Postprint: Assessment of Water and Fertilizer Management Impacts on CH4 Emissions from Paddy Fields and Their Global Warming Potential

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Abstract

Methane (CH4) is one of the major greenhouse gases, second only to carbon dioxide (CO2) in its contribution to global warming. Rice paddies are an important source of CH4 emissions, and reducing CH4 emissions from rice paddies has a direct effect on mitigating climate warming. Therefore, understanding the patterns and characteristics of CH4 emissions from rice paddies is particularly important for controlling and reducing such emissions. To understand the main influencing factors and their degree of impact on greenhouse gas emissions from rice paddies, estimate the global warming potential of greenhouse gases from rice paddies, and seek mitigation measures for agricultural emissions, we established a database of CH4 emissions from rice paddies by collecting published literature, and employed factorial analysis and regression analysis methods to analyze the characteristics of daily CH4 emissions and global warming potential, as well as possible influencing factors. The results showed that both daily CH4 emissions and warming potential from rice paddies increased with the background content of soil organic matter. The magnitude of daily CH4 emissions from different types of rice paddies followed the order: late rice in double-cropping rice > early rice in double-cropping rice > single-cropping rice > late rice in rice-wheat rotation; the warming potential of CH4 from late rice paddies was greater than that from early rice paddies. Under different fertilizer treatment conditions, daily CH4 emissions from rice paddies showed the following pattern: straw incorporation > combined application of organic fertilizer > chemical nitrogen fertilizer biochar. Controlling irrigation water volume could reduce the comprehensive warming potential of CH4 from rice paddies, showing the pattern: continuous flooding > sun-drying of fields > alternate wetting and drying > controlled irrigation. The research results indicate that the production and emission processes of CH4 from rice paddies are jointly influenced by multiple factors, including soil organic matter content, fertilizer management, water management, and cropping systems. Therefore, fertilizer and water management should be appropriately adjusted according to different soil conditions and cropping systems to reduce greenhouse gas emissions from rice paddies and decrease their warming potential.

Full Text

Preamble

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Impact of Water/Fertilizer Management on Methane Emission in Paddy Fields and Global Warming Potential

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Abstract: Methane (CH) is a major greenhouse gas, second only to CO in its contribution to global warming. Paddy fields represent an important source of CH emissions, and reducing these emissions has direct benefits for climate change mitigation. Understanding the patterns and characteristics of CH emissions from rice paddies is therefore crucial for developing effective control strategies. To identify the main factors influencing greenhouse gas emissions from paddy fields, estimate their global warming potential, and explore mitigation measures, we constructed a comprehensive database of CH emissions from rice paddies by compiling published literature. Factorial and regression analyses were employed to examine CH daily fluxes, global warming potential (GWP), and potential influencing factors. Results showed that both daily CH emissions and GWP increased with soil organic matter content. Among different rice cultivation systems, daily CH emissions followed the order: late rice in double-cropping systems > early rice in double-cropping systems > single-cropping rice > late rice in rice-wheat rotation systems. The GWP of late rice paddies exceeded that of early rice paddies. Under different fertilizer treatments, daily CH emissions ranked as: straw incorporation > combined organic manure > chemical nitrogen fertilizer biochar. Controlled irrigation significantly reduced the comprehensive GWP of CH emissions, with the following pattern: continuous flooding > mid-season drainage > alternate wetting and drying > controlled irrigation. These findings demonstrate that CH production and emission in paddy fields are jointly influenced by soil organic matter content, fertilizer and water management, and cropping systems. Adjusting fertilizer and water management practices according to specific soil conditions and cultivation systems can effectively reduce greenhouse gas emissions and minimize warming potential.

Keywords: Paddy field; Greenhouse gases; Methane (CH) emission; Global warming potential; Soil organic matter; Water and fertilizer management; Cropping system

Introduction

Methane (CH) is one of the three major greenhouse gases, ranking second only to carbon dioxide (CO) in its contribution to global warming. Rice paddies constitute a significant source of atmospheric CH, accounting for approximately 15% of total CH emissions [1]. According to China’ s Second National Communication on Climate Change [2], agricultural CH emissions in 2005 represented 56.6% of the nation’ s total CH emissions, with rice paddies contributing 31.5% of agricultural CH emissions. China’ s rice cultivation area comprises about 25% of its total arable land and approximately 20% of global rice acreage. Consequently, reducing CH emissions from rice paddies is critically important for climate change mitigation.

