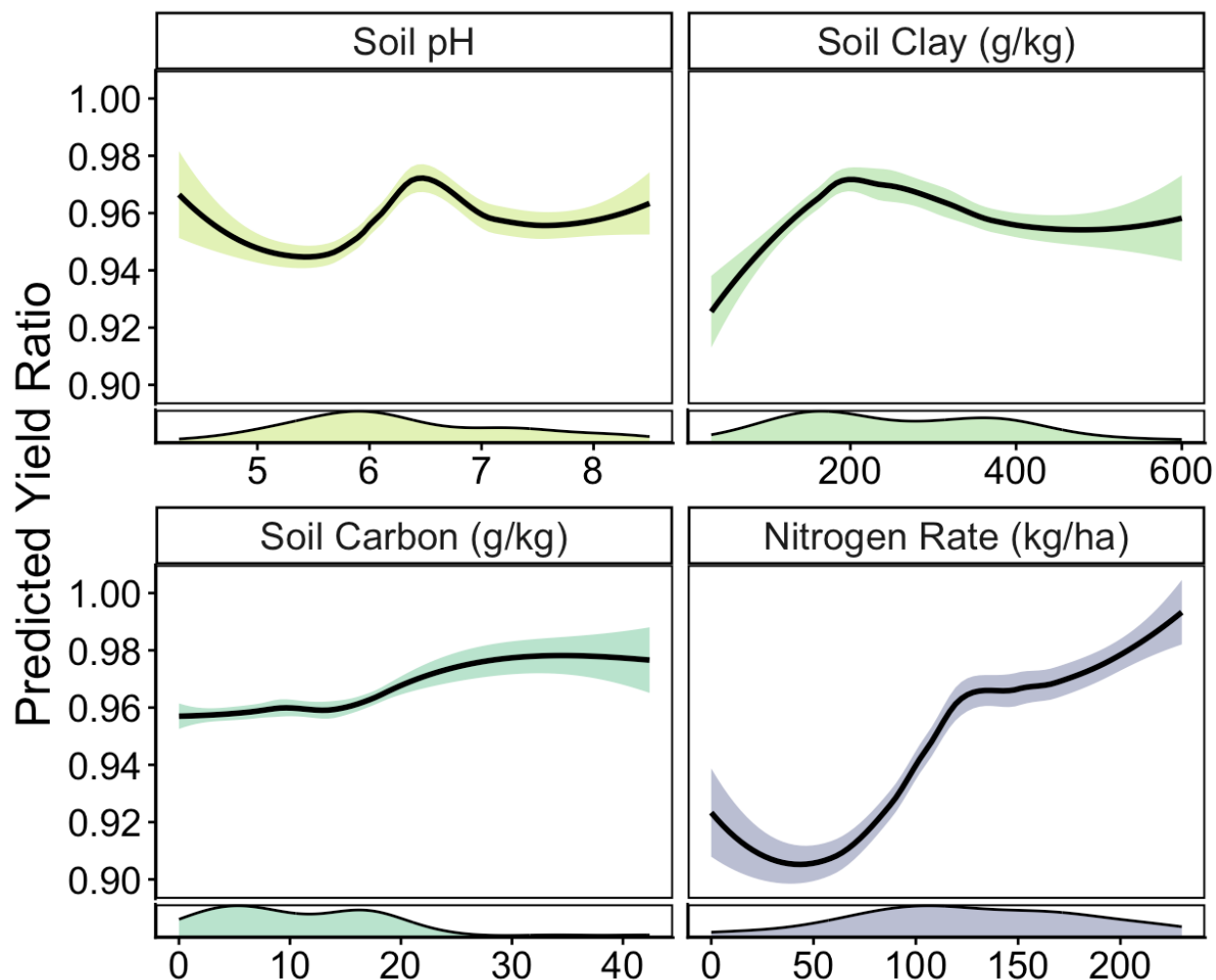


Figure 1.4. Accumulated Local Effects (ALE) plots displaying the four most important variables in the Random Forest model (Figure 1.3). The black lines show regression point estimates based on predicted yield, and the color ribbons indicate 95% confidence intervals. The histograms at the bottom show the distribution of observations in the data set.

Six additional variables had lower relative importance in the Random Forest model: soil texture class, residue management, previous crop, establishment system, crop rotation, and climate zone. None of these variables showed statistically significant differences among categories in the mixed-effects meta-regressions (Figure 1.5).

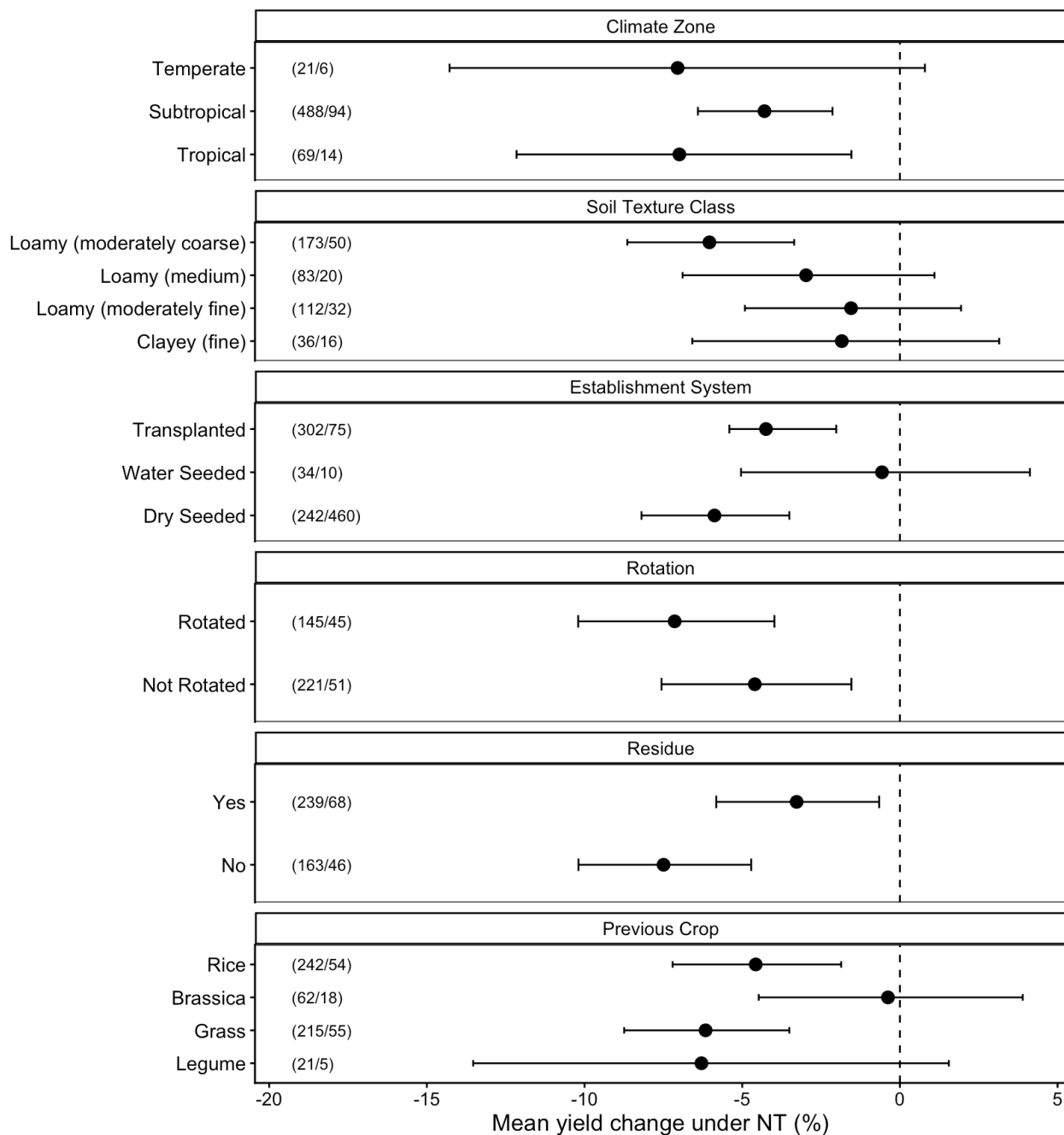


Figure 1.5. Effect of NT within climate, establishment system, previous crop class, residue management, rotation, and soil texture class categories. Error bars represent 95% confidence intervals (CIs), and the numbers refer to number observations/studies for each variable. Within each variable, there were no significant different differences between categories ($P < 0.05$).

4 Discussion

4.1 Mean impact of NT on rice yields

The adoption of NT has been limited in rice relative to upland crops, and its application in flooded rice systems has received far less global attention. This study represents the most comprehensive global synthesis to date, examining the moderating factors that influence rice yields under NT. While previous quantitative reviews have evaluated NT in rice, many have either not considered moderating factors or have focused on a single country (i.e., China; Huang et al., 2015; Liao et al., 2021; Zhao et al., 2019). Results from these studies have been inconsistent (Table 1.3). Liang et al. (2016) reported a 3.8% decrease in NT rice yields relative to CT, whereas Pittelkow et al. (2015a) reported a 7.5% decrease. In contrast, several other smaller meta-analyses focusing on specific regions or on other aspects (i.e. GHG emissions) reported no significant yield response (Huang et al., 2015, 2018; Liao et al., 2021; Zhao et al., 2019) (Table 1.3). In the present study, across the full dataset, we found a significant 4.8% reduction in rice yields under NT (Figure 1.2). This magnitude of yield decline may explain the historically low adoption rates of NT in rice systems, as even modest yield penalties can outweigh potential cost or environmental benefits in smallholder and intensively managed rice systems.

Despite consistently lower short-term yields in rice, it remains unclear whether NT could offer longer-term advantages similar to those reported for upland crops. In upland systems, NT has been shown to perform comparably to CT once improvements in soil structure and biological activity begin to accumulate (Blanco-Canqui & Ruis, 2018) and yields often increase over time as these soil benefits develop (Pittelkow et al., 2015a). Whether the same pattern occurs in flooded rice systems is uncertain. We did not evaluate long-term studies, but previous work suggests that NT may need to be maintained for more than three years before improvements in

soil properties and crop performance become noticeable (Liang et al., 2016). However, from a management standpoint, continuous NT in rice systems may not be feasible due to the ruts in the field which can occur when harvesting rice under moist soil conditions (Jat et al., 2020). These gaps highlight the need for long-term studies, as short-term assessments may not fully capture NT's agronomic potential. In the short term, several interacting mechanisms likely contribute to NT yield penalties, including impaired early crop establishment when planting into surface residues, slower N mineralization and transient N immobilization under reduced soil disturbance, and altered disease or pest dynamics associated with residue retention (Kumar & Ladha, 2011; Kusumawardani et al., 2022; Pittelkow et al., 2012; Savary et al., 2019). Together, these interacting mechanisms suggest that short-term yield penalties under NT in rice are not the result of a single limiting factor, but rather reflect cumulative constraints on early crop establishment, nutrient dynamics, and biotic stress under flooded conditions.

Even with these yield penalties, there are situations where NT may still be an economical option in rice systems. NT can reduce fuel use, tractor passes, and associated emissions (Gathala et al., 2011; Jat et al., 2020), lower land preparation costs (Abdalla et al., 2013), and allow for more timely planting by avoiding tillage delays following rainfall (Kumar & Ladha, 2011). In systems where erosion risk is low and continuous CT does not substantially deplete soil carbon, NT may still improve soil strength for machine operations, reduce labor bottlenecks, and contribute to long-term sustainability goals (Bouman et al., 2007; Saharawat et al., 2010).

4.2 Variables of importance

The Random Forest model identified several key variables that helped mitigate yield reductions under NT and explained 34% of the observed variance in yield responses ($R^2 = 0.34$). The remaining variance is likely attributable to unmeasured factors such as site-specific field

management practices, cultivar or genotype differences, and inter-annual climate variability, which are rarely reported consistently across field studies but strongly influence crop performance in flooded rice systems (Pittelkow, Liang, et al., 2015; van Ittersum et al., 2013). SOC levels above 18 g kg^{-1} , clay content between $180 - 350 \text{ g kg}^{-1}$, a pH range of $6 - 7$, and N rates above 120 kg ha^{-1} were all associated with improved NT yields.

Importantly, the SOC and clay thresholds identified in this study correspond closely with commonly recognized ranges associated with productive and well-buffered agricultural soils. Soil organic carbon levels in the range of $15 - 20 \text{ g kg}^{-1}$ have frequently been identified as critical for sustaining soil fertility, microbial activity, and nitrogen mineralization in intensively managed cropping systems, including rice. Below this range, nutrient supply and soil structural stability are often limiting, whereas above it, gains in crop performance tend to diminish as mineral-associated organic matter pools approach saturation and additional carbon inputs provide declining marginal benefits (Loveland & Webb, 2003; Oldfield et al., 2019; Wang et al., 2024). Similarly, the clay range associated with improved NT performance ($\approx 180 - 350 \text{ g kg}^{-1}$) corresponds closely to loam and clay loam texture classes, which are widely considered optimal for rice production due to their capacity to retain nutrients, buffer redox fluctuations, and stabilize ammonium under flooded conditions (Arunrat et al., 2025; Dobermann et al., 2002; Kirk, 2004). These thresholds likely reflect a balance between chemical buffering, physical structure, and anaerobic biogeochemical regulation in paddy soils rather than sharp physiological limits, helping explain why NT yield penalties are moderated – but not eliminated – under these fertility and texture conditions. Even under these more favorable conditions, improved NT yields did not surpass CT yields (Figure 1.4). Notably, each of these variables are associated with improved fertility. Broadly, improved fertility has been shown play a critical role in moderating

NT outcomes in upland crops (Lundy et al., 2015) and rice (Liang et al., 2016). Below, we discuss how these factors impact soil fertility as well as other areas of possible impact which may benefit NT rice systems.

Under NT, higher SOC may buffer the reduced soil disturbance by sustaining microbial activity and nutrient turnover despite slower residue incorporation. From a nutrient cycling perspective, elevated SOC enhances cation exchange capacity, improving retention and availability of key macronutrients such as nitrogen, phosphorus, and potassium (Gupta Choudhury et al., 2014). On the physical side, increased SOC reduces soil bulk density, increases porosity, and improves aggregate stability – factors that collectively support better root proliferation and access to water and nutrients (X. Liu et al., 2023; Qi et al., 2022a).

As reported here, higher N application rates have been well documented to improve NT yields in upland crops and rice (Huang et al., 2015; Lundy et al., 2015; Pittelkow, Linquist, et al., 2015; Wang et al., 2022; Yang et al., 2023). Without tillage, residue decomposition is slowed, temporarily leading to N immobilization near the soil surface. No-till typically enhances SOC accumulation near the soil surface (<10 cm; Blanco-Canqui et al., 2021). In these soils with moderate to high SOC, this immobilization may be more pronounced due to the slow decomposition of plant residues (Kusumawardani et al., 2022), while in coarse-textured soils, greater leaching can further limit plant-available N (Rhea, 2022). These interactions between N dynamics, SOC, and soil texture highlight the need for precise N management under NT to avoid early-season N deficits that can contribute to yield penalties.

A pH range of 6 – 7 had a positive effect on NT yields in this study. Both Liang et al., (2016) and Huang et al. (2015) reported that NT yields were lower at soil pH values below 6.0; however, they did not report similar findings when soil pH was > 7.0. Near neutral soil pH

conditions enhance N availability by promoting nitrification and reducing ammonia volatilization (Liang et al., 2016). In contrast, acidic soils can suppress microbial decomposition, limit nutrient release, and reduce tiller and panicle production (Huang et al., 2015; Naz et al., 2022). Low pH also reduces organic matter solubility by forming complexes with iron and aluminum, which slows decomposition, alters microbial communities, and can lead to SOC accumulation while limiting nutrient availability for crops (Liu et al., 2021). Under alkaline conditions, N losses through volatilization are more likely, particularly under NT systems where fertilizers are often surface applied (Rochette et al., 2009). Also, iron becomes less bioavailable due to reduced solubility and diminished root uptake efficiency (Saleem et al., 2023). Thus, in NT systems extreme pH conditions can disrupt the balance between SOC accumulation and nutrient availability, influencing yield outcomes.

