Methane Production, Emission and Possible Control Measures in the Rice Agriculture

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ABSTRACT

In the rice field methane is produced in the soil layer with depths of 2–25 cm. The vertical profile of methane production rate in the paddy soil during the water covering period differs from that in the paddy soil in dry phase. Only a small part, about 30%, of the produced methane is emitted to the atmosphere through rice plant, air bubbles, and molecular diffusion. Therefore, the methane emission rate from the rice field depends not only on the methane production rate in the soil, but also on the transport efficiency of the rice plant, air bubble formation that in turn depends on the production rate, and molecular diffusion.

Field measurements show that methane emission rates from a particular rice field have very large diurnal, seasonal and interannual variations, which are related to soil characteristics, water regime, farming procedure, local climate, and rice growing activities. The relationship between the methane emission rate and the above mentioned factors is very complicated. The emission rates from different rice fields differ greatly not only in the absolute value, but also in the temporal variation patterns.

Methane emission rate from the rice field may be significantly reduced by scientific management of fertilizer and irrigation. While the use of SO_4^{2-} containing fertilizer and fermented organic fertilizer may reduce the methane emission significantly, the most promising measure for reducing methane emission from rice field is the frequent drainage irrigation procedure.

Key words: Methane, Production, Emission

I. INTRODUCTION

Methane (CH_4) is one of the most important trace gases in the atmosphere. Like CO_2, CH_4 is a very important radiatively active gas that governs the Earth's climate. The presence of 1.7 ppm CH_4 in the atmosphere causes the global average surface temperature to be about 0.4 K higher than it would be with zero CH_4. The enhancement of greenhouse effect for the increase of atmospheric CH_4 from 0.7 ppm to 1.7 ppm is about half of that due to an increase of atmospheric CO_2 from 275 ppm to 345 ppm. Unlike CO_2, CH_4 is a chemically active gas. An increase of atmospheric CH_4 will also change the chemistry of the atmosphere, and hence exert indirect effects on the Earth's climate.

Despite the importance of atmospheric CH_4, the causes responsible for its current increase are not yet well understood. While the concern about the enhancement of greenhouse effect due to the increase of atmospheric CO_2 has stimulated numerous research programs in atmospheric, oceanic and biospheric sciences since early 1950s, little was known about the increase of atmospheric CH_4 until early 1980s.

The present globally averaged concentration of atmospheric CH_4 is 1.75 ppm, and it is increasing with a rate of 0.9% per year. The increase is most likely to be caused by the increases of CH_4 sources, while a reduction of CH_4 sink strength can not be excluded. Cattle, fossil fuel mining, and flooded rice fields are most important anthropogenic sources that have dramatic increases since the industrial revolution, especially after the World War II. This may, at least partly, explain the increase of atmospheric CH_4 from about 0.7 ppm to 1.75 ppm in the last 200 years.

The harvested area of flooded rice fields of the world has increased from $80\times 10^{10}m^2$ to about 145×10^{10} m^2 in the last 4 decades and is likely to be continuously increased by the improvement of irrigation system in major rice growing countries. Although the area and flooded time periods of the global rice fields are well documented, the estimate of global total emission of CH_4 from rice fields remains most uncertain. Recent in–situ measurements show that CH_4 emission rates from rice fields are of very large temporal and spatial variations.

In this paper we report the measurements of CH_4 production in the rice paddy soil and CH_4 emission rates over different locations in China and the experiments for reducing CH_4emission from rice fields.

II. CH_4 PRODUCTION RATE IN RICE PADDY SOIL

CH_4 production rates in different rice paddy soils were measured over the rice fields in Taoyuan, Hunan Province, China. Detailed description of experiment method has reported elsewhere (Shangguan Xingjian and Wang Mingxing et al., 1993).