Methane emissions from rice paddies result from the anaerobic decomposition of organic matter in flooded soils—a highly complex process [3] influenced by soil physicochemical properties, climatic conditions, cultivation practices, rice varieties, and field management measures [4]. CH production occurs through two primary pathways: (1) an acidogenic route where specialized hydrogenotrophic methanogens reduce CO using H or directly utilize formic acid and CO to form CH; and (2) a non-acidogenic route where methylotrophic methanogens demethylate simple methyl-containing compounds, accounting for approximately 70% of total CH production. Once produced, CH is transported to the atmosphere through three mechanisms: molecular diffusion, ebullition (bubble transport), and plant-mediated transport via aerenchyma tissue [5]. Plant-mediated emission represents the dominant pathway, with rice roots efficiently transporting approximately 80% of produced CH to the atmosphere through their aerenchyma [6–8].

Key factors influencing CH emissions include soil temperature, pH, water management, and fertilizer application. Soil temperature directly affects organic matter decomposition, microbial activity, and CH production and transport rates. The optimal temperature for methanogenic microorganisms is 35-37°C, and during the rice growing season, daily CH flux variations correlate with diurnal soil temperature changes [9]. Soil pH primarily influences organic matter decomposition rates and methanogen activity, with neutral conditions favoring CH production. When pH falls below 5.75 or exceeds 8.75, methanogenic activity is suppressed, substantially reducing or eliminating CH emissions [10]. In flooded paddies with high soil organic matter content, methanogen activity is elevated, leading to greater CH emissions that correlate positively with soil organic matter content [11-12]. Irrigation methods and water depth also affect CH emissions; shallow irrigation reduces emissions, with fluxes increasing as water depth rises up to 10 cm [13]. Compared with continuous flooding, mid-season drainage can reduce CH emissions by 36-65% [14-16], while intermittent irrigation can decrease emissions by 32-93% [17-19].

Different water management practices create a trade-off between CH and N O emissions [20]. While reducing CH emissions often increases N O emissions [8], the global warming potential of N O far exceeds that of CH . Therefore, water management strategies aimed at mitigating CH must also consider N O emissions and their combined effects. Nitrogen fertilizer indirectly influences CH emissions by affecting other factors. Increased nitrogen application can suppress CH emissions [21], with the greatest reduction occurring when moving from low to medium nitrogen rates, and minimal change from medium to high rates [22]. Urea application results in higher CH emissions than ammonium nitrate or ammonium sulfate [23]. Straw and green manure incorporation significantly increases CH emissions, with emissions rising as incorporation rates increase [24]. Additionally, applying unfermented farmyard manure and manure residues increases CH emissions, whereas fermented biogas residues can reduce emissions [21]. Combined application of chemical and organic fertilizers effectively reduces CH emissions without compromising yield, representing a valuable mitigation strategy.

Extensive measurement and monitoring data reveal distinct regional patterns of CH emissions from Chinese rice paddies, with the highest fluxes in southwestern China (averaging 16.8 mg(CH) · m^{2} · h^{1}), followed by the middle and lower Yangtze River regions, lower emissions in northern and southern China, and the lowest fluxes in northeastern rice cultivation areas [25]. Emission peaks occur during the regreening and tillering stages. To facilitate greenhouse gas emission estimates, this study compiled published literature to establish a comprehensive database [25]. We conducted factorial analyses of CH emissions from different rice cultivation systems (early rice in double-cropping, late rice in double-cropping, typical single-cropping rice, and rice-wheat rotation) under various management practices to identify key influencing factors and their relative importance, and to analyze the integrated global warming potential under different water management regimes. This work provides a scientific basis for estimating CH emissions and developing rational mitigation strategies for rice paddies.

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1. Materials and Methods

1.1 Data Sources

We systematically searched literature databases (CNKI, Wanfang, VIP, ScienceDirect, and SpringerLink) for domestic and international journal articles and graduate theses published before 2015 related to CH_4 emissions from Chinese rice paddies. Search keywords included "CH_4 emission," "methane," "water management," and "fertilizer management."