Finally, our finding that soil clay content between 180 – 350 g kg⁻¹ was associated with increased NT yield ratios aligns with the categorical texture results and the tendency for NT yield gaps to narrow as soils become finer textured (Figure 1.5). Clay-rich soils tend to interact more favorably with NT because their physical and chemical properties amplify several benefits. Physically, higher clay content enhances aggregate stability and protects soil structure, allowing NT systems to maintain surface aggregation and resist structural degradation (Blanco-Canqui & Ruis, 2018; Jahangir et al., 2021). Clay-rich soils also retain nutrients more effectively than sandy soils, which can experience high N leaching (Tahir & Marschner, 2017). Finally, clay minerals promote SOC stabilization by binding organic matter and protecting it from decomposition, which supports greater nutrient protection relative to coarser soils (Chan et al., 2002; Qi et al., 2022b). Overall, finer-textured soils appear better suited to NT because they

enhance water retention and nutrient availability, helping mitigate slower nutrient cycling associated with residue retention (Chakraborty et al., 2017).

4.3 Establishment System and Climate

Evidence from some studies suggest that yield responses to NT might differ among establishment systems (Chakraborty et al., 2017), while others show no difference (Mishra et al., 2023). In our analysis, we found a slight, but non-significant yield advantage of WS rice under NT (Figure 1.5), though this trend should be interpreted cautiously given the limited representation of WS systems (only 6% of studies analyzed, Table 1.2). These findings align with those from Huang et al. (2015) and Liang et al. (2016) indicating no major differences among establishment system in their responses to NT.

The geographical distribution of the studies in this dataset was highly skewed, with 80% conducted in subtropical climates, 15% in tropical climates, and only 5% in temperate climates (Table 1.2). This imbalance may introduce regional biases in soil type, climate conditions, and agricultural practices that influence NT performance. NT yield reductions appeared largest in temperate climates, contrary to findings from upland crops where yield penalties tend to be greatest in tropical environments and least in temperate ones (Corbeels et al., 2015; Pittelkow, Linquist, et al., 2015; Steward et al., 2019). Average yield reductions were similar across all climatic zones; however, variability was much higher in temperate zones. Several temperate observations overlapped with zero or even showed yield increases, suggesting that NT may have more potential in temperate environments, but additional studies are needed to clarify these patterns.

4.4 Crop rotation and residue management

No-till, crop rotation, and residue retention form the three core pillars of conservation agriculture (CA; *FAO, 2025*) and are widely recognized for improving soil health, reducing pest and disease pressure, enhancing water-use efficiency, and stabilizing yields across upland cropping systems (Ferdinand & Baret, 2024; J. Liu et al., 2023). Global syntheses indicate that NT alone frequently reduces yields, whereas combining NT with residue retention and crop rotation can substantially improve yield outcomes (Pittelkow et al., 2015a; Rodenburg et al., 2021; Steward et al., 2019).

However, in rice systems, our findings suggest that these additional CA components – crop rotation and residue management – had limited influence on mitigating NT yield penalties (Figure 1.5). Several factors likely explain this difference from upland systems. Flooded soils suppress many soilborne pests and diseases through anaerobic conditions, reducing the need for rotation as a pest management tool (Tiedje et al., 1984). Although Huang et al. (2015) reported some benefits of rotation in NT rice systems in China, other studies in conventionally flooded rice systems found no significant yield advantage of rotated vs. continuous rice (Qin et al., 2010; Smith & Baltazar, 1991). Together, these findings indicate that conservation agriculture principles developed for upland systems cannot be directly transferred to rice without accounting for the unique biogeochemical and hydrological conditions of flooded soils.

Residue management also played a smaller role under NT in flooded rice compared to upland crops. In upland systems, residue retention is critical for conserving soil moisture, particularly in arid climates where residues act as a mulch to reduce evaporation (Gicheru, 1994). In contrast, flooded systems maintain high soil moisture regardless of surface residues. Moreover, because flooded rice fields accumulate large amounts of organic matter from roots

and incorporated straw, surface residues play a comparatively smaller role in sustaining soil fertility.

4.5 Limitations and future research directions

As with any global synthesis, this study has several limitations that should be considered when interpreting the results. First, data availability constrained the inclusion of potentially important variables, including fertilizer placement, residue management, and rice cultivar or genotype. Other papers have shown each of these variables to potentially influence rice yield, but are rarely reported consistently across field studies, limiting their inclusion in this meta-analysis. Second, only 23% of studies reported measures of variance for both NT and CT yields, requiring imputation for the remaining observations. While it is standard practice to impute SE in agronomic papers, standardized reporting in agronomic papers could be helpful for future meta-analyses. Finally, the dataset was dominated by short- to medium-term studies and by subtropical environments, particularly in Asia. As a result, the analysis could not robustly assess long-term yield trajectories under NT or fully evaluate NT performance in temperate rice systems. Long-term experiments that track changes in soil structure, nutrient cycling, and yield stability under NT are important for future studies. Importantly, our analysis evaluated individual moderators rather than interactions among variables. Due to data sparsity and inconsistent reporting, we were unable to robustly assess whether combinations of favorable conditions (e.g., high SOC, optimal clay content, neutral pH, and adequate N rates occurring simultaneously) might collectively eliminate or reverse NT yield penalties. While individual moderators did not result in NT yields exceeding CT yields, it remains possible that synergistic effects under multiple optimal conditions could improve outcomes. Future research should explicitly test these interactions using long-term, multi-factor field experiments. Together, these limitations highlight

important directions for future research, particularly regarding long-term dynamics and interactive soil-management effects.

5 Conclusion

This study found an overall 4.8% reduction in rice yields under NT compared to CT. Yield responses were strongly influenced by SOC, N application rate, soil pH, and clay content, with improved NT performance observed under higher fertility and intermediate-textured soils. In contrast, crop rotation and residue retention – key components of conservation agriculture in upland systems – had limited influence on NT yield outcomes in flooded rice.

Although NT yield did not exceed CT yields even under favorable conditions, these results identify the soil and fertility contexts in which NT is most likely to be agronomically viable. This study provides the most comprehensive and up-to-date quantitative synthesis of NT effects on rice yields and offers a framework to guide region-specific evaluation of NT adoption.

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CHAPTER TWO

Title: Water-seeded summer stale seedbeds show yield potential comparable to conventionally tilled systems

Authors: Mia Godbey^{a*}, Whitney Brim-DeForest^b, Luis Espino^c, Bruce Linquist^a

^aDepartment of Plant Sciences, University of California, Davis, Davis, CA, USA

^bUniversity of California Cooperative Extension, Yuba City, CA, United States

^cUniversity of California Cooperative Extension, Oroville, CA, United States

*Corresponding author: Department of Plant Sciences, University of California, Davis, One Shields Ave., Davis CA 95616

Abstract

In California rice systems, increasing droughts and spring rainfall can force growers to leave fields fallow for an entire growing season. This allows for seedbed work during the summer, creating opportunities for alternative establishment strategies the following season. This study evaluated a summer stale seedbed (SSB) in which a seedbed is prepared during the summer of a fallow year and then, in the following growing season, it is flooded and water-seeded without additional tillage. Our objective was to compare the SSB system to a conventionally tilled water-seeded system (CT) in terms of yield potential, nitrogen (N) response, stand establishment, pest and disease severity, and potential water savings. Experiments were conducted in a replicated experiment station trial as well as four on-farm sites throughout the Sacramento Valley in 2022 and 2023. In the experiment station trial, grain yield ranged from approximately 6.5 to 9.8 Mg ha⁻¹ across N rates with no significant yield differences between CT and SSB at any N rate. Regression analysis indicated similar N requirements for maximum yields (133 and 137 kg N ha⁻¹ for CT and SSB, respectively). On-farm trials confirmed these findings. Grain yields were similar despite a 29% reduction in plant stand for SSB. While disease severity (aggregate sheath spot and stem rot) and seed midge varied across locations, the differences between establishment systems were not significant. Stored soil moisture was greater in the SSB system by approximately 4 mm in the 0 – 30 cm depth, indicating greater conservation of preplant soil water. Overall, these results demonstrate the potential of SSB systems to reduce tillage while maintaining yields.

Plain Language Summary

Rice growers in California are increasingly challenged by drought, variable precipitation and water availability, and rising production costs. In recent years, many fields have been left fallow during the summer growing season, creating opportunities to test alternative management approaches. We evaluated a stale seedbed system in which fields are prepared during the summer fallow period and then planted the following year without additional tillage. Overall, the results were promising. We found in on-farm and research station trials that the summer stale seedbed system produced grain yields comparable to conventional tillage and that yield responses to nitrogen were similar between systems. Pest and disease severity was generally similar between sites. One issue with the stale seedbed is that the plant stand after planting was lower. The stale seedbed also conserved more soil water before planting than conventional tillage.

Abbreviations

SSB – summer stale seedbed

CT – conventional tillage

1. Introduction

California's irrigated rice (*Oryza sativa* L.) production, concentrated in the Sacramento Valley, spans approximately 212,000 hectares annually, making the state the second-largest rice producer in the U.S. and home to the highest average rice yields, at approximately 9.5 Mg ha⁻¹ (Childs, 2025; USDA NASS, 2024). In contrast to most other rice-growing regions worldwide, which often rotate rice with other crops and rely on dry-seeding or transplanting, nearly all California rice is grown as a monoculture on heavy clay soils using a water-seeding system in which pregerminated seed is aerially broadcast into flooded fields that remain submerged until draining for harvest (Hill et al., 2006). Aerial water-seeding has long been central to California rice production, with more than 90% of fields traditionally planted using aircraft (Hill et al., 1994). This practice was developed in the 1920s and has since become highly refined, aiding in the suppression of barnyard-grass (*Echinochloa crus-galli* (L.) P. Beauv) while maintaining high nitrogen-use efficiency and productivity (Linguist et al., 2025). However, the increasing prevalence of herbicide-resistant weed populations has reduced the effectiveness of this system, prompting research into alternative establishment methods such as dry- and drill-seeding with delayed flooding (Fischer et al., 2000).

An increasing amount of rice area has been left fallow over the past 10 to 15 years (Salvato et al., 2025), driven by two primary factors: delayed planting caused by late spring rainfall and reduced water availability during drought years. In some years, prolonged or intense spring precipitation prevents field preparation and timely planting, and growers unable to plant by the June 1 crop insurance deadline may claim prevented planting insurance and leave fields unplanted (USDA-RMA, 2012; Zhang et al., 2025a). In contrast, drought years constrain water availability, further reducing planted acreage and delaying planting (Smith, 2023; Medellín-

Azuara et al., 2022; Sumner & Matthews, 2022). Gebremichael et al. (2021) reported that total fallow or idle cropland in California's Central Valley nearly tripled between 2007 and 2016, increasing from approximately 180,000 to 450,000 ha. Rice production followed a similar trajectory, with planted area shrinking by 18%, 22%, and 51% during the drought years of 2015, 2021, and 2022 (Gebremichael et al., 2021; *USDA/NASS 2024 State Agriculture Overview for California*, n.d.).

Given the extensive irrigation infrastructure and long-standing efficiency of California's water-seeded system, any alternative establishment method must be both economically viable and capable of producing competitive yields to gain acceptance among growers (Hill et al., 2006). Accordingly, recent research has largely emphasized modifications within the existing water-seeded production system, such as improved water management, nutrient management, weed and pest control, and alternative stale seedbed approaches, rather than fundamental changes to the establishment system itself (Ceseski, 2021; LaHue & Linquist, 2021).

One potential approach that leverages the increased fallow area is the use of stale seedbeds (SSB). A stale seedbed is an "old" seedbed that is prepared well in advance of planting and has minimal further soil disturbance prior to crop establishment (Harrell et al., 2011). The time between seedbed preparation and planting can vary depending on the purpose of the SSB, which may include weed control or facilitating earlier planting the following season. For weed control, the seedbed can be prepared in the spring and irrigated (or flushed) to promote weed emergence. Once weeds have emerged, they are killed with a non-selective herbicide such as glyphosate, and the crop is planted without additional tillage (Pittelkow et al., 2012b; Lundy et al., 2014; Linquist et al., 2008). In the mid-south USA, seedbeds are sometimes prepared in the fall to facilitate earlier planting, allowing rice to be drill-seeded directly into the prepared

seedbed the following spring (Harrell et al., 2011). This practice is less compatible with conventional California rice management where rice straw is typically incorporated following harvest and fields are often flooded during the winter to promote straw decomposition (Linquist et al., 2006). We propose a summer SSB in which a seedbed is prepared during the summer for fields that are let fallow, and then fields are planted the following spring without additional tillage. An important potential benefit of summer SSB management is greater flexibility for timely planting, particularly when spring rainfall delays field preparation. Early planting has been associated with higher rice yields in California (Linquist et al., 2025), and completing seedbed preparation during the previous summer may allow growers to plant when conditions are suitable. Another potential benefit is greater conservation soil moisture by eliminating the need for spring tillage. Similar benefits have been reported in no-till systems in other crops, where reduced soil disturbance can facilitate more timely planting and increase soil water storage at planting (Erenstein and Laxmi, 2008; Adil et al., 2024).

Although SSBs have been widely studied in dry-seeded rice systems, few studies have examined them in water-seeded rice systems. Previous work has examined fall and spring stale seedbeds in water-seeded rice, generally showing that these practices result in similar yield potential and N response as conventional systems (Linquist et al., 2008; Pittelkow et al., 2012a). No studies to date have examined summer SSB where the interval between seedbed preparation and planting may be 9 to 12 months. This extended period without tillage may alter soil N cycling and indigenous N availability, which have previously been shown to differ among rice establishment and tillage systems (Pittelkow et al., 2012a, 2014). The timing and extent of residue incorporation may also influence disease pressure as rice residue can serve as a source of overwintering inoculum for stem rot and aggregate sheath spot, and residue management has

been shown to affect subsequent disease severity (Cintas and Webster, 2001). These changes in soil N availability and residue dynamics could ultimately influence crop establishment, N requirements, disease pressure, and grain yield in ways not seen in previous water-seeded studies.

Given the novelty and limited research on this system, the objective of this study was to evaluate the agronomic performance of a summer SSB relative to a CT system with a focus on yield potential, N requirements, stand establishment, disease prevalence, and preplant soil-water storage. Addressing these gaps is critical for determining whether SSB can function as a viable management strategy within California's water-seeded rice system under increasing climatic and operational constraints.

2. Materials and Methods

2.1 Site Description

Four on-farm trials (two per year) were conducted in 2022 and 2023 growing seasons, and one replicated trial at the Rice Experiment Station (RES) in 2023. All experiments were conducted within the Sacramento Valley (Fig. 2.1) which has a Mediterranean climate characterized by warm and dry conditions during the growing season (May – October). The average growing season precipitation and minimum and maximum air temperatures were 7.5 mm, 13.2°C and 30.7°C, respectively (CIMIS, 2025). At all sites, soils were fine textured, and

slightly acidic (pH 5.4 to 6.5) with soil organic matter contents ranging from 26.0 to 36.0 g kg⁻¹ (Table 2.1).