Fig.1. a, b is the vertical profile of the measured average CH_4 production rates in the paddy soil in Hunan, China, during the early rice period. As shown in Fig.1, CH_4 is mainly produced in the cultivated soil layer with a depth range of about 2–20 cm in Hunan. The soil layer with a depth (from the water–soil interface downwards) range of 0–2 cm is the oxic area of the cultivated layer, and hence little CH_4 is produced here. At the bottom of the taken soil corer (>25 cm), which is already the hard soil below the cultivated layer, production rate is close to zero. All the above features were also found in other places (e.g., Italy). But very interestingly, the vertical distributions of CH_4 production rates observed in Hunan vary with different treatments of water cover. As shown in Fig.1a, in the field with regular water cover, the CH_4 production rate reaches maximum in the upper layer (3–7 cm) of the cultivated soil and decreases with increasing depth. But in fields with no water cover, its vertical profile changes, with its largest value occurring at the soil layer with depths of about 7–15 cm. This result is also observed in the late rice season in Hunan (data not presented). We believe that this may be due to the unique agriculture practice in Hunan. Before transplanting, green manure, rice straw and so on are surface supplied to the rice fields, not mixed well in the different soil depths, causing the higher nutrition for microorganisms in the upper soil layer in the water–covered field. During the experiment, we did often see rice straw in the upper soil corer while taking subsamples. When paddy field is in the open air for some time for some reason (e.g. water management), the penetration of air to the surface soil may force anaerobic microorganism and bacteria to move to the deep soil layer. Therefore higher methane production rate is found in the deeper soil. For instance, in the moisture treatment field, highest methane production rate was found 7 cm deep in the paddy soil with its average value 234.6 ng CH_4 / g(d.w.) • hr on August 4. Because of both the very high temperature in this August and the water shortage stage, soil moisture was lowering down quite a lot on August 17, highest methane production rate was found at the depth of 15 cm with its average 28.196 ng CH_4 / g(d.w.) • hr, nearly no methane was produced in the sharrow soil depth. We even find the vertical distance that methanogenesis "moves" downward also depends on how long the paddy soil is open to the air. That is to say, longer the field is kept no water, not only deeper is methane mainly produced in the soil but also less is formed. The deep methane production

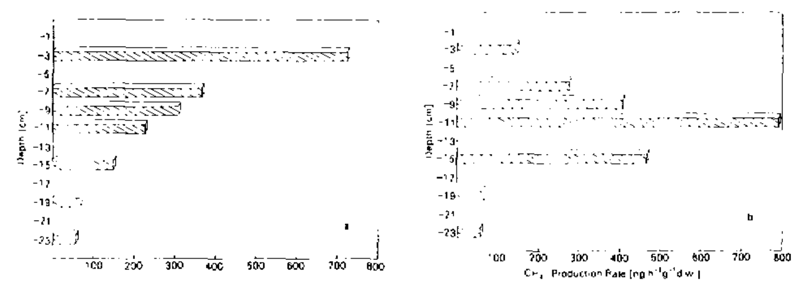

Fig.1. a,b Vertical profile of CH_4 production in a rice paddy in Taoyuan, Hunan Province during the early rice (a. May, b. June and July, 1992).

area in the soil will also lower down the transport efficiency of produced methane to the atmosphere. That is why we observed very low methane emission in this field in the water shortage period.

Preliminary analysis of the production and emission rate data in May, 1992 shows that production rates in paddy soils treated with different fertilizers can explain quite well the emission rates. For example, in the first month after transplanting, the CH_4 emission rates from rice fields treated by normal, organic, chemical, and fermented (from biogas pits) fertilizers are 22.81, 29.28, 13.93 and 18.55 mg $CH_4/m^2 \cdot hr$ respectively, while the production rates are 308.45, 274.31, 143.03 and 156.94 ng $CH_4/g(d.w.) \cdot hr$ respectively. Therefore we consider that the influence of fertilizer on methane emission from rice paddies is mainly by affecting methane production in paddy soil. The chemical fertilizer (urea and KCl) is most likely to inhibit CH_4 productions in the soil.

The ratio of CH_4 emission rate to its production rate at a particular time in different fields has not been found yet. There are two reasons that make it difficult for us to know the clear relationship between production and emission. We still do not know (1) how long will it take for the CH_4 produced in the soil to reach the atmosphere, (2) how different the emission condition is in different fields with different fertilizer and water treatment. For example, we found in the beginning of the both early and late rice growing season that there are a lot of green duckweeds floating on the water surface in the fields treated by normal, chemical, and fermented fertilizer, but not in organic manure field. We find before that about 30% of produced methane in the soil is emitted to the atmosphere in the whole rice growing season (Shangguan Xingjian et al., 1993). But we notice that this ratio is different in the fields with different fertilizer and water management. For example, in the early rice period higher methane production rates and lower emission are found in the deep water treatment field. Besides this, the percentage of CH_4 emission rate to its production even appears higher in the beginning of the growing season, showing more clearly in the late rice period (date not presented). The shallow main CH_4 producing area and efficient CH_4 ebullition emission in the beginning of rice growing season can explain this high ratio. This finding is very similar with what was found in Italy (Schütz et al., 1989b), the ratio of CH_4 emission rate to production rate decreases with time in the rice growing season, which implies the great importance of efficiency of transport passage—way and CH_4 reoxidation.