1.2 Database Construction

Data were entered and hierarchically organized in Excel spreadsheets. The database included: (1) publication information (authors, year, source); (2) experimental site details (location, soil type, texture, pH, soil organic matter, total nitrogen, clay content, crop type, growth period); (3) water and fertilizer management (irrigation status, irrigation method, drainage practices, fertilization method, application rates, nitrogen type and amount); (4) daily CH_4 emission rates; and (5) global warming potential. Nitrogen application rates were standardized to $kg(N) \cdot ha^{-1}$. Daily CH_4 emission units were $kg(CH_4) \cdot ha^{-1} \cdot d^{-1}$, and global warming potential (GWP) units were $kg(CO_2\text{-eq}) \cdot ha^{-1} \cdot d^{-1}$.

GWP represents the relative radiative impact of a given substance compared to CO_2 over a specified time interval, serving as a parameter to evaluate the relative climate change impact of various greenhouse gases. According to IPCC greenhouse gas inventory methodology [26], the GWP of CH_4 over a 100-year timeframe is calculated as:

$$\mathbf{GWP = Cumulative\ Emissions \times 25}$$

1.3 Data Analysis

To ensure data representativeness, literature inclusion criteria required: (1) field experimental data; (2) clear documentation of experimental timing, location, soil properties, experimental design, and field management; (3) scientifically sound gas sampling methods with observations covering at least one complete crop growth period. Database data were stratified into subgroups (Table 1).

Because different rice cultivation systems vary in growth period length, soil properties, and temperature regimes, CH_4 emissions and GWP differ accordingly. Since CH_4 emissions primarily result from organic matter decomposition under flooded conditions, we stratified data by soil organic matter (SOM) content ($\leq 25\ g \cdot kg^{-1}$ and $>25\ g \cdot kg^{-1}$ for fertilizer treatments; $\leq 30\ g \cdot kg^{-1}$ and $>30\ g \cdot kg^{-1}$ for water management treatments). We further categorized paddies into early rice, late rice, and single-cropping rice, then conducted subgroup analyses based on fertilizer type, soil amendments, and water management. Factorial analyses were performed according to CH_4 emission patterns under fertilizer and water treatments, with GWP subjected to comprehensive analysis to identify influencing factors.

Chemical fertilizers included urea and compound fertilizers; organic fertilizers primarily consisted of animal manure mixed with soil or straw; straw incorporation referred to complete or partial return of previous wheat or rice straw; biochar was produced from crop residues through high-temperature pyrolysis under anaerobic conditions. Continuous flooding (CF) maintained flooded conditions throughout the growing season until one week before harvest. Mid-season drainage (FDF) involved flooding after transplanting, draining at late tillering, reflooding, and final drainage 1-2 weeks before harvest. Alternate wetting and drying (FD) followed the same pattern as FDF but with intermittent irrigation after reflooding. Controlled irrigation (CI) maintained uninterrupted alternate wetting and drying or kept fields moist without standing water throughout the growth period.

Outlier data were removed using empirical methods based on literature reports and theoretical analysis, eliminating values exceeding ±100% of established upper and lower limits. SPSS software was then used to identify statistical outliers beyond the 95% confidence interval in box plots. Median values, being more representative of central tendency, were selected to represent each dataset. The final database comprised 336 data points from 66 sites nationwide. Data analysis and visualization were performed using Excel.

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2. Results

2.1 Effects of Fertilizer Management on CH Emissions

2.1.1 Early Rice Paddies China' s early rice cultivation is concentrated in Jiangsu, Zhejiang, Anhui, Hunan, Hubei, and Guangdong/Guangxi provinces. Early rice is typically nursed in late March to early April, transplanted in late April to early May, and harvested in mid-to-late July, with a growth period of 85-100 days. Collected CH emission data primarily covered early rice in double-cropping systems, with nitrogen application rates of 100-300 kg(N) · ha^{1}.