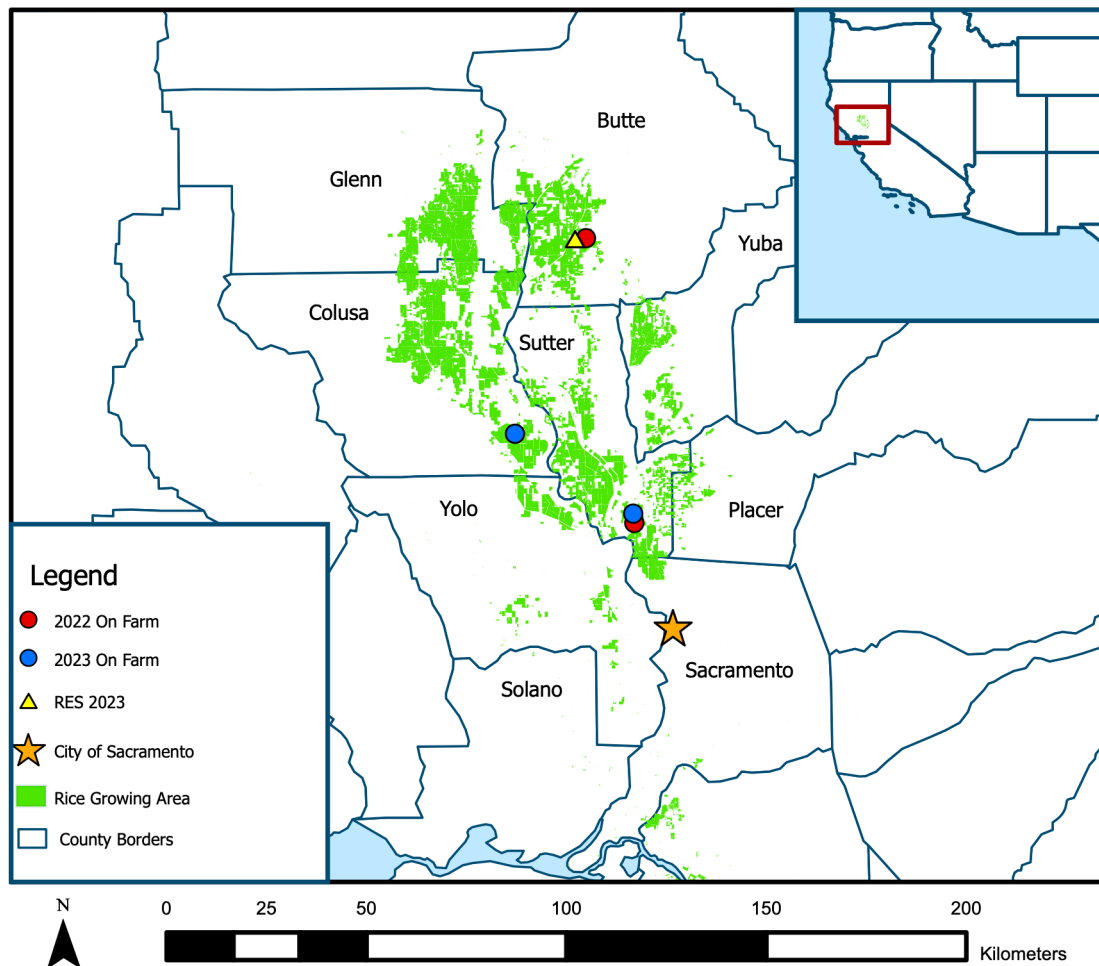


Figure 2.1. Map of on-farm site locations and the Rice Experiment Station (RES) and the rice growing area of the California Sacramento Valley. The red dots represent the on-farm locations from 2022. The blue dots represent on-farm locations from 2023. Controlled experiments were conducted at the RES as indicated by the yellow triangle. The rice cropping area is from the Center for Spatial Information Science and Systems (2024; <https://nassgeodata.gmu.edu/CropScape/>) and county boundaries are from natural earth. The map was produced with ArcGIS Pro 3.6.0 (Esri Inc., 2025).

Table 2.1. Soil characteristics of sites used in 2022 and 2023 including pH, cation exchange capacity (CEC), soil organic matter (SOM), and soil texture. Each site comprised one conventionally tilled (CT) trial and one summer stale seedbed (SSB) trial. Rice Experiment Station (RES) soils were delineated within basins, so RES soil characteristics are averaged across all four basins.

Year	Site	pH	CEC	SOM	Soil Texture
		1:1 soil/water	(meq/100g)	(g kg ⁻¹)	
2022	Nicolaus	5.9	37.4	32.5	Silty clay
	Biggs	5.4	24.35	29.0	Clay loam
	Nicolaus	5.6	31.05	33.0	Silty clay
2023	Colusa	6.45	34.15	35.5	Clay
	RES	5.2	29.2	26.0	Clay

2.2 Experimental Design and Field Management

The fields at all sites had been fallowed the previous growing season. During the preceding summer fallow, fields were disked and leveled to prepare the seedbed. In the spring of the planting year, the SSB treatment received no further tillage, while the CT treatment was prepared using conventional spring tillage consisting of chiseling, disking, and rolling prior to flooding and planting. Rice varieties used and management dates are presented in Table 2.2. All sites received 40 kg K ha⁻¹ and 22 kg P ha⁻¹ as potassium sulfate and diammonium phosphate, respectively, to ensure these nutrients were not limiting. Following fertilizer application, fields were flooded and planted. Weed and pest management at the on-farm trials were managed by cooperating growers, whereas the RES experiment was managed according to standard recommended practices. The areas around the N rate trials were used to quantify stand counts,

soil moisture, and pests and diseases as described below. Rice was harvested at harvest maturity (around 26% moisture) from an area of 14.5 m² using a small plot combine. Grain yield was adjusted to a standard moisture content of 14%.

Table 2.2. Relevant information for each research location in 2022 and 2023. Note that flooding occurred between fertilizer application and planting.

Year	Site	Location	Variety	Fertilizer Application	Planting	Harvest
2022	Nicolaus	38° 48' 53.19" N, 121° 34' 44.59" W	M-211	April 28	May 2	October 4
	Biggs	39° 27' 38.48" N, 121° 42' 9.25" W	M-211	May 2	May 6	October 11
2023	Nicolaus	38° 50' 6.36" N, 121° 34' 52.89" W	M-206	May 3	May 8	October 15
	Colusa	39° 1' 10.47" N, 121° 55' 10.18" W	M-211	May 10	May 16	October 6
	RES	39°27'32" N, 121°44'20" W	M-206	May 24	May 26	October 23

2.2.1 Rice experiment station trial

A replicated experiment was conducted at the RES in 2023 using a split-plot randomized complete block design with four replications, with tillage system (CT or SSB) being the main plots, and N rate (0, 90, 120, 150, 180, or 210 kg N ha⁻¹) the subplots. Each replication consisted of a 0.2-ha basin divided into two equal-sized main plots, with one half assigned to CT and the other to SSB. Within each main plot, individual N-rate subplots measured 3.0 x 6.1 m. Nitrogen fertilizer was injected as aqueous-NH₃ to CT subplots and as hand-applied urea to the SSB subplots before flooding. Around the N rate trials, the rest of the basin was fertilized at a rate of 180 kg N ha⁻¹. After flooding, each plot was planted by manually broadcasting pregerminated seed.

2.2.2 On-farm trials

At each on-farm site, the experimental area consisted of a 0.4 ha area for the SSB treatment and an adjacent CT area within the same field. Within each treatment area, an N rate trial was established. Each N rate was replicated four times within the SSB and CT areas in 3.0 x 6.1 m plots. For both the SSB and CT treatments, N (urea) was hand applied at rates of 0, 84, 140, 196, and 252 kg N ha⁻¹ before flooding. Areas surrounding the N rate trials were fertilized according to the grower's standard N management. After N application, fields were flooded and pregerminated rice seed was planted by airplane.

2.3 Data Collection

2.3.1 Baseline soil sampling

To characterize soil baseline conditions (Table 2.1), prior to fertilizer application, 15 – 20 soil samples (0 – 15cm depth) by tillage treatment were collected with a small shovel and pooled from each on-farm location and from the RES. Soil samples were air-dried and crushed to pass through a 2-mm sieve prior to laboratory analysis (Midwest Laboratories, 2024) for pH (1:1 soil/water), cation exchange capacity (sodium acetate), and organic matter content (Walkley-Black titration). The soil texture classification was derived from Web Soil Survey (USDA NRCS Web Soil Survey).

2.3.2 Preplant soil moisture

To quantify preplant soil moisture, at the on-farm sites, two samples were collected from each 0–15- and 15–30-cm depths in each tillage treatment and pooled separately by depth. At the RES, the same depths were sampled within each block. Samples were collected with a soil corer in the SSB treatment, while in the CT area, the samples were collected with a shovel from the plow layer which was approximately 15-cm deep. Samples were weighed fresh, oven-dried at

105°C, and reweighed once the samples reached a constant weight. Gravimetric water content (GWC) was calculated as the ratio of water mass lost during oven drying to oven-dry soil mass. Based on previously reported values for northern California rice soils, a bulk density of 1.2 g cm⁻³ was assumed (Ruark et al., 2010), and gravimetric water content was converted to soil-water storage (mm) for each 15-cm soil layer.

2.3.3 Stand Establishment Measurements

Plant density was measured only at the on-farm sites to assess crop establishment following aerial seeding, whereas the RES plots were hand-planted. Measurements were collected two to three weeks after planting, once seedlings were established and rooted. A circular sampling ring (30.5 cm diameter; 0.0731 m²) was placed randomly at 10 locations near the division line between each tillage treatment, and the number of established plants within the ring were counted.

2.3.4 Rice seed midge sampling methods

Rice seed midge (*Cricotopus sylvestris*) sampling followed methods described by Clement et al. (1977), with modifications for field-scale sampling. At the on-farm sites in 2022, three 1-m diameter metal rings were placed at three locations along each of the treatment borders, resulting in nine standardized sampling locations per treatment. In 2023, ring enclosures were not used, and samples were collected at comparable border locations. At the RES, small plots (3.0 x 6.1 m) with soil levees were established in each basin for sampling instead of metal rings. At all locations, sampling was done at 10 and 20 days after flooding, except at the Colusa site, where early-season drainage for stand establishment prevented initial sampling. Three samples were collected from the upper 2.5 cm of sediment, passed sequentially through 1-mm,

500-µm, and 300-µm sieves, and processed using glycerol flotation prior to enumeration of midge larvae.

2.3.5 Disease severity index

Tiller diseases, aggregate sheath spot (AGSS; caused by the fungus *Rhizoctonia oryzae-sativae*) and stem rot (SR; caused by the fungus *Sclerotium oryzae*), were evaluated soon after fields had been drained in preparation for harvest (Table S2.1). For each tillage treatment, 6 and 15 tiller samples were taken at the RES or on-farm sites, respectively. Samples were taken on a uniform pattern across treatment basins from approximately the same area. Each tiller sample consisted of three handful (30 to 40) of tillers cut at soil level and combined to create a composite sample. From each composite sample, 30 to 50 tillers per disease were selected and rated using the scale presented in Table S2.1 (Espino et al., 2026). At all sites, samples were taken from areas around the N rate trials which received similar amounts of N. Disease severity index per tillage treatment was calculated as:

$$\text{Disease Severity Index} = \frac{\sum(\text{number of tillers per serverity class} \times \text{severity class})}{\text{total tillers}}$$

2.4 Data Analysis

All statistical analyses were conducted in R (R Core Team, version 2025.05.1+513) and statistical significance was evaluated at $P < 0.05$.

2.4.1 Grain yield analysis

RES grain yield was analyzed according to the split-plot design using linear mixed-effects models fitted with the lmerTest package. Tillage system was treated as the main-plot factor and N rate as the subplot factor. Models included tillage, N rate, and the tillage x N-rate interaction as fixed effects and block and block x tillage as random effects. N rate was first analyzed as a categorical factor to evaluate treatment differences. Fixed effects were evaluated

using Type III tests with Satterthwaite's approximation and estimated marginal means and pairwise comparisons were obtained using the emmeans package.

To quantify yield potential and the N rate required to achieve yield potential within each system, a separate linear mixed-effects model was fitted using the lmerTest package with N rate treated as a continuous variable. Fixed effects included tillage, linear and quadratic N-rate terms, and the interactions of tillage with both linear and quadratic N rate; block and block x tillage were included as random effects. Fixed effects were evaluated using Type III tests with Satterthwaite's approximation. Yield-maximizing N rates were calculated from the fitted quadratic equations, and 95% confidence intervals were obtained by simulation from the fixed-effect variance-covariance matrix using the MASS package.

On-farm grain yield was analyzed using a linear mixed-effects model corresponding to a blocked split-plot design, with location-year as the block, tillage as the whole-plot factor, and N rate as the subplot factor. Tillage, N rate, and their interaction were included as fixed effects, while location-year and location-year x tillage were included as random effects. N rate was first analyzed as a categorical factor for treatment comparisons. Continuous N-rate responses were subsequently analyzed using linear and quadratic terms, and yield-maximizing N rates and predicted maximum yields were calculated from the fitted quadratic response curves as described for the RES.

2.4.2 Preplant soil water storage, plant density, rice seed midge abundance, and disease severity index

Preplant soil-water storage, plant density, rice seed midge abundance, and disease severity index were analyzed separately for the on-farm and RES studies. For the on-farm analysis, subsamples for soil-water storage, plant density counts (measured only on-farm), and

disease severity (for both AGSS and SR) were averaged for each location-year x tillage combination because subsamples represented measurements within the same CT and SSB treatment means across location years. Tillage effects were then evaluated using matched CT and SSB observations across location-years. Data were analyzed using a normal linear model fitted with lme4 and lmerTest, with fixed effects (tillage) evaluated using Type III tests where appropriate.

For the RES analysis, subsamples were averaged within each experimental plot before analysis. Tillage was included as the fixed treatment effect and block as a random effect in linear mixed-effect models using lme4. Estimated marginal means were obtained using the emmeans package.

Rice seed midge abundance was analyzed separately because the count data were over-dispersed (the variance exceeded the mean). These data were analyzed using negative-binomial mixed models fitted with glmmTMB. For the on-farm study, location-year and tillage were included as fixed effects, and sampling location was included as a random effect to account for subsampling. For the RES, tillage and sampling date were included as fixed effects and plot was included as a random effect to account for repeated measurements and subsampling. Fixed effects were evaluated using Wald chi-square tests from the car package, and treatment comparisons were conducted using emmeans.

3. Results

3.1 Grain yield

At the RES, grain yield increased significantly with N rate but was not affected by tillage system, and the tillage x N-rate interaction was not significant (Table 2.3). Grain yields ranged from approximately 6.5 Mg ha⁻¹ in the zero-N treatment to 9.8 Mg ha⁻¹ at higher N rates. Based

on the overlapping confidence intervals, these differences in yield potential or yield-maximizing N rates were not significant between systems. Quadratic response models estimated yield-maximizing N rates of 133 kg N ha⁻¹ under CT and 137 kg N ha⁻¹ under SSB, with corresponding predicted maximum yields of 9.29 and 9.58 Mg ha⁻¹, respectively (Figure 2.2).

Table 2.3. Grain yield across N fertilizer rates within CT and SSB systems at the RES (2023) and on-farm locations (2022 – 2023). On-farm data are averaged across locations and years.