CH_4 production rates were measured two times a day, one in the morning and the other in the afternoon. In order to know its diurnal variation, four times a day with two at night were sometimes measured. But clear relationship between CH_4 production rates and the time of day is not found. As we all know, highest CH_4 emission rate during a day normally appears in the afternoon in Hunan. The diurnal variation of CH_4 production rates in the soil does not match well with that of CH_4 emission rates. This implies that CH_4 emission rate from rice paddies depends not only on its production in the soil but also on the efficiency of its transport passage–way to the atmosphere, as discussed in more detail below.

III. CH_4 EMISSION RATE FROM RICE FIELDS

Chamber technique has been used to measure CH_4 emission rates from different rice fields in China. Detailed description of the equipment and field experiment have been published elsewhere [Schütz et al., 1989a; Dai et al., 1991; Wang et al., 1990]. The results show that the CH_4 emission rates from a particular rice field have very large diurnal, seasonal and interannual variations, and the CH_4 emission rates from different rice fields differ greatly not only in the absolute value but also in the patterns of the diurnal and seasonal variations.

As shown in Fig.2, three different types of diurnal variations have been found in the rice fields in Hunan and Hangzhou, representing two of the four major rice growing regions in China. For the early rice in Hangzhou, two–peak diurnal variation pattern was generally found (Fig.2a). The most pronounced peaks were generally observed in early afternoon, 12:00–15:00, with the maximum to minimum ratios ranging from 1.3–12.0. The second peak was often found at 0:00–3:00 with the maximum to minimum ratios ranging from 1.2–10.0. For the late rice in Hangzhou, the highest peaks were almost always found at midnight, while the lowest value occurred during the day with similar maximum to minimum ratios (Fig.2b). For both the early rice and late rice in Hunan, single peak diurnal variation pattern was generally found with the peak occurring at midday. Only occasionally were found two–peak diurnal variation pattern in Hunan (Fig.2c).

These complex diurnal variation patterns are related to the complex combinations of many factors that govern the CH_4 emission rates from rice fields. The CH_4 emission rates from rice fields depend on the CH_4 production rates in the paddy soil, reoxidation *en route*, as well as the transport efficiency of the transport routes. As discussed above, the CH_4 production rates in the soil have a large and complex diurnal variation, which is determined by the diurnal variations of soil temperature, methanogenesis activities and other soil parameters. The methane produced in the soil emits to the atmosphere through three routes, namely rice plant, air bubbles and molecular diffusion, which all have complex diurnal variations that depend on the rice growing activities, air and soil temperatures and soil physical properties. Experiments show that on the average only about 30% of the produced CH_4 is

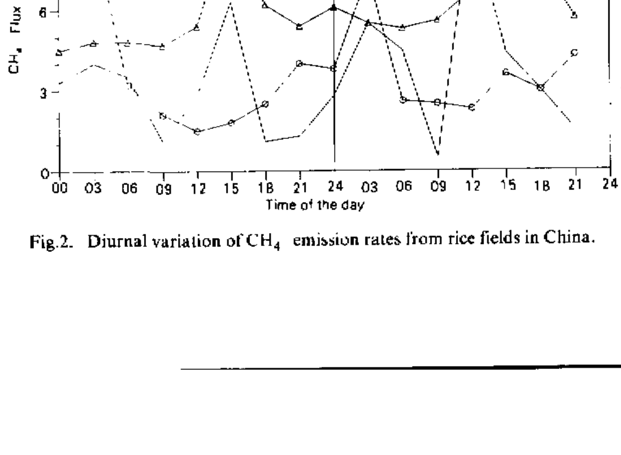

Fig.2. Diurnal variation of CH_4 emission rates from rice fields in China.