CH emissions were influenced not only by background soil organic matter (SOM) content but also by fertilizer type (Figure 1 [Figure 1: see original paper]). When SOM 25 g · kg^{1}, median daily CH emissions were 1.61 kg(CH) · ha^{1} · d^{1} for chemical nitrogen fertilizer alone, 1.83 kg(CH) · ha^{1} · d^{1} for combined organic manure, and significantly higher at 2.49 kg(CH) · ha^{1} · d^{1} for chemical fertilizer plus straw incorporation. As SOM content increased, CH emissions rose accordingly. When SOM > 25 g · kg^{1}, daily CH emissions from combined organic manure and straw incorporation treatments increased by 0.45 kg(CH) · ha^{1} · d^{1} (24%) and 0.96 kg(CH) · ha^{1} · d^{1} (39%), respectively, compared to SOM 25 g · kg^{1}. In contrast, chemical nitrogen application showed no significant effect on early rice CH emissions across different SOM backgrounds. Limited data for biochar amendments (all with SOM > 25 g · kg^{1}, n=8) showed median daily CH emissions of 1.02 kg(CH) · ha^{1} · d^{1}, substantially lower than other fertilization methods.

2.1.2 Late Rice Paddies Late rice includes both double-cropping late rice and rice-wheat rotation late rice, typically nursed in mid-to-late June, transplanted in mid-to-late July, and harvested in late October to early November, with a growth period of 105-130 days. Late rice receives more intensive management due to its greater contribution to total yield.

Overall CH emissions from late rice paddies were higher than from early rice (Figure 2 [Figure 2: see original paper] and Table 2). For double-cropping late rice, daily CH emissions increased progressively under chemical fertilizer, combined organic manure, and straw incorporation treatments. With SOM 25 g · kg^{1}, median daily emissions were 2.44, 2.98, and 3.80 kg(CH) · ha^{1} · d^{1}, respectively—representing 22% and 56% increases over chemical fertilizer alone for combined organic manure and straw incorporation. With SOM $>$ 25 g · kg^{1}, emissions under each fertilizer treatment were slightly lower, but biochar application significantly reduced double-cropping late rice CH emissions to a median of 1.02 kg(CH) · ha^{1} · d^{1}.

Rice-wheat rotation, typical in the middle and lower Yangtze River region, improves drainage and suppresses methanogen activity by interrupting continuous flooding. Consequently, CH emissions were substantially lower, with median daily fluxes generally below 2 kg(CH) · ha^{1} · d^{1}. At SOM 25 g · kg^{1}, median emissions were 0.55 kg(CH) · ha^{1} · d^{1} (chemical fertilizer) and 0.51 kg(CH) · ha^{1} · d^{1} (biochar), increasing to 0.99 and 1.82 kg(CH) · ha^{1} · d^{1} under combined organic manure and straw incorporation, respectively. At SOM $>$ 25 g · kg^{1}, all fertilizer treatments showed higher emissions, with the ranking: straw incorporation $>$ combined organic manure $>$ chemical nitrogen $>$ biochar, the latter significantly reducing emissions.

2.1.3 Single-Cropping Rice Paddies Single-cropping rice is cultivated primarily in northeastern, northern, and northwestern China, with nursery sowing around Qingming Festival (early April), field transplanting in late April to early May, and harvest in late September to early October (growth period: 120-150 days). Fertilizer type significantly affected CH emissions (Figure 3 [Figure 3: see original paper]). At SOM 25 g · kg^{1}, chemical fertilizer alone yielded median emissions of 0.78 kg(CH) · ha^{1} · d^{1}, while combined organic manure and straw incorporation increased emissions by 97% and 283%, respectively, and biochar reduced emissions by 46%. At SOM $>$ 25 g · kg^{1}, median daily emissions were 1.08 kg(CH) · ha^{1} · d^{1} (chemical fertilizer), 2.70 kg(CH) · ha^{1} · d^{1} (combined organic manure), 6.19 kg(CH) · ha^{1} · d^{1} (straw incorporation), and 0.93 kg(CH) · ha^{1} · d^{1} (biochar), demonstrating more pronounced differences.