RES			On-Farm	
Treatment	N Rate	Yield	N Rate	Yield
	<i>kg ha⁻¹</i>	<i>kg ha⁻¹</i>	<i>kg ha⁻¹</i>	<i>kg ha⁻¹</i>
CT	0	6518	0	8484
	90	8899	84	10962
	120	9533	140	11671
	150	9200	196	12259
	180	8711	252	12168
	210	8716	-	-
SSB	0	6908	0	8513
	90	8952	84	10670
	120	9848	140	11606
	150	9661	196	12225
	180	9118	252	12067
	210	8660	-	-
ANOVA				
Tillage		0.584		0.591
N Rate		< 0.001		< 0.001

Tillage x N Rate

0.924

0.982

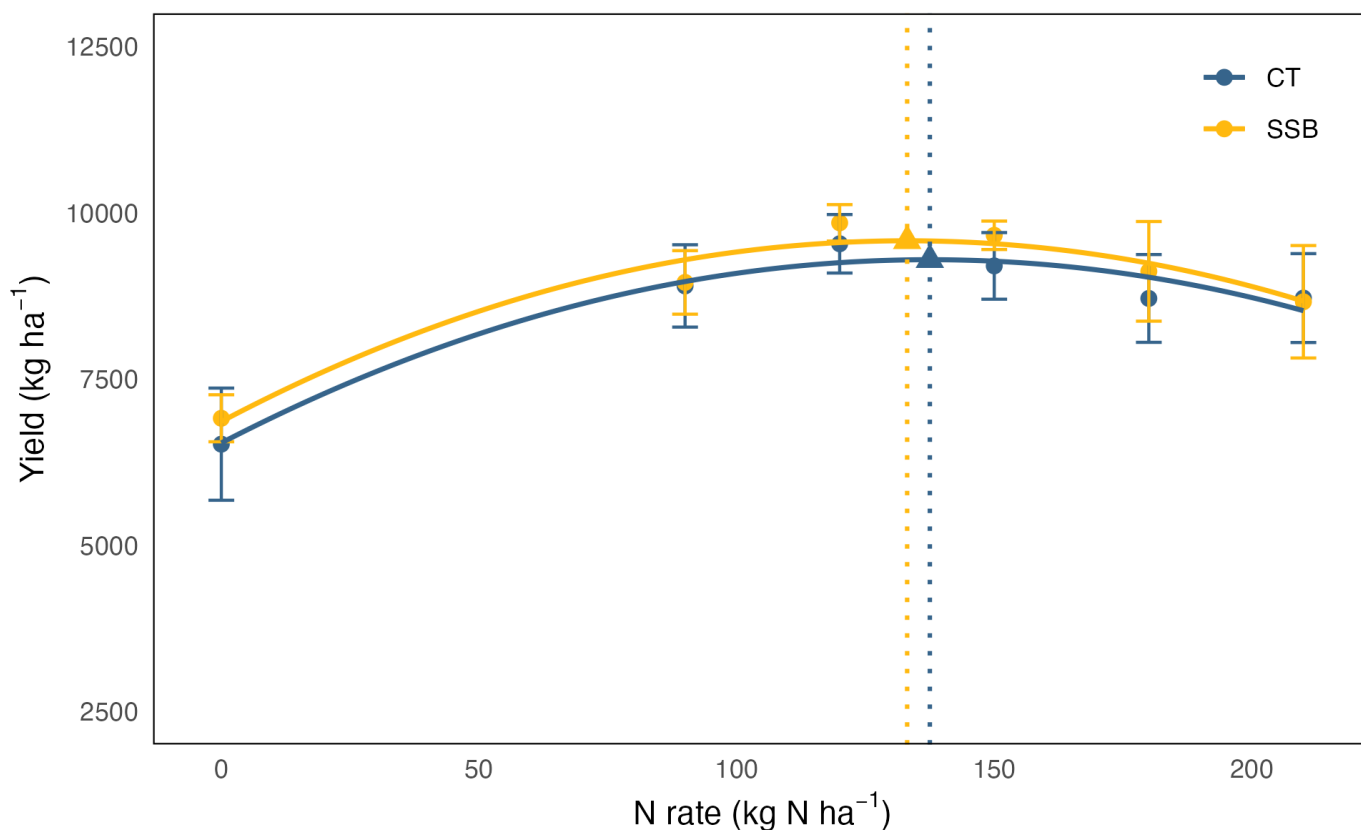


Figure 2.2. Grain yield response to N rates under conventional tillage (CT) and summer stale seedbed (SSB) at the Rice Experiment Station (RES) in 2023. Points represent treatment means, lines represent fitted quadratic response functions, and vertical lines indicate the estimated N rate associated with maximum predicted grain yield for each tillage system. Values shown within the figure indicate the estimated yield-maximizing N rate with corresponding 95% confidence intervals in parentheses and predicted maximum grain yield for each tillage system.

On-farm grain yield differed among locations and years, with maximum yields of 11.21 to 13.18 Mg ha⁻¹. However, when analyzed together, there was a significant response to N, but tillage and the tillage x N-rate interaction were not significant (Table 2.3). When N rate was

treated as a continuous variable, grain yield exhibited significant linear and quadratic responses to applied N. The N response different among location-years, with significant location-year linear N and location x quadratic N interactions. Neither tillage nor its interactions with the linear or quadratic N-rate terms were significant, indicating similar yield responses to N under CT and SSB. The fitted quadratic response curves estimated yield-maximizing N rates of 217 kg N ha⁻¹ under CT and 226 kg N ha⁻¹ under SSB, with corresponding predicted maximum yields of 13.45 and 13.36 Mg ha⁻¹, respectively (Figure 2.3).

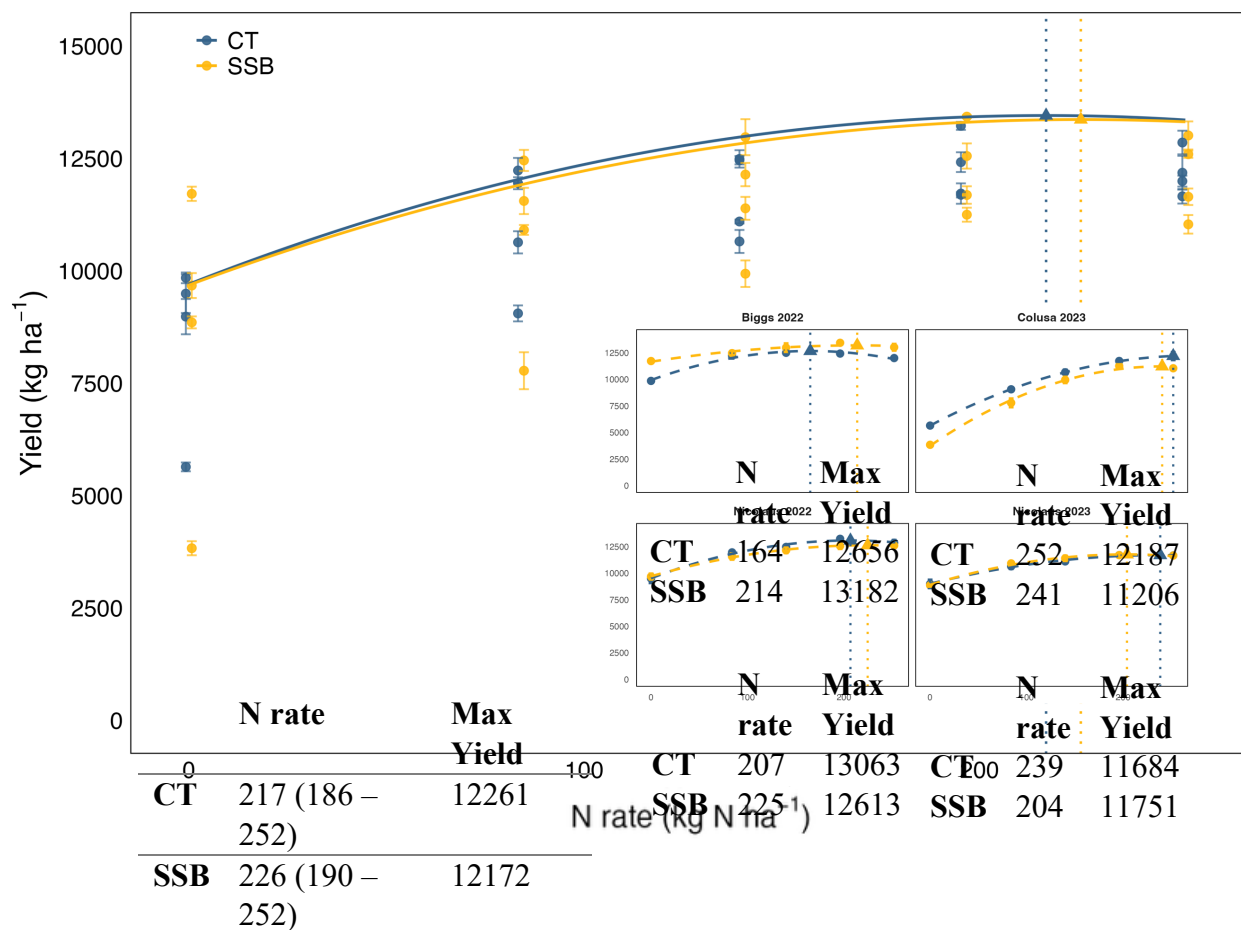


Figure 2.3. On-farm grain yield response to N rate under conventional tillage (CT) and summer stale seedbed (SSB) across four location-years. Points represent location-year means at each N rate, and lines represent quadratic response functions estimated from the mixed-effects model.

Vertical lines indicate the estimated N rate associated with maximum predicted grain yield for each tillage system. Values shown within the figure indicate the estimated yield-maximizing N rate with corresponding 95% confidence intervals in parentheses and predicted maximum grain yield for each tillage system.

3.2 Preplant soil-water storage

Preplant soil-water storage was greater under SSB than CT (Figure 2.4). In the surface layer (0 – 15-cm), the difference was more pronounced. Averaged across the RES and the on-farm sites, mean water storage in the 0 – 15-cm layer was 5.15 mm under SSB and 2.04 mm under CT, representing approximately 2.5 times greater water storage under SSB. Water storage in the 15 – 30-cm layer was also greater at both locations, although only significantly so at the RES. On average, SSB contained 6.81 mm compared with 5.86 mm under CT. Averaged across depths, the SSB had 1.99 mm more preplant soil-water storage than the CT.

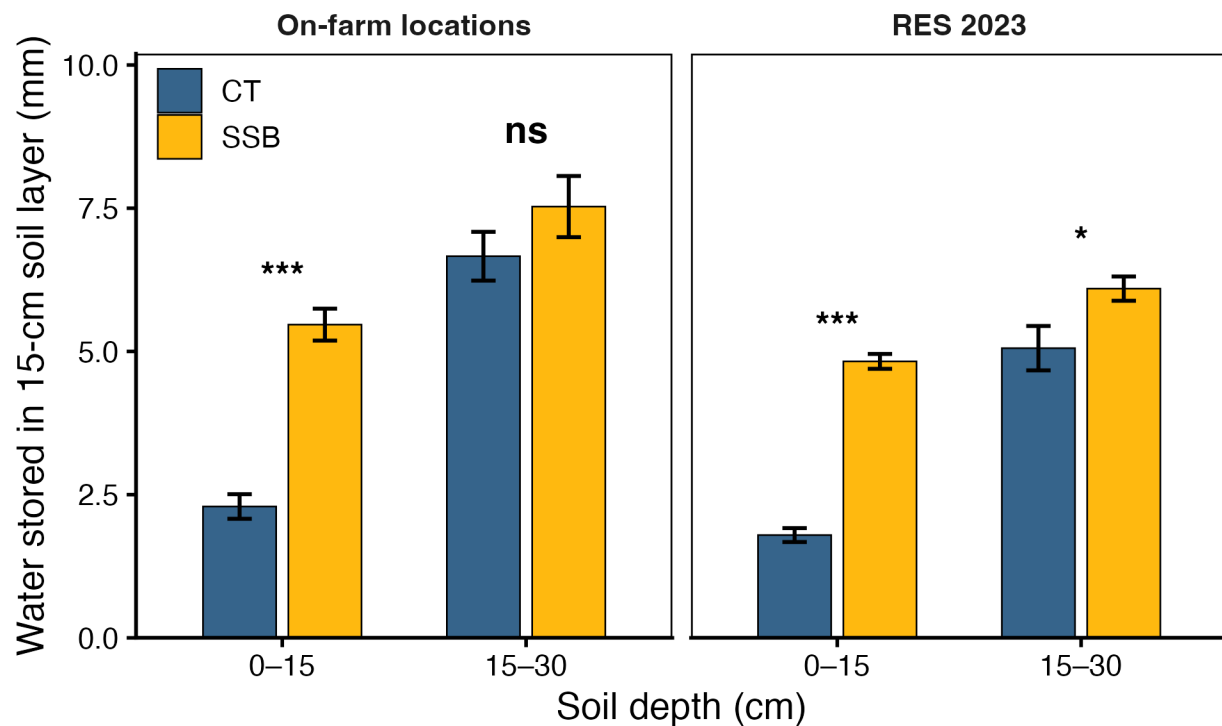
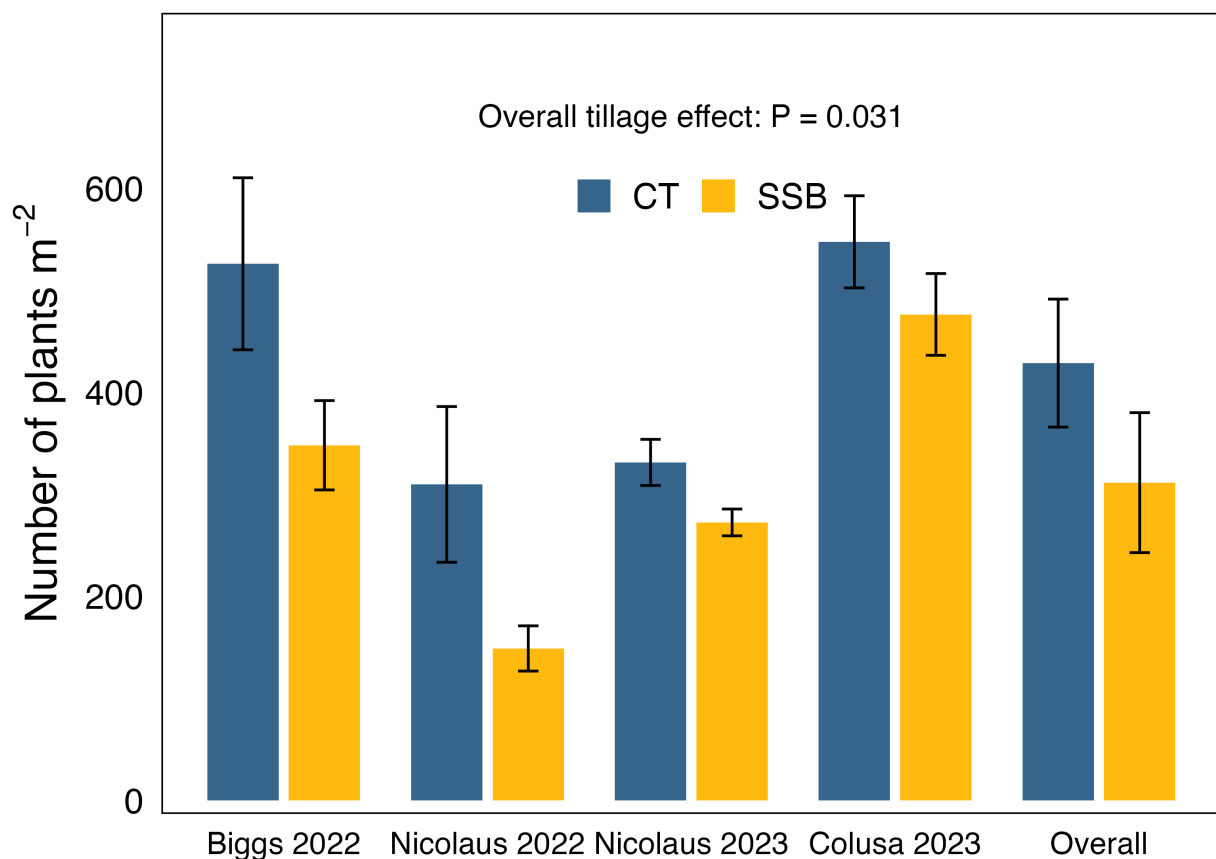


Figure 2.4. Preplant water stored in the 0 – 15 and 15 – 30 cm soil layers under conventional tillage (CT) and summer stale seedbed (SSB) at four on-farm location-years and the Rice Experiment Station (RES). On-farm bars represent means across location-years, whereas RES bars represent means across four blocks with standard-error bars. Asterisks indicate significant differences between tillage systems within depth (ns = not significant, * = $P < 0.05$, *** = $P < 0.001$).

3.3 Plant Density

Plant density differed among location-years ($P = 0.021$; Figure 2.5) and ranged from 149 to 547 plants m^{-2} . Plant density was greater under CT than SSB at all four on-farm location-years. On



average, SSB significantly reduced plant density by 29.1% when compared to CT; the reduction ranged from 13.0% at Colusa in 2023 to 51.9% at Nicolaus in 2022.

Figure 2.5. Established rice plant density under conventional tillage (CT) and summer stale seedbed (SSB) across four on-farm location-years. Bars for individual location-years represent field-level means, with error bars represent standard errors calculated from within-field subsamples. Overall bars represent the mean of the four location-year means, with error bars representing the standard error across location-years.

3.4 Seed midge

Midge abundance varied across locations (Figure S1). They were most abundant in the 2023 locations (both RES and on farm). However, analysis of on-farm and RES data indicate no significant differences in midge abundance as affected by tillage.

3.5 Disease severity index

Across locations, the disease severity index for both AGSS and SR was relatively low (< 2.0 ; Figure 2.6). For AGSS, there was a significant difference in disease severity index across locations with Colusa 2023 having greater severity than the other locations ($P = 0.0044$, data not shown). For both on-farm locations and the RES, which were analyzed separately, tillage had no effect on disease severity index.