emitted to the atmosphere. Thus the diurnal variation pattern of CH_4 emission rates is largely determined by the diurnal variation pattern of transport efficiency. Of the three transport routes, rice plant is the most important one. Our experiments show that the transport through the rice plant accounts for more than 95% of the total CH_4 emitted. Thus the diurnal variations of rice plant growing activities may be most responsible for forming the complex variation patterns of the emission rates. Different rice species may have different patterns of growing activities in response to the changes of living environment. The afternoon peak may be due to the higher production rate in the soil and higher transport efficiency through air bubbles and molecular diffusion under higher soil temperature in the afternoon. The midnight peak is more difficult to explain. One possible explanation is the lower transport efficiency through the rice plant at midday. Some of the rice species tend to have a rest under the condition of very strong sunlight in the early afternoon in summer. The rice plant may close its air transport route to prevent moisture loss at midday, which may simultaneously block the route of CH_4 from the soil to the atmosphere and that of O_2 from the atmosphere to the soil surrounding the rice root. Shortage of O_2 in the surroundings of the rice root may greatly reduce the reoxidation of produced CH_4 in the soil. Thus, the produced CH_4 may be accumulated in the soil or form more gas bubbles at midday. The emission of accumulated CH_4 through the rice plant after sunset when rice plant reopens its air transport route may be responsible for the midnight peak, while the emission through air bubbles may be responsible for the peak in late afternoon.

In addition to the diurnal variation, large seasonal variations were also observed. For both the early and late rice in Hangzhou, three apparent periods of high emission were generally found. One occurs a week after the transplanting, one occurs shortly before flowering, and the third shortly after flowering (Wang et al., 1990). During the whole growing season there are also short–term fluctuations (days) in addition to the longer–term period (weeks) of high and low emission. The short–term fluctuations may be closely related to the changes of local weather system, while the longer–term variations are due to the changes in the availability of organic substrates for the methanogenesis in the soil. The first peak is apparently due to the organic substrates left in the fields before flooding, and the second and third ones are due to the root exudates or root litter and dead roots. However, no significant longer–term peak was found in the rice fields in Hunan (Fig.3). Except the short–term fluctuations, the emission rates increase with the growing of rice plant and reaches the maximum emission about a week

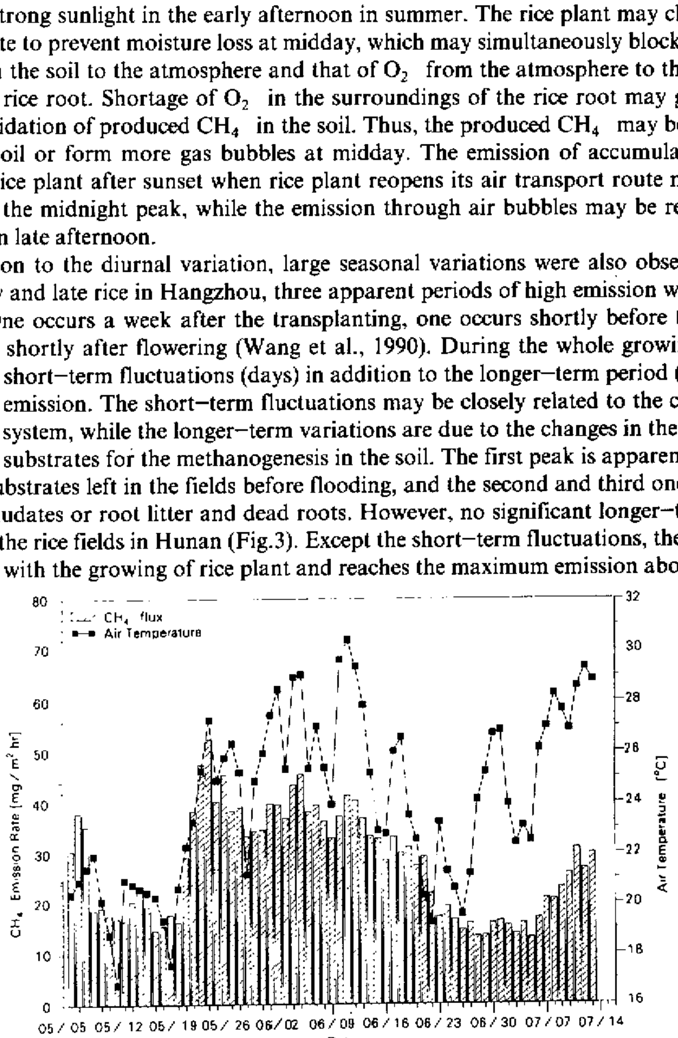

Fig.3. Seasonal variation of CH_4 emission rate and air temperature in Hunan Province during the early rice growing season (normal fertilized field).