Across all paddy types, daily CH emissions varied substantially by fertilizer and amendment type (Table 2). Early rice in double-cropping systems emitted 1.02-3.45 kg(CH) · ha^{1} · d^{1}, late rice in double-cropping and rice-wheat systems emitted 0.52-3.80 and 0.48-1.86 kg(CH) · ha^{1} · d^{1}, respectively, while single-cropping rice emitted 0.78-6.19 kg(CH) · ha^{1} · d^{1}. The overall ranking was: double-cropping late rice $>$ double-cropping early rice $>$ single-cropping rice $>$ rice-wheat rotation late rice, demonstrating that rice-wheat rotation significantly reduces CH emissions.

2.2 Effects of Water Management on CH Global Warming Potential

2.2.1 Early Rice Paddies CH production and emission are closely linked to soil moisture status. During drainage periods, the shift from anaerobic to aerobic conditions significantly promotes nitrification.

Based on water management practices, data were stratified into four subgroups: continuous flooding (CF), flooding-drainage-reflooding-final drainage (FDF), flooding-drainage-alternate wetting and drying-final drainage (FD), and controlled irrigation (CI). Regardless of SOM level (30 or >30 g · kg^{1}), CH emissions followed the pattern: CF > FDF > FD > CI (Figure 4 [Figure 4: see original paper] and Table 3). Soil organic matter background significantly affected emissions. At lower SOM (30 g · kg^{1}), GWP decreased by 25%, 12%, 45%, and 39% for CF, FDF, FD, and CI, respectively, with FD and CI showing significant reductions. Continuous flooding produced the highest emissions, while mid-season drainage and intermittent irrigation substantially reduced CH fluxes. Overall, GWP in early rice paddies decreased systematically from CF to FDF to FD to CI, indicating that controlled irrigation is the most effective mitigation measure.

2.2.2 Late Rice Paddies Late rice paddies in double-cropping systems exhibited higher GWP under all irrigation modes compared to early rice, primarily due to higher air and soil temperatures during the late rice growing season, which intensified carbon and nitrogen transformation processes.

As shown in Figure 5 [Figure 5: see original paper] and Table 3 , CH GWP in double-cropping late rice varied by water management. At SOM 30 g · kg^{1}, CF produced the highest GWP (median: 6,700.00 kg(CO -eq) · ha^{1}), with FDF, FD, and CI reducing emissions by 11%, 49%, and 68%, respectively. At SOM > 30 g · kg^{1}, CF GWP was 7,362.67 kg(CO -eq) · ha^{1}, with FDF, FD, and CI reducing emissions by 26%, 60%, and 56%, respectively. The CI mode showed slightly higher emissions than FD but without significant difference, suggesting minimal SOM influence on late rice CH emissions.

In rice-wheat rotation late rice paddies (Figure 6 [Figure 6: see original paper] and Table 3), GWP was generally lower at SOM 30 g · kg^{1}, decreasing from CF to FDF to FD to CI. However, N O GWP increased sequentially, accounting for 1%, 3%, 13%, and 50% of total GWP, respectively. Controlled irrigation reduced CH emissions but increased N O emissions by creating aerobic conditions favorable for nitrification. Nevertheless, the reduction in CH far outweighed the increase in N O, making controlled irrigation an effective overall mitigation strategy.

At SOM > 30 g · kg^{1}, CH GWP increased significantly, likely due to wheat straw incorporation from the previous season providing abundant substrate for methanogens under anaerobic conditions. Under these conditions, N O GWP proportions were 7%, 25%, and 81% for FDF, FD, and CI, respectively, while CH contributions to total GWP remained dominant at 95%, 94%, 91%, and

42%. The trend remained consistent with SOM 30 g · kg ^{1}, with CH GWP increasing by 47%, 55%, 29%, and 95% across irrigation modes. Controlled irrigation demonstrated the greatest reduction in overall GWP, confirming its effectiveness as a mitigation measure.

2.2.3 Single-Cropping Rice Paddies At SOM 30 g · kg ^{1}, FDF, FD, and CI reduced CH GWP by 281.89, 912.39, and 2,887.89 kg(CO -eq) · ha ^{1}, respectively, compared to CF. The overall GWP in single-cropping rice paddies decreased systematically from CF to FDF to FD to CI (Table 3). Controlled water management proved highly effective, reducing total greenhouse gas emissions by 3–64% compared to continuous flooding, with controlled irrigation showing the best mitigation performance (Figure 7 [Figure 7: see original paper]).