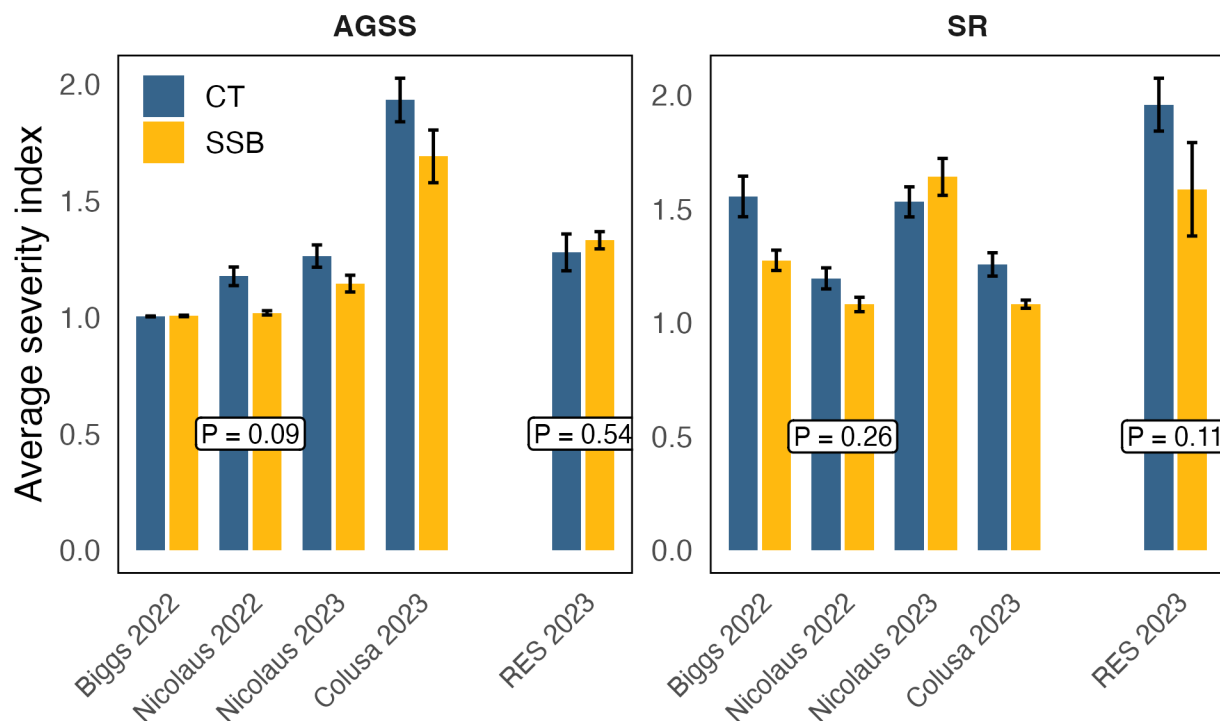


Figure 2.6. Mean aggregate sheath spot (AGSS) and stem rot (SR) severity index under conventional tillage (CT) and summer stale seedbed (SSB) management across four on-farm location-years and at the Rice Experiment Station (RES) in 2023. Bars represent means $\pm$ SE. P-values in the boxes represent the overall effect of tillage across location-years at the on-farm sites, and P-values shown for the RES represent the effect of tillage at the RES.

4 Discussion

4.1 Yield potential

Across both the RES and on-farm locations, the yield potential under the SSB system were similar to those achieved under CT (Figures 2.2 & 2.3). These findings agree with previous studies reporting comparable productivity with fall and spring SSB systems in both drill-seeded and water-seeded rice systems (Harrell et al., 2011; Pittelkow et al., 2012; Linquist et al., 2008). Similar yields were maintained despite a 29% reduction in plant stand density under the SSB system across the on-farm locations (Figure 2.4). Rice can compensate for lower plant populations through increased tillering and panicle development (Kumar et al., 2017). Previous studies have shown that near-maximum yields can be maintained across a relatively broad range of rice plant densities, with populations of approximately 160 – 240 plants m² considered near optimal in several studies (Counce, 1987; Counce and Wells, 1990; UC Rice Production Workshop, 2024). In California water-seeded systems, relatively high seedling rates are commonly used to compensate for seed loss from wind, predation, and other establishment losses (Ceskeski et al., 2022). Thus, although stand density was reduced under SSB, plant populations generally remained sufficient to maintain yield. That said, this remains a concern and future work should focus on how to enhance stand establishment.

Several mechanisms may explain lower stand establishment under SSB. First, establishment in water-seeded rice depends on adequate seed contact and anchorage at the soil surface. Planting into a flooded, firm, undisturbed soil surface may increase the potential for seed or seedling movement (V. Kumar & Ladha, 2011; Pittelkow et al., 2012b). This can be especially the case under windy conditions where wave action can disrupt seedlings during establishment. Secondly, fertilizers may remain closer to the soil surface under SSB because they are not incorporated by

tillage. While urea (used in this study), has been shown to move downward upon flooding (Broadbent et al., 1958), phosphorus can remain near the surface and promote algal growth that can interfere with rice establishment (Ohadi et al., 2022; Spencer et al., 2006). In conventional systems, farmers recognize this problem and will often apply P fertilizer after the stand has established (Lundy et al., 2012; Spencer and Linquist, 2014). Surface residue can also reduce seedling emergence in reduced-tillage rice systems by limiting seed-soil contact (Mohanty and Painuli, 2004). However, in this study and in others that have examined management on fallow fields (Zhang et al., 2025a), surface residues are minimal.

Seed midge populations in rice fields are known to vary with flooding history, crop development, water conditions, and the availability of organic matter and detritus (Clement et al., 1977a, b; Al-Shami et al., 2010; Stevens et al., 2006). However, in this study midge abundance was not consistently affected by tillage across the on-farm and RES studies. The contrasting responses among locations and the decline in abundance between sampling dates at RES suggest that local environmental conditions and sampling timing were more influential than seedbed preparation. As with diseases, the impact of tillage systems on other rice arthropod pests should be evaluated.

Differences in pest or disease severity could contribute to yield differences between tillage systems. Disease and arthropod pressure in the locations used for our study was low. The only diseases observed were AGSS and SR. Rice seed midge were present at very low densities, and other arthropod pests were not detected. There were no significant differences in the severity index of AGSS or SR, (Figure 2.6) or in the abundance of rice seed midge (Figure S2.1) between the SSB and CT systems. Tillage and residue management can have a significant effect on the incidence and severity of SR and AGSS (Webster et al., 1976; Cintas and Webster, 2001). Zhang

et al. (2025c) found that a one-year fallow can reduce the severity of stem rot. While in our study fallowing did not result in a significant stem rot severity reduction, disease ratings tended to be greater under CT. It is possible that the low disease pressure in this study neglected the effect of a year fallow on SR. The impact of tillage system on disease severity should be evaluated under conditions of greater disease diversity and severity.

4.2 Response to nitrogen fertilizer

Rice fields in California are typically continuous rice systems and are flooded for much of the year, being flooded during both the growing season and the winter fallow season (Linquist et al., 2006). This long period of flooding can lead to a build-up of phenols which can inhibit N uptake (Olk et al., 2009; Zhang et al., 2025b). Interrupting this history of flooding with a summer fallow period has been shown to make soil N more available for crop uptake (Zhang et al., 2025b). The on-farm and RES fields in this study had all been fallowed the previous year, and the generally high yields seen in the zero N plots suggest that the indigenous soil N supply was high, regardless of whether the soil was tilled or not before planting.

The grain yield responses to applied N were similar between CT and SSB, and the estimated yield-maximizing N rates did not differ between systems. This was seen in both the RES and on-farm studies (Fig. 2, 3); although, on-farm responses were more variable than those observed at the RES, reflecting heterogeneity in soil properties, field history, and management among locations. Similarly, Harrell et al. 2011 reported comparable N requirements between SSB and CT rice. While tillage can influence soil N cycling, crop N uptake, and N-use efficiency in rice (Linquist et al., 2006; Liang et al., 2016), our results suggest that the reduction in tillage under summer SSB did not substantially alter crop N requirements following a fallow year.

Importantly, at the RES the fertilizer source and placement differed between CT and SSB systems, with aqueous-ammonia injected in CT and surface-applied urea in SSB. Because N source and placement differed between systems, these results represent the response of the overall production systems rather than an isolated tillage effect. Some studies have reported that surface-applied N is used less efficiently than N injected or incorporated beneath the soil surface (Schnier et al., 1990; Linquist et al., 2009). The similar response reported here, may be because the soil is dry at the time of application and urea moves downward into the soil when the field is flooded (Broadbent et al., 1958). In contrast, the N rate required to maximize yield at the on-farm sites was nearly twice that at the RES. This difference may reflect variation in indigenous soil N supply among sites, which can substantially influence rice response to fertilizer N (Espe et al., 2015).

4.3 Potential Savings and Benefits

Reduced spring tillage operations can contribute to water savings by minimizing soil disturbance and reducing soil water evaporation prior to flooding. Because the SSB treatment received no spring tillage, soil water stored during the winter and early spring was likely better conserved by reducing evaporation losses associated with soil disturbance, compared with CT where spring tillage occurred prior to flooding. Preplant soil-water storage was consistently greater under SSB in the 0 – 15 cm layer (and to a lesser degree at 15 – 30 cm) at both the RES and on-farm sites (Figure 2.5), which is consistent with greater soil-water conservation commonly reported under reduced- and no-tillage management in rice as well as other cropping systems (Ceskeski et al., 2022; Pittelkow et al., 2015; Six et al., 2004; Zhao et al., 2022). Greater preplant surface-soil water storage reduces the amount of water needed to saturate the upper soil

profile during initial flooding; however, direct measurements of irrigation input would be required to fully quantify field-scale water savings.

The SSB practice also reduces fuel consumption, labor requirements, and machinery wear by shifting tillage and leveling operations to the summer fallow period and eliminating multiple spring tillage passes (Pittelkow et al., 2012a; Singh et al., 2018). Furthermore, moving field preparation to the preceding summer may allow growers to plant earlier in the spring by eliminating the need to complete tillage and leveling operations before flooding and seeding. This flexibility may be particularly valuable during wet springs when field preparation is delayed. Previous California research has shown that earlier planting is associated with greater yield potential (Linquist et al., 2025), and extension research has estimated yields to be approximately 0.6 Mg ha⁻¹ lower when planting is delayed from early to late May. Although planting dates were the same between systems in the present study, avoiding such delays represents an important potential benefit of the SSB system.

5 Conclusion

This study demonstrates that summer SSB can achieve grain yields and N-rate responses comparable to conventional tillage across both replicated research trials and diverse on-farm environments, without requiring additional fertilizer N to reach maximum productivity. Disease responses were influenced by location, but tillage did not significantly affect either AGSS or SR severity, common tiller diseases in California. Although SSB reduced plant density relative to CT, this reduction did not translate into lower yield potential, suggesting that compensatory tillering or greater growth by surviving plants likely maintained grain production. Collectively, these findings indicate that preparing SSBs during the summer fallow period represents a practical reduced-tillage strategy capable of maintaining yield performance while offering

operational flexibility for California rice growers. By shifting field preparation earlier and reducing spring tillage operations, SSB systems may also provide economic and environmental benefits under increasingly variable climate and water availability. Further research should focus on improving stand establishment under SSB, examining these systems under higher arthropod and disease diversity, and better quantifying potential water savings.

Supplementary Material

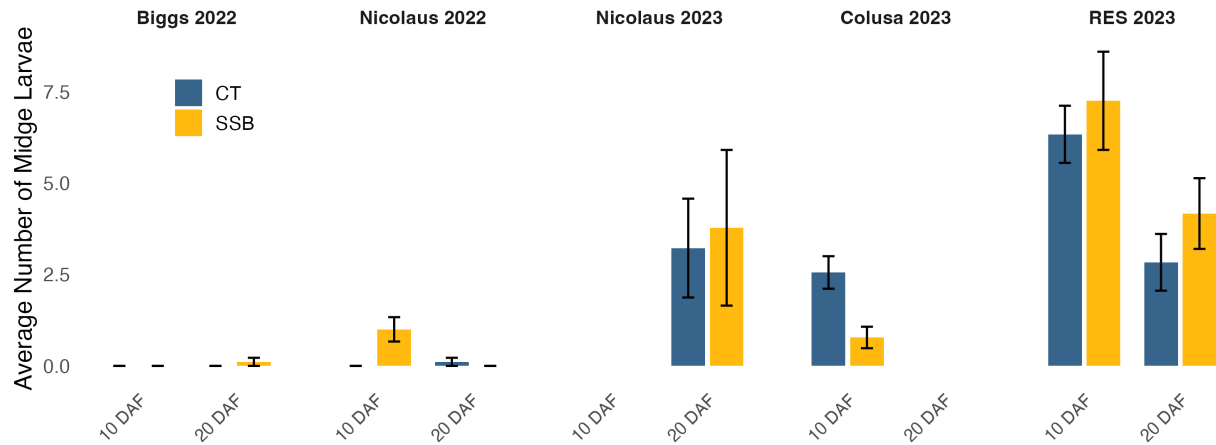


Figure S2.1. Mean number of midge larvae per sample ($\pm$ SE) in conventional tillage (CT) and summer stale seedbed (SSB) rice systems across five site-years. Samples were collected at approximately 10 and 20 days after flooding (DAF). In the on-farm study, midge abundance was not significantly affected by tillage, and the location-year $\times$ tillage interaction was not significant. At the Rice Experiment Station (RES), midge abundance was not affected by tillage ($P = 0.549$) but decreased significantly between 10 and 20 DAF ($P = 0.002$); the tillage $\times$ sampling-date interaction was not significant ($P = 0.482$).

Table S2.1. Stem rot and aggregate sheath spot disease severity scale (Krause and Webster 1972).

Severity class	Stem rot	Aggregate sheath spot
0	No disease	No disease
1	Disease lesions on outer leaf sheath	Disease affecting second leaf below flag leaf or lower
2	Disease lesions have penetrated into inner leaf sheaths	Disease affecting leaf below flag leaf
3	Disease lesions on culm but transverse section of culm not rotted	Disease affecting flag leaf
4	Transverse section of culm is completely rotted	Disease affecting panicle

Tiller sampling dates:

2022: Nicolaus, 9/8; Biggs, 9/15

2023: Colusa, 9/11; Nicolaus, 9/11; RES, 9/14

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CHAPTER THREE

Title: Agronomic performance of reduced tillage in California rice systems

Authors: Mia Godbey^{a*}, Nawal Taaime^a, Whitney Brim-DeForest^b, Luis Espino^c, Bruce Linquist^a

^aDepartment of Plant Sciences, University of California, Davis, Davis, CA, USA

^bUniversity of California Cooperative Extension, Yuba City, CA, United States

^cUniversity of California Cooperative Extension, Oroville, CA, United States

*Corresponding author: Department of Plant Sciences, University of California, Davis, One Shields Ave., Davis CA 95616

Abstract

California rice is predominantly produced using a conventional tillage, water-seeded system. Although highly productive, this system requires substantial water. At the same time, increasingly variable weather conditions, including drought and late spring rains, present additional challenges to rice production. A field experiment conducted in 2024 and 2025 evaluated alternative establishment systems with the potential to reduce water use and allow earlier planting. These systems included drill-seeding (DS) rice using a no-till drill-seeder into a stale seedbed prepared the previous summer (SSB-DS) or directly into no-till soil following the previous rice crop (NTDS) with straw either chopped and retained (NTDS-Chopped) or removed (NTDS-Removed). These systems were compared with the conventional water-seeded system (CT-WS). Grain yield was evaluated across five N fertilizer rates, and crop emergence and disease severity were quantified to identify potential constraints to production. Relative to CT-WS, SSB-DS had similar or greater yield potentials in both years. The two NTDS systems had comparable yields and the lowest potential overall, averaging 16.2 and 9.8% less than the SSB-DS and CT-WS, respectively. The modeled N rate associated with maximum yield was at least 12 kg N ha⁻¹ greater for DS systems than for CT-WS. Emergence and final stand density did not explain differences in yield among DS systems. SSB-DS generally had among the lowest stem rot and aggregate sheath spot severity, although differences were not always significant. Overall, SSB-DS maintained high productivity while reducing spring tillage, allowing earlier planting, and providing potential for reduced water use.

Keywords

Stale seedbed; no-till; drill-seeded; yield potential; nitrogen response; seedling emergence; disease

Highlights

- Summer stale seedbed maintained or increased yield.
- No-till drill-seeded rice had lower yield in 2024.
- Emergence timing was similar among drill-seeded systems.
- Reduced tillage did not increase major rice disease.