after transplanting. The emission rates then remain high until a sharp decrease when the field was drained for harvesting. This kind of seasonal variations of CH_4 emission rates from rice field were also found in the rice fields in Sichuan (Wang et al., 1992). This may indicate a more stable organic content in the paddy soil in these two regions.

Large interannual differences in the seasonal average emission rates were found in Hangzhou and Sichuan (Wang et al., 1992). Emission rates in 1988 were much lower than those in 1987 and 1989 in Hangzhou. In Sichuan emission rates showed lowest in 1989 for the period of 1988–1991. These interannual differences may be partly accounted for by the changes of local climate. For instance, it experienced a cold summer in Sichuan in 1989, which would reduce the CH_4 emission rates from rice fields in summer when the emission rate should be high in normal years. However, this process can not explain the interannual differences found in Hangzhou. More studies need to be done.

IV. CONTROL MEASURES FOR METHANE EMISSION FROM RICE PADDIES

Control of CH_4 flux from rice fields can be reached by fertilizer application and water management with the rice production not being lowered down. Influence of different types of fertilizers on methane emission has been studied in Hangzhou (1987,1988,1989), Zhejiang Province and Taoyuan (1991, 1992), Hunan Province of China. Since May 1992, different water management, including constant moisture (no water cover), frequent drainage (3–day–interval), regular water cover (3 cm in depth) and deep water cover (10 cm in depth) have been carried out in Taoyuan, Hunan Province.

Although the fertilizer effect is not very clear in Hangzhou because of high nutrition of this particular paddy soil, the use of SO_4^{2-} containing fertilizer reduces the CH_4 emission fluxes. For instance, the flux (26.19 ± 3.16 mg $CH_4/m^2 \cdot hr$) from fertilized field received SO_4^{2-} is only about half of that (47.02 ± 7.80 mg $CH_4/m^2 \cdot hr$) from unfertilized field for early rice 1989. The existence of SO_4^{2-} may cause the competition between sulfate reducers and methanogenic bacteria for substrates (H_2, acetate), thus reducing CH_4 production in the paddy soil.

In Hunan, the local farming practice of fertilization is the combination of organic and chemical fertilizer with a ratio of 1:1. We have been studying the effects of four different types

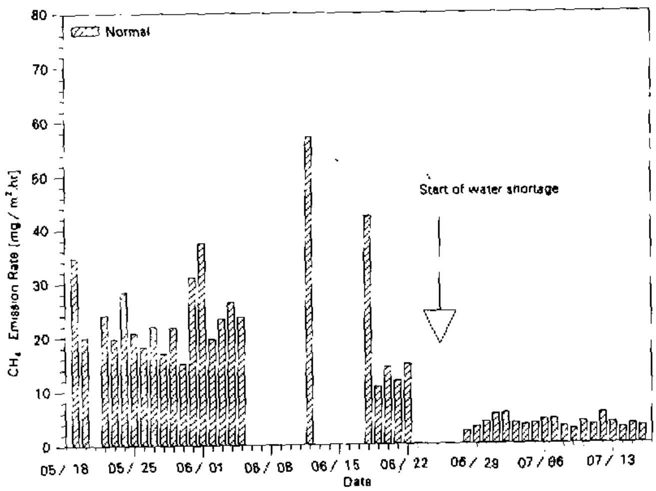

Fig.4. Seasonal variation of CH_4 emission in Hunan Province during the early rice growing season of 1991.

of fertilizations on methane emission, which are regular local practice of fertilization, full organic (green manure, rice straw and pig remains), full chemical (mainly urea and KCl), and fermented fertilizer (residue from biogas pits). Methane emission rates and other information are listed in Table 1. As shown in Table 1, lowest CH_4 flux is found in the field treated by full chemical fertilizer, which is followed by those treated with fermented, normal and organic in 1991. As discussed before, application of only chemical fertilizer inhibits methane formation in paddy soil, which reduces its emission rate. For the late rice 1991, significant reduction of CH_4 emission rates is found in the field treated by chemical and fermented fields, while the rice production in the four fields appears similar. Therefore, one possible way to control CH_4 emission is that certain ratio of chemical fertilizer is applied scientifically together with other organic fertilizer.