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3. Discussion

3.1 Comparative Analysis of CH Emissions Across Paddy Types

Under chemical fertilizer, combined organic manure, and straw incorporation treatments, late rice CH emissions averaged 0.5 times higher than early rice emissions, likely due to higher temperatures during the late rice growing season that enhanced microbial activity and accelerated organic matter decomposition. In contrast, rice-wheat rotation CH emissions were lower than both early and late rice in double-cropping systems, with reductions of 51%, 47%, and 36% compared to early rice, and 66%, 66%, and 59% compared to late rice under chemical fertilizer, combined organic manure, and straw incorporation, respectively. Note that the single-cropping rice dataset was relatively small, requiring further validation.

Soil organic matter content significantly influenced CH emissions. While late rice emissions showed no significant change with increasing SOM, early rice, rice-wheat rotation, and single-cropping rice emissions increased markedly [27–28]. At higher SOM background levels (>25 g · kg ^{1}), all fertilizer treatments resulted in increased CH emissions compared to lower SOM (25 g · kg ^{1}), with particularly significant increases in single-cropping rice paddies.

3.2 Effects of Fertilizer Management on CH Emissions

Fertilizer application, particularly organic fertilizers, represents a critical factor influencing CH emissions. Different fertilizer types affect CH emissions differently across paddy types. This study demonstrates that combined organic manure and straw incorporation both increased daily CH emissions, with the ranking: straw incorporation [1.83–3.45 kg(CH) · ha ^{1} · d ^{1}] > combined organic manure [0.99–2.98 kg(CH) · ha ^{1} · d ^{1}] > chemical nitrogen [0.55–2.44 kg(CH) · ha ^{1} · d ^{1}].

Straw incorporation provides substantial organic carbon (primarily crude fiber, cellulose, hemicellulose, and lignin) to the soil, supplying the material basis for CH production and promoting emission [27-28]. Organic manure also contains readily utilizable carbon (such as organic acids and amino sugars) and humic acids that activate soil microorganisms and enhance methanogen activity, thereby stimulating CH emission [29-30]. The organic manure in this study (primarily pig and cattle manure) contained highly active, easily degradable components that promoted soil organic carbon mineralization and increased CH production under anaerobic conditions.

Biochar application significantly reduced CH emissions compared to organic manure and straw incorporation. However, its mitigation effect relative to chemical fertilizer alone was evident only in double-cropping rice, not in single-cropping rice. This may be because double-cropping paddies remain flooded longer, maintaining lower redox potentials (Eh) where biochar’ s functional groups (-OH, -CH -, C=C, ester C=O) and ash components (K, Na, Ca, Mg) can ameliorate strongly reducing conditions and inhibit methanogenesis [31-32]. Single-cropping paddies have shorter flooding periods and relatively weaker reducing conditions, limiting biochar’ s effectiveness. Further research is needed to validate these findings due to limited available literature.

3.3 Effects of Water Management on CH Global Warming Potential

Water management controls both aerobic/anaerobic soil conditions and directly influences soil carbon and nitrogen cycling, affecting the trade-off between CH and N O emissions and their combined GWP. Analysis revealed that CH GWP followed the pattern: CF > FDF > FD > CI, with CI in late rice showing slightly higher median GWP than FD but maintaining an overall decreasing trend. Total GWP exhibited the same ranking: CF > FDF > FD > CI. CH contributed over 90% (range: 50-99%) of total greenhouse gas emissions, remaining the dominant contributor.

Mid-season drainage (FDF), typically implemented for 1-2 weeks during late tillering in well-drained areas, creates aerobic conditions that promote nitrification and N O production from unabsorbed nitrogen. Although N O has a higher GWP than CH , the limited duration of drainage results in relatively small N O contributions to total GWP (2-58%) [16-17,27]. Therefore, mid-season drainage remains a practical and effective mitigation measure. However, controlled irrigation requires substantial labor and resources, limiting its widespread adoption. Consequently, FDF and FD remain common water management practices, with mid-season drainage representing a simple yet effective mitigation strategy for current conditions in China’ s major rice-producing regions.

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Note: Figure translations are in progress. See original paper for figures.