1. Introduction

Agricultural systems are constantly changing in response to climate, economics, and labor demands. California is no exception, with drought, changing weather patterns, and increasing production costs affecting how, where, and whether crops are grown (Gebremichael et al., 2021; Salvato et al., 2025). These pressures create a need for systems that provide greater flexibility in the timing of field operations and reduced input rates or costs of inputs like water or tillage, while maintaining productivity. In California, rice is grown primarily in the Sacramento Valley and accounts for approximately 20% of U.S. rice production (USDA-NASS, 2022; California Rice Commission, 2026). The region's heavy clay soils, developed from former wetland landscapes, are well suited to rice production but less suitable for many alternative crops (Hill et al., 2006; Rosenberg et al., 2025; Salvato et al., 2024, 2025). In addition to supporting highly productive rice systems (Linguist et al., 2025), these rice fields also provide valuable wildlife habitat (Eadie et al., 2025).

The California rice system is unique in that it relies on a highly intensive conventional tillage water-seeded system (CT-WS). In this system, fields are typically tilled and leveled before pre-germinated seed is aerially broadcast into flooded soil, and the flood is maintained until shortly before harvest (Hill et al., 2006). The main purpose of the flood is to suppress weed germination and growth (Fischer et al., 2000; Smith and Hill, 1990; Linguist et al., 2015). Following harvest, rice straw is generally incorporated through tillage, and fields may be flooded during winter to promote residue decomposition (Linguist et al., 2006; Matthews et al., 2026). This system is highly productive; however, changing weather patterns, drought, and rising costs are challenging its sustainability. During drought years, planted areas can be substantially reduced due to limited water availability (Gebremichael et al., 2021). In years when irrigation water is available, late

spring rainfall can delay field operations and result in fields being left fallow (Lund et al., 2018; Pancorbo et al., 2023; Salvato et al., 2025; Zhang et al., 2025a). Consequently, fallowed rice area has increased over the past 15 years, and it is not uncommon for 10 to 25% of rice fields to be left fallow yearly (Salvato et al., 2025).

Several alternative agronomic management practices have been or are being studied that may provide greater flexibility and reduce water consumption under these changing conditions. One option is shifting from a water-seeded (WS) to a drill-seeded (DS) system. In DS systems, rice is planted into non-flooded soil and established using rainfall or one or more flush irrigations before the permanent flood is applied. Delaying the permanent flood can reduce early-season irrigation requirements and water use relative to WS systems (Linguist et al., 2015). Drill-seeding has become increasingly important in other temperate rice-producing regions, including southeastern Australia, where adoption has been driven in part by the need to increase water productivity (Dunn et al., 2020). California remains one of the last predominantly WS rice-producing regions; however, research has shown that DS systems can maintain yield potential comparable to WS rice when appropriately managed (Pittelkow et al., 2012; Geoghan and Linguist, 2025).

A second option is the use of stale seedbeds (SSBs). A SSB is prepared in advance of planting and maintained without additional soil disturbance before crop establishment. Its use depends on the management objective. Spring SSBs are commonly used for weed management, in which the soil is prepared and irrigated to stimulate weed emergence before weeds are killed and the crop is planted without further tillage (Fischer et al., 2009; Pittelkow et al., 2012; Brim-DeForest et al., 2017; Ceseski et al., 2022). Fall-prepared SSBs are used in rice production in the mid-southern United States, where seedbeds are prepared after harvest in the fall and planted the

following spring without additional soil disturbance, facilitating earlier planting (Harrell et al., 2011). The recent frequent occurrence of summer fallow in California rice systems provides an opportunity for seedbed preparation. Rather than leaving a fallowed field unworked until the following spring, growers could prepare the seedbed during summer and plant directly into it the following spring without further tillage.

A third option is the practice of no-till (NT). Although commonly practiced in other crops (Triplett and Dick, 2008), its use in rice remains limited and has been associated with reduced yield potential (Godbey et al., 2026). No-till rice systems have not been widely tested in California; one potential challenge is straw management. Because California rice systems are highly productive, substantial amounts of straw remain after harvest. Under conventional tillage, straw can be incorporated into the soil, whereas in NT systems, residue remains concentrated on the soil surface, where decomposition may be slower (Saigusa et al., 1999). Retaining this residue may help conserve soil moisture and suppress weed emergence (Chauhan and Abugho, 2013), but large amounts of undecomposed rice straw can also affect nutrient availability and early crop growth (Rao and Mikkelsen, 1976; Pittelkow et al., 2012) and serve as an inoculum source for diseases such as stem rot, aggregate sheath spot, and blast (Webster et al., 1981; Cintas and Webster, 2001; Greer and Webster, 2001; Miller and Webster, 2001). In particular, surface residue can increase N immobilization and reduce N availability during early crop growth (Rao and Mikkelsen, 1976; Saigusa et al., 1999; Pittelkow et al., 2012). Surface residue may also increase N losses through ammonia volatilization, creating additional challenges for N management in NT systems (Pittelkow et al., 2012). Thus, the amount and management of rice straw may be particularly important to the success of NT rice systems.

Together, these practices, alone or in combination, may offer opportunities to improve the sustainability of California rice systems. Drill seeding can reduce water use by delaying the permanent flood (Dunn et al., 2020; Linqvist et al., 2015). When combined with a summer SSB or NT, additional water savings may be possible because reduced soil disturbance can help conserve soil moisture and limit evaporative losses (Blanco-Canqui and Wortmann, 2020). Drill-seeding with a NT drill into a summer SSB or NT system also reduces tillage requirements and allows growers to plant earlier. Earlier planting is particularly important in California, where the growing season is relatively short, because it provides greater flexibility in planting and has been associated with greater yield potential (Linqvist et al., 2025).

Given these considerations, a two-year field experiment was established to compare the conventional tillage water-seeded system (CT-WS) with a summer stale seedbed drill-seeded system (SSB-DS), and two no-till drill-seeded (NTDS) systems. In the NTDS systems, straw from the previous crop was either chopped and retained on the soil surface (NTDS-Chopped) or removed (NTDS-Removed). The objectives were to determine the yield potential of each system and the N rate associated with maximum yield. Seedling emergence and disease severity were also evaluated to determine whether differences in either could contribute to yield differences among systems.

2. Materials and Methods

2.1 Site Description

This experiment was conducted during the 2024 and 2025 growing seasons at the Rice Experiment Station near Biggs, California (39°27'47" N, 121°43'35" W). The region has a semi-arid Mediterranean climate, with precipitation occurring primarily from November through March. Average growing-season precipitation (May – October) during the two study years was

3.39 mm, and average minimum and maximum air temperatures were 12.68 and 32.54°C, respectively (CIMIS, 2025). The experimental field is located on an Esquon–Neerdobe soil complex, classified as fine, smectitic, thermic Xeric Epiaquerts and Duraquerts. The soil has a clay texture consisting of approximately 29% sand, 26% silt, and 45% clay (Pittelkow et al., 2012), and a soil pH of 5.26, cation exchange capacity of 31.68 meq 100 g⁻¹, and soil organic matter of 28.9 g kg⁻¹.

2.2 Experimental Design and Field Management

The nitrogen rate portion of the experiment was arranged as a split-plot randomized complete block design with four replications. System was the main-plot factor and N fertilizer rate was the subplot factor. The four systems were CT-WS, SSB-DS, NTDS-Chopped, and NTDS-Removed. Each system was established in a 0.2-ha basin. Within each system, five N fertilizer rates (0, 84, 140, 196, and 252 kg N ha⁻¹) were established as subplots measuring 3.0 × 6.1 m. The area surrounding the N-rate subplots was fertilized at 180 kg N ha⁻¹.

The four systems represented distinct combinations of soil disturbance, seedbed preparation, establishment method, planting timing, and residue management (Figure 3.1). Following harvest of the preceding rice crop, straw was incorporated in CT-WS and SSB-DS, chopped and retained on the soil surface in NTDS-Chopped, or baled and removed in NTDS-Removed, leaving approximately 30% of the straw as stubble. All systems were winter flooded except SSB-DS; winter flooding is commonly used to promote rice straw decomposition (Linguist et al., 2006; Matthews et al., 2026). Seedbed preparation in CT-WS consisted of chiseling, two disk passes, leveling, and rolling. The same tillage sequence was completed during the preceding summer fallow for SSB-DS, with no additional tillage before planting, whereas no tillage was performed in either NTDS system. In both years, each system was planted when field and weather

conditions permitted. Because SSB-DS and the NTDS systems did not require spring tillage, they were planted earlier than CT-WS (Table 3.1). Because multiple management practices differed concurrently among treatments, system was treated as the experimental factor rather than the individual effects of tillage, establishment method, planting timing, or residue management.

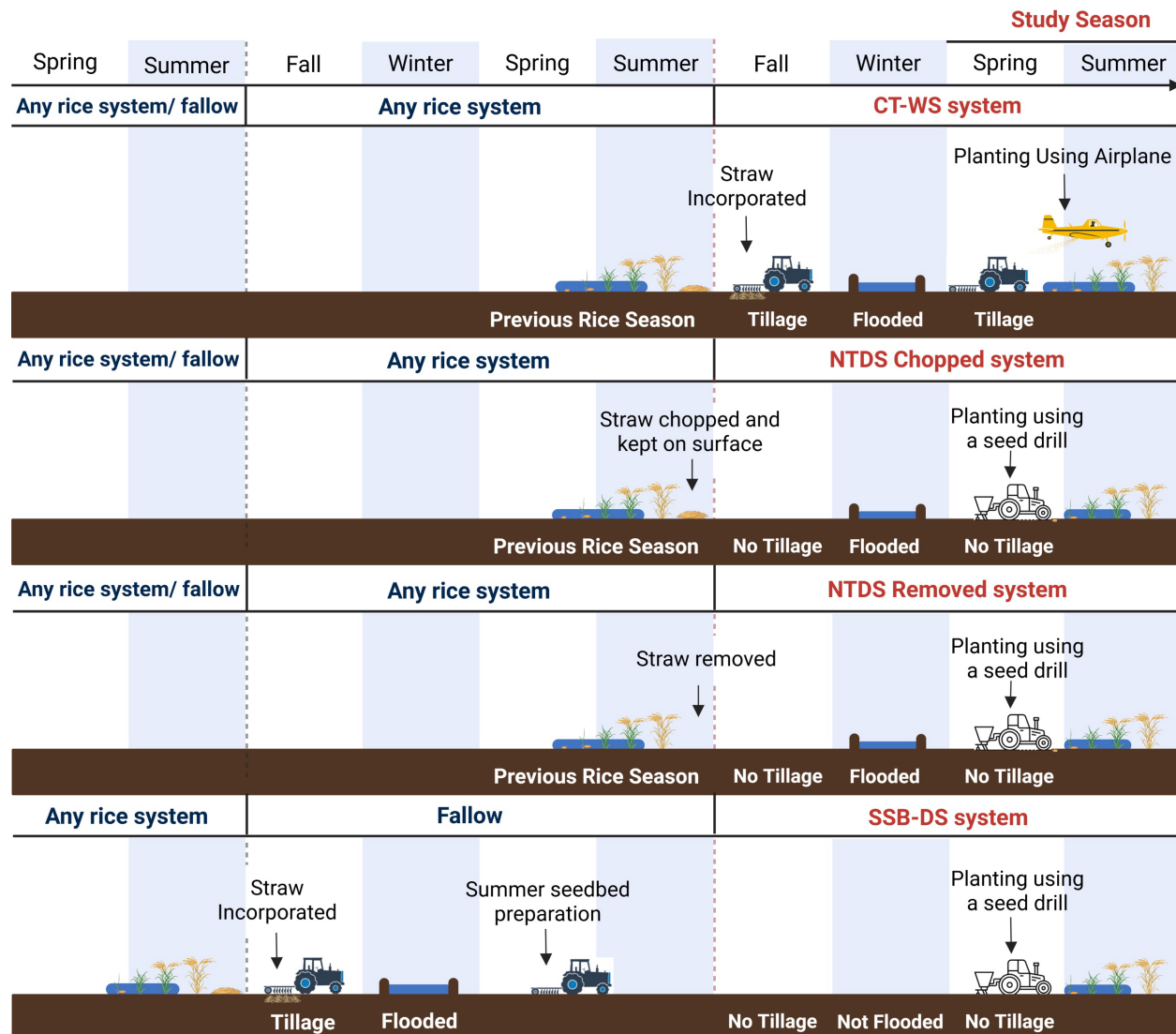


Figure 3.1. Diagram of rice systems in this study. CT -WS system: conventional till water-seeded; NTDS Chopped: no-till drill-seeded rice with straw chopped; NTDS Removed: no-till drill-seeded rice with straw removed; SSB-DS: stale seedbed drill-seeded

Table 3.1. Important dates for each system in 2024 and 2025 at the Rice Experiment Station.

Treatment	Flood	Plant	Flush	Drain	Fertilizer	Permanent Flood	50% Heading	Harvest
2024								
CT-WS	5/26	5/28	NA	NA	5/23	NA	8/16	10/7
NTDS Chopped	NA	5/1	5/2 – 5/3	5/6	5/29	5/29 – 5/30	7/26	9/16
NTDS Removed	NA	5/1	5/2 – 5/3	5/6	5/29	5/29 – 5/30	7/26	9/16
SSB-DS	NA	5/1	5/2 – 5/3	5/6	5/29	5/29 – 5/30	7/26	9/16
2025								
CT-WS	5/19	5/21	NA	NA	5/16	NA	8/9	10/7
NTDS Chopped	NA	4/21	4/22 – 4/ 24	4/28	5/21	5/21 – 5/22	7/20	09/5
NTDS Removed	NA	4/21	4/22 – 4/ 24	4/28	5/21	5/21 – 5/22	7/20	09/5
SSB-DS	NA	4/21	4/22 – 4/ 24	4/28	5/21	5/21 – 5/22	7/20	09/5

Treatments are
 CT-WS (conventional till water-seeded),
 NTDS Chopped (no till drill-seeded residue chopped),
 NTDS Removed (no till drill-seeded residue removed), and
 SSB-DS (stale seedbed drill-seeded).

A short-duration, medium-grain Calrose cultivar, M-206 (Jodari et al., 2004), which is widely grown in California, was planted in all systems at a rate of 168 kg ha⁻¹. In CT-WS, seed was hand broadcast into the floodwater within each N-rate plot, whereas the DS systems were planted using a Great Plains NT drill seeder with a 17.8 cm row spacing. Nitrogen was applied as urea before flooding in CT-WS and before permanent flooding in the NTDS and SSB-DS systems. Phosphorus, potassium, and sulfur were applied uniformly to prevent deficiencies of these nutrients. Weeds, pests, and diseases varied between the WS and DS systems, but they were managed according to statewide recommendations to minimize yield loss within the N rate plots. Additional management practices and important dates are summarized in Table 3.1.

2.3 Data Collection

2.3.1 Baseline soil sampling

To characterize baseline soil properties, 15 – 20 soil cores were collected from the 0 – 15 cm depth before fertilizer application and pooled separately by system within each basin. Composite samples were air-dried, crushed, and passed through a 2-mm sieve before laboratory analysis by Midwest Laboratories (Midwest Laboratories, 2025). Soil pH was determined using a 1:1 soil-to-water ratio, cation exchange capacity using the sodium acetate method, and soil organic matter using Walkley – Black titration.

2.3.2 *Emergence*

Rice emergence was monitored at three randomly selected locations within each DS system replicate. At each location, two flags were placed 30.5 cm apart along a planted rice row to establish a fixed sampling area that was monitored throughout the emergence period. A seedling was considered emerged when visible rice leaf tissue first protruded above the soil surface. Fields were monitored following planting, and daily counts began when the first emerged rice seedlings were observed. The number of emerged seedlings within each marked row segment was recorded daily until no additional seedlings were observed in any of the monitored segments. Daily emergence was expressed as a percentage of the final seedling count within each segment, with the final count representing 100% emergence. Final seedling counts were also used to estimate stand density based on a drill row spacing of 17.8 cm.