Scientific management of irrigation procedure of rice paddy fields appears to be more promising as it will maintain the soil nutrition balance. In 1991, we found by chance that CH_4 emission was reduced significantly because of water shortage during both early (Fig.4) and late rice growing season. Table 1 shows the results of an investigation of different kinds of water management described above for early rice 1992. The lowest CH_4 flux is found in the fields treated by constant moisture and deep water cover (about 10 cm), while the highest rice

Table 1. Methane Emission Rates and Rice Production from Rice Fields Treated with Different Fertilizers

		CH_4 Emission Rate ($mg\,CH_4/m^2 \cdot hr$)	Rice Production ($Kg/100\,m^2$)
1991 (Fertilizer Treatment)			
Early Rice	Normal	26.47	43.70
	Organic	38.64	39.20
	Chemical	6.51	38.20
	Fermented	15.91	34.10
Late Rice	Normal	50.12	39.30
	Organic	56.21	39.50
	Chemical	14.34	39.90
	Fermented	22.54	39.30
1992 (Water Management)*			
Early Rice			
	Normal (3 cm)	25.99	35.00
	Constant Moisture	14.39	34.10
	Frequent Drainage	22.68	39.40
	Deep (10 cm)	14.71	44.70

* Absolute values need further calibration.

production is found in the deep water cover field. By this we can clearly see that reasonably deep water cover of rice fields may reduce the CH_4 emission significantly while keeping the rice production. As most rice paddies in major rice growing countries are with a very shallow water cover, the improvement of irrigation system in those countries to raise the depth of water cover to reasonable level may be one of the most promising measures to reduce CH_4 emission from the rice fields while keeping high rice production. The problem is that such a high water level of rice fields we carried out the experiment (10 cm) is not easy to maintain in most of the rice growing regions. Another point shown in Table 1 is that if flooded water cover of paddy fields is not kept high enough, the methane emission from rice fields will significantly increase.

Very interestingly, we again found during water shortage time that CH_4 emission rate was close to zero at the end of early rice (Fig.5) and some period of late rice, August 1 to August 20, 1992 (data not shown), over the constant moisture field. During that time period, the field was dried and soil moisture was lowering down a lot. This finding makes us believe that the controlling of CH_4 emission rate can be done by lowering the soil moisture. In order to keep rice production as high as possible, reasonably deep water cover is necessary periodically to satisfy plant growing. That is to say, frequent drainage of a better time schedule may be a good way to reach our goal. As shown in Table 1, methane emission from the field treated by frequent drainage would not be lowered down too much, while the rice production is also quite high. This means that the three–day–interval frequent drainage is not efficient enough to control methane, a better time schedule of drainage is worth further investigating.

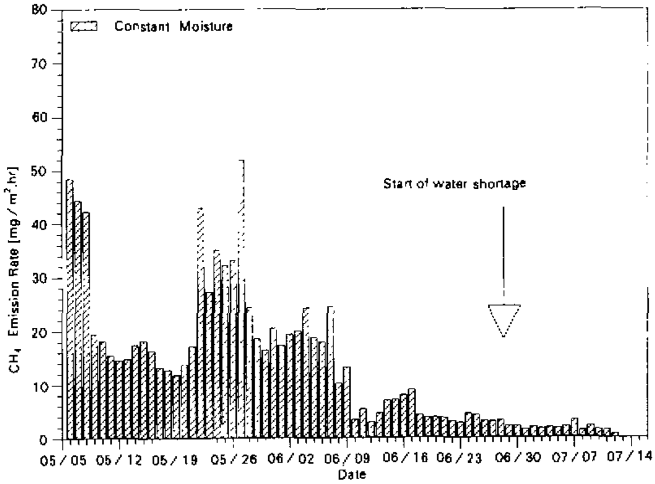

Fig.5. Seasonal variation of CH_4 emission in Hunan Province during the early rice growing season of 1992.

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