2.3.3 *Disease severity*

Aggregate sheath spot (AGSS; *Rhizoctonia oryzae-sativae*) and stem rot (SR; *Nakataea oryzae*) were the only disease observed in the trial area. The severity of these diseases was evaluated in 3.0 x 6.1 m plots that did not receive a fungicide treatment. Tiller samples were taken when basins were drained for harvest. Each sample consisted of three handfuls (30 – 40) of tillers from each plot, cut at soil level. All tillers from a plot were combined and 30 to 50 tillers

were randomly selected and rated for AGSS or SR severity using the scales presented in Table S1 (Espino et al., 2026). Disease severity index was calculated as:

$$\text{Disease Severity Index} = \frac{\sum(\text{number of tillers per severity class} \times \text{severity class})}{\text{total tillers}}$$

2.3.4 Yield

At harvest, grain yields from the N rate plots were taken using an Almaco small plot combine, and yields were adjusted to 14% moisture content.

2.4 Data Analysis

All statistical analyses were conducted in R (R Core Team, R version 4.5.1 2025-06-13). Data manipulation and calculation of summary statistics were performed using the dplyr package (Wickham et al., 2023). Linear mixed-effects models were fitted using lmerTest (Kuznetsova et al., 2017), and fixed effects were evaluated using Type III tests with Satterthwaite's approximation for denominator degrees of freedom. Estimated marginal means and Tukey-adjusted pairwise comparisons were obtained using emmeans (Lenth, 2026). Quadratic regressions were fitted using functions in the base R stats package. Figures were produced using ggplot2 (Wickham, 2016). Statistical significance was evaluated at $P < 0.05$.

Grain yield was analyzed according to the split-plot experimental design, with system as the main-plot factor and N rate as the subplot factor. Year, system, N rate, and all interactions were included as fixed effects. Year was treated as a fixed effect because the objective was to evaluate treatment responses specifically in the two years included in the study. Block nested within year and the whole-plot experimental unit (block x system within year) were included as random effects to account for the experimental design. Because the year x system interaction was

significant, systems were compared within each year using estimated marginal means averaged across N rates. Fisher's least significant difference (LSD; $\alpha = 0.05$) was used for pairwise comparisons among systems. Systems were also compared within each year x N-rate combination using Fisher's LSD for graphical presentation.

Quadratic regressions were fitted separately by year and system to describe grain-yield responses to increasing N rate and estimate the N rate associated with maximum modeled yield. Modeled maximum N rates exceeding the highest experimental N rate of 252 kg N ha⁻¹ were considered extrapolations and were not interpreted as fertilizer recommendations.

For SR and AGSS disease severity index, the data were analyzed separately using models containing year, system, and their interaction as fixed effects, with replicate nested within year included as a random effect. Systems severity index estimated marginal means were compared within each year using Tukey-adjusted pairwise comparisons.

Time to 50% emergence (E50) was estimated for the DS system and expressed as days after flush (DAF₅₀) or accumulated growing degree days (GDD₅₀). GDDs were calculated from daily maximum and minimum air temperatures using a GDD model calibrated for M-206 (Sharifi et al., 2017) starting at the initial flush date in each year. The model calculates daily thermal time from mean daily air temperature using a base temperature of 11.7°C, with lower and optimum temperature thresholds of 13.1 and 29.9°C, respectively. Final stand density, DAF₅₀, and GDD₅₀ were analyzed using a linear mixed-effects model with year, system, and their interaction as fixed effects, with block nested within year included as a random effect.

3. Results

3.1 Grain yield

Grain yields ranged from 5.2 to 11.1 Mg ha⁻¹ in 2024 and from 4.0 to 12.5 Mg ha⁻¹ in 2025 (Figure 3.2). Across years, grain yield was affected by system and N rate, whereas the main effect of year was not significant (Table 3.2). Significant year x system and year x N rate interactions indicated that system performance and the overall yield response to N differed between years. In contrast, the system x N rate interaction was not significant, indicating no evidence that yield responses to N differed among systems. The year x system x N rate interaction was also not significant, indicating that differences in N response among systems did not vary between years.

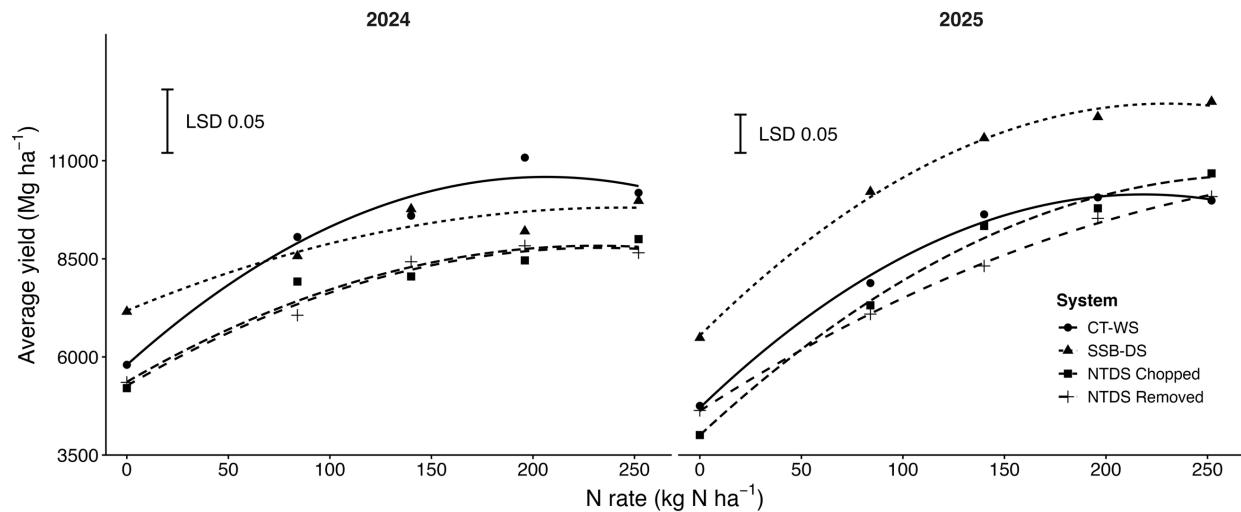


Figure 3.2. Rice grain yield response to N fertilizer rate under four production systems in 2024 and 2025. Points represent treatment means and lines represent quadratic regressions fitted separately by year and production system. Vertical bars indicate Fisher's least significant difference (LSD; $\alpha = 0.05$) for comparisons among production systems within individual N rates. Statistical tests for year, production system, N rate, and their interactions are presented in Table 3.2.

Table 3.2. Analysis of variance (ANOVA) for rice grain yield as affected by year, production system, N fertilizer rate, and their interactions in 2024 and 2025. N rate was treated as a categorical subplot factor. Block was nested within year as a fixed blocking effect, and block x system within year was included as a random whole-plot effect. Fixed effects were evaluated using Type III tests with Satterthwaite's approximation.

Effect	df	F value	P value
Year	1	1.46	0.243
System	3	22.23	<0.001
N rate	4	162.37	<0.001
Year × System	3	6.75	0.003
Year × N rate	4	8.48	<0.001
System × N rate	12	0.98	0.477
Year × System × N rate	12	1.12	0.352

In both years, grain yield responded significantly to N fertilizer, generally increasing with N rate before plateauing at the higher N rates, although a plateau was not always seen (Figure 3.2). At 0 kg N ha⁻¹, SSB-DS had the highest yield in both years. In 2024, CT-WS and SSB-DS produced similar maximum observed yields, averaging 10.53 Mg ha⁻¹, whereas maximum yields in NTDS-Chopped and NTDS-Removed were lower and similar to one another, averaging 8.92

Mg ha⁻¹. In 2025, the highest observed yields were 12.5 Mg ha⁻¹ for SSB-DS, 10.7 Mg ha⁻¹ for NTDS-Chopped, 10.1 Mg ha⁻¹ for NTDS-Removed, and 10.1 Mg ha⁻¹ for CT-WS.

Quadratic regressions further characterized differences in yield response to N fertilizer (Table 3.3). In 2024, estimated maximum yields were highest for CT-WS and SSB-DS and lower for the two NTDS systems, with N rates associated with maximum yield ranging from 206 to 237 kg N ha⁻¹. In 2025, maximum yields were 10.1 Mg ha⁻¹ for CT-WS and 12.4 Mg ha⁻¹ for SSB-DS, occurring at 218 and 230 kg N ha⁻¹, respectively. For NTDS-Chopped and NTDS-Removed, the fitted curves did not reach a maximum within the experimental N rate, indicating that the N rate associated with maximum yield was greater than the highest N rate evaluated (252 kg N ha⁻¹); therefore, maximum yield and the corresponding N rate were not estimated.

Table 3.3. Modeled N rates associated with maximum modeled grain yield and corresponding maximum modeled yields (with 95% confidence intervals) for four rice production systems in 2024 and 2025. Values were estimated from system-specific quadratic regressions. In 2025, the maximum N rates and yields could not be determined for either NTDS system as the estimates were outside the boundaries of the N rates in the study.

Year	Production system	Modeled N rate for maximum yield, kg N ha ⁻¹	Modeled maximum yield, Mg ha ⁻¹ (95% CI)
2024	CT-WS	206	10.59 (9.99 – 11.57)
	NTDS Chopped	231	8.83 (8.22 – 12.54)
	NTDS Removed	234	8.78 (8.17 – 13.41)
	SSB-DS	237	9.80 (9.20 – 15.07)
2025	CT-WS	218	10.14 (9.65 – 10.72)
	NTDS Chopped	-	-
	NTDS Removed	-	-
	SSB-DS	230	12.45 (11.95 – 13.07)

Treatments are
CT-WS (conventional till water-seeded),

NTDS Chopped (no till drill-seeded residue chopped),
NTDS Removed (no till drill-seeded residue removed), and
SSB-DS (stale seedbed drill-seeded).

3.2 Emergence

Emergence and stand density were quantified only in the DS systems. Emergence began 11 d after the initial flush in 2024 and 12 d after the initial flush in 2025. System did not significantly affect emergence; however, there was a significant year effect (Table 3.4) with DAF₅₀ occurring at 11.9 d in 2024 and 14.7 d in 2025 (Figure 3.3). The delay in 2025 was at least partially associated with cooler temperatures in 2025, as when emergence was expressed using GDD, the differences between years were no longer significant (Table 3.4). The GDD to reach DAF₅₀ was approximately 84 and 93°C d in 2024 and 2025, respectively (Figure 3.3). The final stand density was not affected by year, system, or their interaction (Table 3.4) and averaged 2.95×10^6 plants ha⁻¹ across systems and years.

Table 3.4. Analysis of variance for final rice stand density, time to 50% emergence expressed as days after flush (DAF₅₀) and accumulated growing degree days (GDD₅₀), stem rot severity, and aggregate sheath spot severity among drill-seeded systems in 2024 and 2025.

Response	Effect	df	F value	P value
Final Stand Density	Year	1	0.222	0.654
	System	2	0.196	0.825
	Year x System	2	3.295	0.072
DAF ₅₀	Year	1	12.31	0.013
	System	2	1.69	0.226
	Year × System	2	0.21	0.816
GDD ₅₀	Year	1	1.412	0.280
	System	2	1.534	0.255
	Year × System	2	0.217	0.808
Stem Rot Severity	Year	1	0.379	0.561
	System	3	0.808	0.506
	Year × System	3	1.253	0.320
Aggregate Sheath Spot Severity	Year	1	1.056	0.344
	System	3	8.495	<0.001
	Year × System	3	0.816	0.502

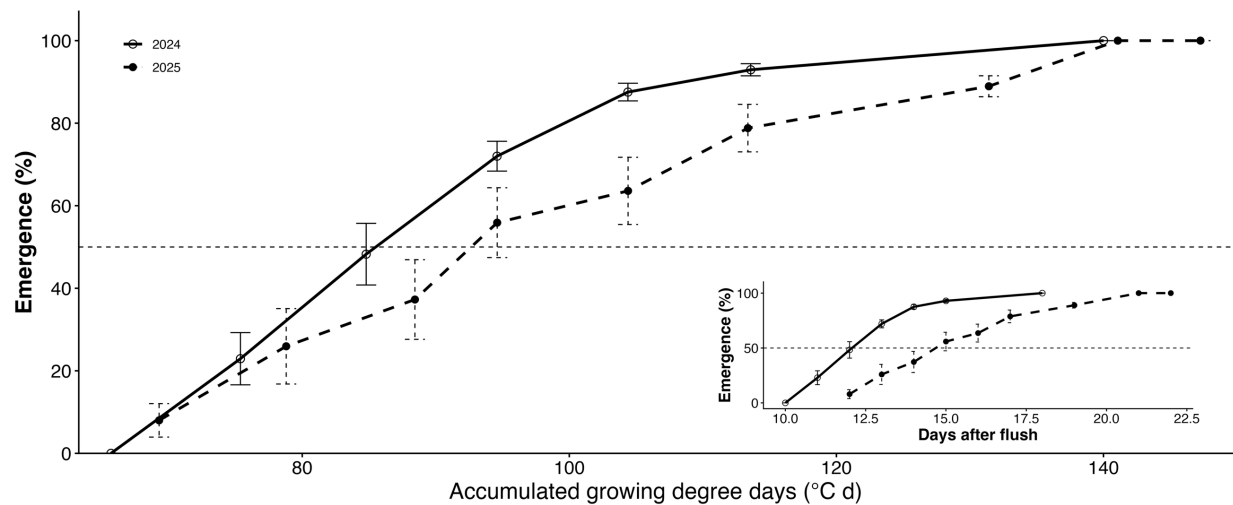


Figure 3.3. Rice emergence as a function of accumulated growing degree days (GDD; main panel) and days after flush (DAF; inset) for drill-seeded production systems in 2024 and 2025. Emergence is expressed as a percentage of the final seedling count within each monitored row segment. Statistical results for time to 50% emergence expressed as DAF₅₀ and GDD₅₀ are presented in Table 3.4.

3.3 Disease

Stem rot severity was not affected by year, system, or the year x system interaction and averaged 1.3 across years (Figure 3.4). No significant pairwise differences among systems were detected. Aggregate sheath spot severity was low and ranged from 0.05 to 0.34. Severity differed among systems but was not affected by year, and there was no year x system interaction. Averaged across years, AGSS severity was greater in CT-WS than in SSB-DS, NTDS Chopped, and NTDS Removed, while the three reduced-tillage systems did not differ from one another.

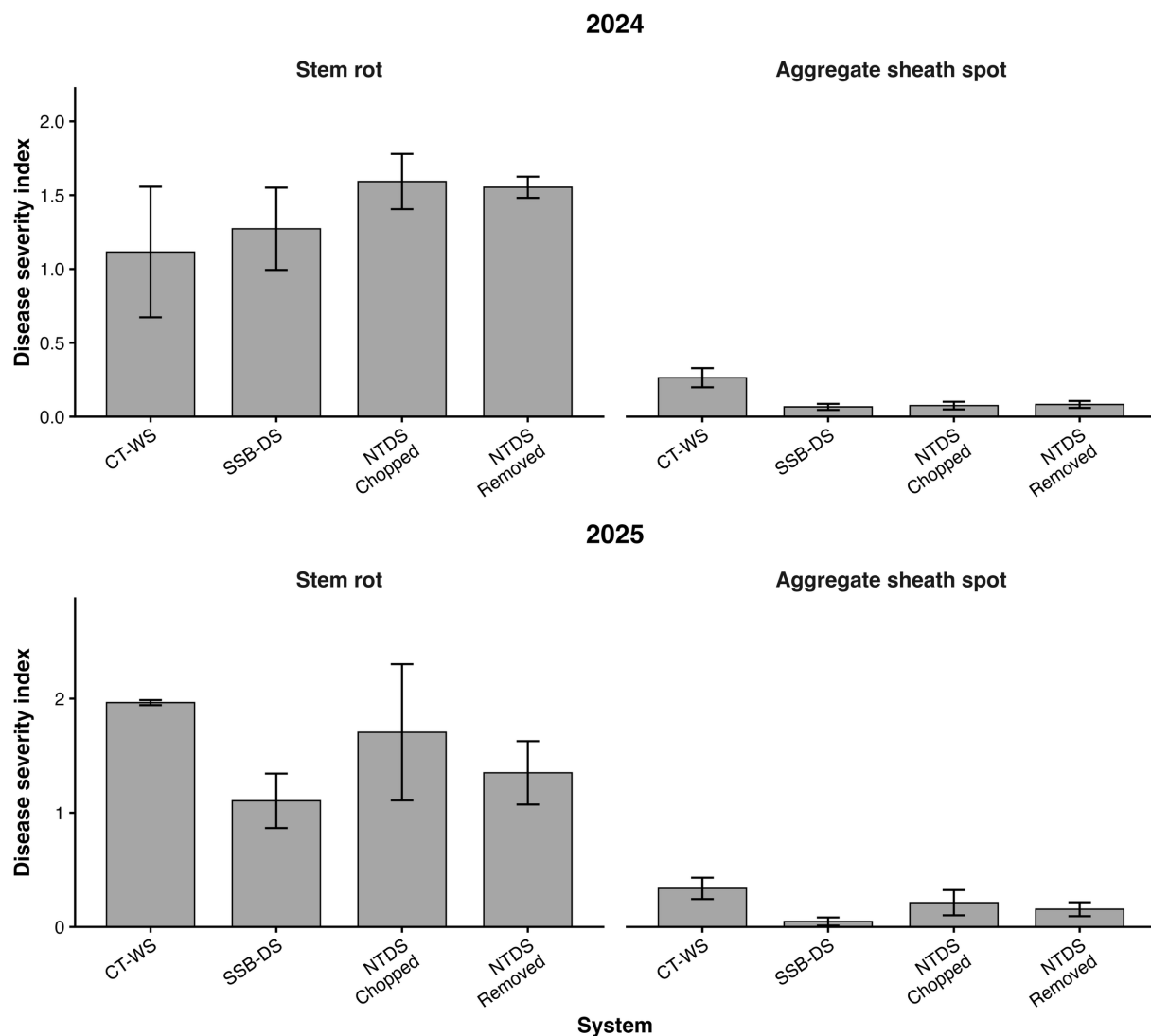


Figure 3.4. Mean stem rot and aggregate sheath spot severity index under conventional water-seeded (CT-WS), summer stale seedbed drill-seeded (SSB-DS), no-till drill-seeded with copped residue (NTDS Chopped), and no-till drill-seeded with removed residue (NTDS Removed) in 2024 and 2025. Bars represent means $\pm$ SE for untreated plots. Bars represent means across four experimental replicates, and error bars represent standard errors.

4 Discussion

4.1 Grain yield potential

4.1.1 CT-WS vs SSB-DS yields

Grain yield potential among the systems varied between the two years (Figure 3.2; Table 3.3). Comparing CT-WS and SSB-DS, yield responses differed between years. Similar yields have been reported between conventional water-seeded and drill-seeded stale-seedbed systems (Pittelkow et al., 2012), between stale-seedbed and conventionally tilled drill-seeded systems (Harrell et al., 2011; Pittelkow et al., 2012), and between conventional water- and drill-seeded rice systems (Geoghan and Linquist, 2025). Together, these studies suggest a similar yield potential between CT-WS and SSB-DS as observed in 2024. However, in 2024, when averaged across N rates, SSB-DS yielded 2.12 Mg ha^{-1} , or about 25% more than the CT-WS in 2025.

The reason for the greater yield performance of SSB-DS relative to CT-WS observed in 2025 is unclear. Because the N-response curves for CT-WS and SSB-DS were similar, differences in N response were unlikely to account for the yield advantage. Instead, differences in seedbed conditions or crop establishment associated with management during the preceding fallow period may have contributed, although these factors were not directly evaluated. Aggregate sheath spot severity was greater in CT-WS than in SSB-DS, although severity was generally low, suggesting that disease pressure may have contributed only partially to the observed yield difference. Stem rot severity also tended to be lower in SSB-DS than in CT-WS, although this difference was not significant. Similarly, Zhang et al. (2025a) reported lower SR severity in water-seeded rice following a year-long fallow, as occurred in the SSB-DS system, compared with rice grown

continuously. Espino et al. (2026) reported a 0.26 Mg ha⁻¹ yield decline for each unit increase in SR severity. The difference in SR severity observed here was less than 1.0 and not significant, suggesting that SR alone was unlikely to account for the observed yield difference.

Importantly, these systems were planted at different times and therefore progressed through phenological growth stages under different temperature conditions, which may have affected yields. Espe et al. (2017) found that sustained temperatures below 13°C during booting or temperatures above 36°C during flowering can reduce yield. Because the DS systems were planted earlier, they experienced different temperatures at these critical stages (Figure 3.5). For example, SSB-DS headed earlier than CT-WS and, in 2024, experienced daytime temperatures exceeding 40°C during flowering, whereas CT-WS flowered later under cooler conditions. This may explain the slightly lower, although non-significant, yield of SSB-DS relative to CT-WS in 2024 and its lower yield in 2024 compared with 2025; however, it does not explain the lower yield of CT-WS in 2025. In 2025, the nighttime temperatures were cooler than in 2024 and in some cases, were at or below the critical threshold of 13°C; however, this was the case for both CT-WS and SSB-DS and therefore does not explain the lower yield of CT-WS in 2025.

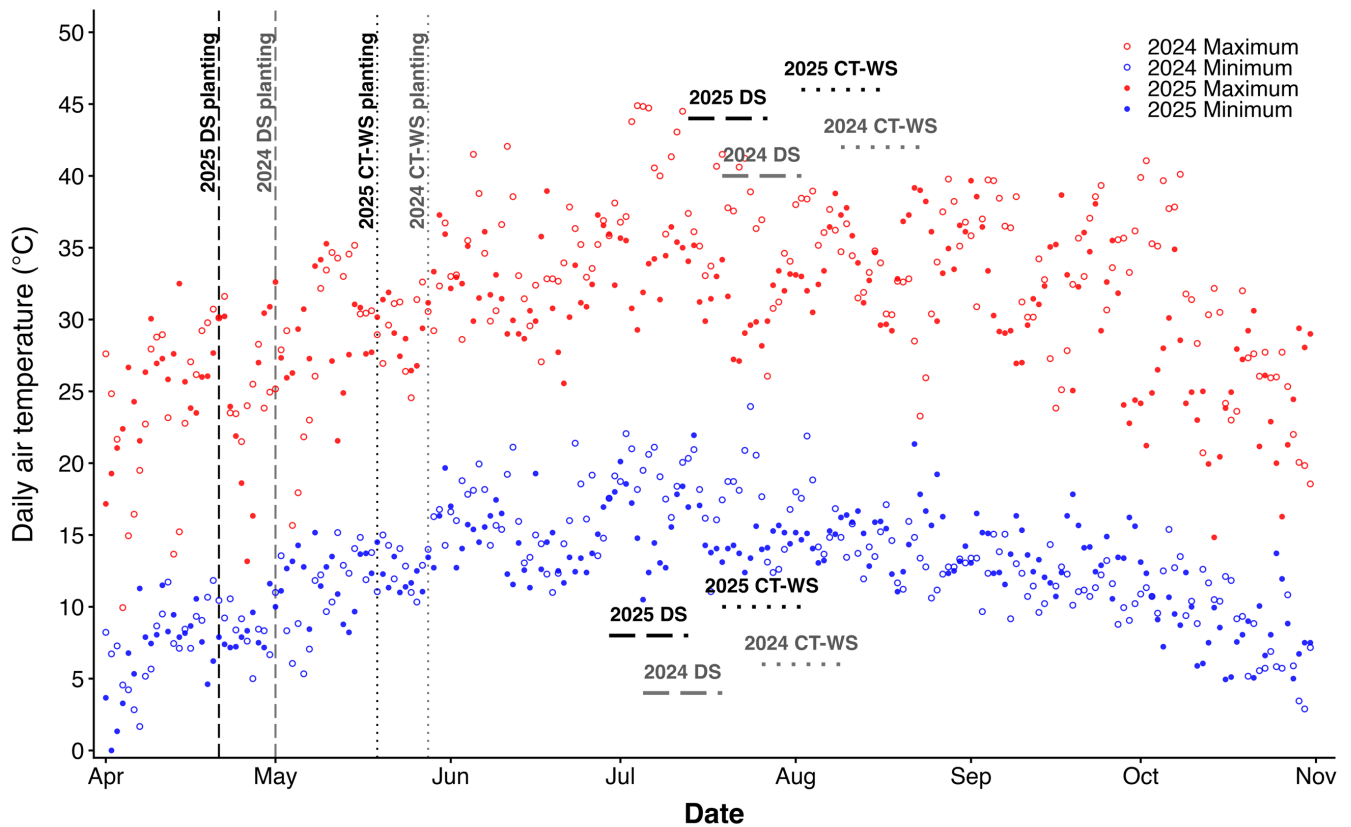


Figure 3.5. Daily maximum and minimum air temperatures from April through October in 2024 and 2025. Vertical lines indicate planting dates for conventional water-seeded (CT-WS) and drill-seeded (DS) systems, with gray lines representing 2024 and black lines representing 2025. Dotted lines indicate CT-WS and long-dashed lines indicate DS. Horizontal segments near the minimum-temperature series indicate the booting period, defined as 7 to 21 d before 50% heading. Horizontal segments near the maximum-temperature series indicate 50% heading.

Finally, herbicide programs differed between the WS and DS systems. Herbicide application can result in crop injury and affect rice yield depending on herbicide rate and application timing

(Becerra-Alvarez and Al-Khatib, 2024). However, previous studies comparing WS and DS systems also used different herbicide programs in each system while reporting comparable yields (Harrell et al., 2011; Pittelkow et al., 2012). Overall, our findings indicate that SSB-DS yields are comparable to or greater than the CT-WS system; however, we are not able to identify a single factor explaining the annual differences in yield potential between these systems. These differences are likely associated with multiple factors rather than a single measured response and would require more targeted research to resolve.

4.1.2 No-till yields

The NTDS systems were among the lowest-yielding systems in both years within the bounds of N rates evaluated. The specific effect of N rate on yields is discussed below; however, averaged across the three highest N rates in both years, NTDS-Chopped and NTDS-Removed yielded 16% less than SSB-DS, and 9.8% less than the CT-WS. Lower yields under NTDS are consistent with several global meta-analyses reporting that NT reduces rice yield (Liang et al., 2016; Chakraborty et al., 2017; Godbey et al., 2026). Godbey et al. (2026) found that NT performed best at clay contents between 180 – 350 g kg⁻¹; soils at this study site contained 450 g kg⁻¹ clay, which may have contributed to the lower NTDS yields. Other studies have also associated reduced NT performance with changes in soil physical properties, including greater bulk density and penetration resistance, which can restrict root growth and crop productivity (Blanco-Canqui and Ruis, 2018; Salahin et al., 2021).

The similarity in yields between NTDS-Chopped and NTDS-Removed indicates that residue management alone was not responsible for the lower productivity, further supporting findings from Godbey et al. (2026) that residue retention had limited influence on NT rice yield across studies. Importantly, although residue was retained on the soil surface after harvest in NTDS-

Chopped, the fields were flooded during the winter and much of the straw had decomposed by the following spring, consistent with previous observations of overwinter rice straw decomposition in California (Linquist et al., 2006). In other crops, heavy surface residue under NT can interfere with furrow opening, seed placement, and seed-soil contact and can contribute to uneven crop establishment (Aikins et al., 2019). However, because emergence and final stand density did not differ between NTDS-Chopped and NTDS-Removed in this study, residue interference with establishment was unlikely to be a major cause of the yield difference. Instead, characteristics shared by both NTDS systems, including the absence of soil disturbance, drill-seeded establishment, water management, and associated nutrient dynamics, may have contributed to their lower yields.

4.2 Response to Nitrogen

Nitrogen fertilizer was a major determinant of grain yield for all systems. At low N rates, yields were consistently greatest in SSB-DS, reflecting greater access to soil-derived N following the fallow period (Zhang et al., 2025b); however, this did not translate into a lower N rate required to achieve maximum yield. Based on the quadratic regression analysis, the N rate associated with maximum yield was at least 12 kg N ha⁻¹ greater for all DS systems than for CT-WS (Table 3.3). The greater N requirement observed for SSB-DS is consistent with previous California research, in which water-seeded SSB required 30 – 35 kg N ha⁻¹ more than conventional systems to maximize yield (Pittelkow et al., 2012). In 2025, the lack of a plateau in the NTDS yield response suggests that greater N availability alone may not fully explain their lower productivity. For the NT systems, the 2024 N-response provides little evidence that the lower yields were simply due to a greater N requirement. Other studies have shown that NT rice performs better at higher N rates, although yields may remain below those under conventional

tillage. A recent meta-analysis similarly found that N rates of 120 – 180 kg N ha⁻¹ were needed for NT rice to achieve yields comparable with conventional tillage and that NT reduced N uptake and N-use efficiency (Godbey et al., 2026). Finally, all alternative systems were drill-seeded, which can introduce drainage periods, which alters soil moisture conditions during establishment compared with WS rice and influence N transformations loss pathways (Geoghan and Linquist, 2025), potentially increasing N requirement for all DS systems. However, other studies have not shown there to be differences between WS and DS systems (Pittelkow et al., 2012).

4.3 Crop establishment

We expected to see differences in seedling emergence between the different DS systems due to differences in previous tillage and residue management which can influence soil temperature, moisture, and seedbed conditions affecting crop emergence (Mohanty and Painuli, 2004; Blanco-Canqui and Ruis, 2018). The SSB treatment was tilled but remained undisturbed for an extended period before planting, allowing the crop residues to decompose before crop establishment; in contrast, NTDS was planted directly into an undisturbed surface carrying either stubble and/or residues from the previous crop. Despite these differences, there was no measurable difference in emergence or final stand density (Table 3.4; Figure 3.3). This is notable given the contrasting yield responses among systems, particularly in 2025, when SSB-DS had the greatest yield potential and the NTDS systems had the lowest. Similar crop establishment across systems suggests that differences in emergence and final stand density did not account for these yield responses and that factors affecting crop growth later in the season likely contributed. Although days to 50% emergence (DAF₅₀) differed between years, the accumulated growing degree days were similar across both years. This is consistent with previous work using temperature-based models to predict rice emergence in California WS systems (Lundy et al., 2014).

4.4 Disease

Differences in tillage and residue management alter pathogen survival because crop residues can serve as a source of inoculum for diseases such as stem rot and aggregate sheath spot (Bockus and Shroyer, 1998; Cintas and Webster, 2001). Fallowing has also been shown to reduce disease severity (Zhang et al., 2025a). Our findings show limited effects of the systems on disease severity. In both years AGSS severity was highest in the CT-WS and lowest in the SSB-DS system, although this difference was only significant in 2025. This lower AGSS severity in SSB-DS relative to the CT-WS is likely due to a combination of the preceding fallow period and drill-seeded establishment, as the DS treatments generally had lower AGSS severity. For SR, the findings are inconclusive; however, Zhang et al. (2025a) found that SR severity was lower in water-seeded rice following a fallow year than where rice was grown in the previous year. One limitation in our study is that the levels of SR and AGSS inoculum in the experimental basins was not measured before the systems were established. Different levels of inoculum due to differences in systems and management conducted during previous years may obscure trends.

5. Conclusion

Findings here suggest that the SSB-DS system is a promising alternative to the commonly practiced CT-WS system in California. Grain yields were comparable to or greater than CT-WS, and SSB-DS also offers the potential advantages of water savings and earlier planting. The data suggest that a higher N rate may be required to achieve maximum yields. However, this system can only be implemented on fields fallowed during the preceding season, which typically represents 10 - 25% of California rice area. The NT systems are also promising from the perspective of water use and reduced tillage costs, but they had significantly lower

yields, which may make these systems uneconomical. Further research is needed to evaluate the economic potential of these systems and identify areas where yields may be improved.

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Conclusion

Reducing tillage in rice production has the potential to decrease soil disturbance, reduce field operations, conserve soil moisture, and provide greater flexibility in the timing of field preparation. However, the findings of this dissertation demonstrate that the agronomic consequences of reduced tillage depend strongly on how tillage is reduced and how reduced-tillage practices are integrated with other components of the production system. Across the global literature, continuous no-till rice generally resulted in lower yields than conventional tillage, although the magnitude of this yield penalty varied with soil and management conditions. In California, however, shifting tillage to a preceding summer fallow period provided an alternative approach to reducing spring tillage while maintaining productivity. Summer stale seedbed systems maintained yields when used with water seeding and had similar or greater yield potential than conventional water-seeded rice when combined with drill seeding. In contrast, continuous no-till drill-seeded systems had lower yield potential. Collectively, these findings suggest that strategic reductions in tillage may provide a more agronomically viable pathway for California rice production than the complete elimination of tillage.