Seasonal Production and Emission of Methane from Rice Fields

Final Report: DE-FG03-97ER62401

M. A. K. Khalil
Department of Physics, Portland State University, P.O.Box 751, Portland, Oregon 97207, USA.
khalilm@pdx.edu

R. A. Rasmussen
Department of Environmental Science & Engineering, Oregon Graduate Institute, 20000 N.W. Walker Rd., Beaverton, Oregon 97006, USA. rrasmus@ese.ogi.edu

Lixin Ren
M-X. Wang
Institute of Atmospheric Physics, Academia Sinica, Beijing 100029, P.R. CHINA

M. J. Shearer
Environmental Science and Resources Program, Portland State University, P.O. Box 751, Portland, Oregon 97207, USA. mshearer@pdx.edu

R. W. Dalluge
Department of Environmental Science & Engineering, Oregon Graduate Institute, P.O. Box 91000, Portland, Oregon 97291, USA. dalluge@ese.ogi.edu

Chang-Lin Duan
Institute of Mountain Disasters and Environment, P.O. Box 417, Chengdu, Sichuan, 610041, P.R. CHINA

Submitted to: Dr. Michael Riches
U. S. Department of Energy
19901 Germantown Road
Germantown, MD 20874-1290

I. Introduction

Methane (CH_4) is a greenhouse gas regarded second only to carbon dioxide in its ability to cause global warming. Methane is important because of its relatively fast increase, and also because it is, per molecule, some 60 times more effective than carbon dioxide in causing global warming (IPCC, 2001). The largest present anthropogenic sources of methane are rice fields, cattle and biomass burning (see Khalil and Shearer, 2000). The global emissions from these sources are still not well known. In the middle 1980s there were few available data on methane emissions from rice fields leading to estimates of a global source between 100-280 Tg/yr (reviewed in Khalil and Rasmussen, 1990). Extensive worldwide research during the last decade has shown that the global emissions from rice fields are more likely to be in the range of 30-80Tg/yr. While this work has led to a substantial reduction in the estimated emissions, the uncertainty is still quite large, and seriously affects our ability to include methane in integrated assessments for future climate change and environmental management.

China dominated estimates of methane emissions from rice fields because it was, and is, the largest producer of rice, and major increases in rice production had taken place in the country over the last several decades. The major aim of an earlier project (DE-FG06-85ER60313) was to obtain direct measurements of methane flux from rice fields under normal agricultural practices in a region that produces a large fraction of the world=s rice. Data from seven years of measurements of methane fluxes were obtained at a site near TuZu, Sichuan province, China, with additional measurements at locations in Indonesia and near Guangzhou and Beijing in China. This early work was summarized in a series of papers (Khalil et al., 1998a, 1998b, 1998c, 1998d, 1998e; and Khalil and Rasmussen, 1998). The main site at TuZu had large seasonal methane emissions relative to other locations globally. In the final year of the original project, measurements were taken at a site near JinSa, about 100 km north of TuZu, with different soil characteristics and agricultural practices. The resulting emissions were very different. The goals of the project described here (DE-FG03-97ER62401) were to identify which factors led to the difference in methane flux between two relatively close locations, and to use this information to make better regional and global estimates of methane emissions from rice fields.

Some major factors that significantly affect methane emissions have emerged from the recent research. These are the use of organic fertilizers, water management and certain soil characteristics, all of which affect the anaerobic bacteria which produce methane as a by-product of their lifecycle. Use of organic fertilizers and incorporation of rice straw into the soil leads to high emissions compared to fields fertilized with chemical fertilizers and nutrient amendments

(Schütz et al. 1989; Lindau and Bollich, 1993; Chen et al., 1993; Cicerone et al., 1992; Denier van der Gon and Neue, 1995). If standing water is maintained in the fields throughout the growing season, higher methane emissions occur than if the field is intermittently flooded (Sass et al., 1992; Husin et al., 1995; Yagi et al., 1996). Intermittent flooding can occur by controlled irrigation, or the prevailing climatology of rainfall. The effect of soil conditions on CH_4 emissions is less certain, but appears to influence emissions probably through drainage and chemical characteristics (Sass et al. 1994; Neue et al., 1994; Wang et al., 1993; Bouwman, 1991). Our research at JinSa focused on the use of organic vs. chemical fertilizers, and water management as the principal differences between rice agriculture management at JinSa and TuZu.

Although the focus of the project has always remained on methane emissions from rice fields, a number of other, broader objectives were also included in the research. First, the experiments were designed to determine the factors that control methane emissions from rice fields. This is important because it allows us to extrapolate the field data to larger scales including the provinces, all of China, or the whole world. Secondly, we wanted to determine the relation between the production of methane in the soil and emission to the atmosphere through the rice plant. Third, we wanted to evaluate the effect of our findings on the understanding of the methane cycle and generally to maintain a current understanding of atmospheric methane. This allowed us to continuously modify, improve and extend the experiments in China. Finally, the experiment was designed to fit into the analysis of the global sources and sinks of methane to account for the observed atmospheric trends and distributions. To this end we continued measurements at the continental background site at Minqin in the Gansu Province of China. This was one of the first sites of its kind, and has produced a unique record of atmospheric composition.

This report summarizes the work in each of the following areas: The design of the experiment, the main results on methane emissions from rice fields, delineating the factors controlling emissions, production of methane in the soil, survey of water management practices in sample of counties in Sichuan province, and results of ambient measurements including data from the background continental site.

II. Experimental Design

The main experiment in the field consists of placing a chamber on the rice plants and taking air samples at regular intervals. Since the chamber is air tight, the measured buildup of methane concentrations is a direct indicator of the flux. Each measurement is used to calculate the number of grams of methane in the chamber. The change in the number of grams of methane in the chamber over the time of the measurement is divided by the area covered by the chamber to arrive at the flux in mg/m^2/hr as a standard unit of flux. Flux in these units is generally between 0 and 100. The air samples from inside the chamber are analyzed using a gas chromatograph equipped with a flame ionization detector and optimized for measuring methane. The use of a high precision GC/FID at the field site made it possible for us to obtain thousands of flux measurements during the course of the experiment. The technique is the same as that used in the earlier experiments in TuZu, and is documented in Khalil et al. (1998a).

Each flux measurement required 4 samples taken about 5 minutes apart. This timing allows us to cover the plants for a short time so as not to disturb the growth or the flux. The frequency of measurements was designed to capture the diurnal variability of the emissions. In the 1997 season, nighttime measurements were taken to see if the extrapolation of the daytime cycle to nighttime was accurate. Plots without plants were also measured in that season, to compare methane emissions through the plants to emissions from bubbling. The number of fields sampled in the 1997 and 1998 seasons was designed to reveal the variability of the emissions across several adjacent fields. Metadata including water level, Eh, pH, air and soil temperature, wind speed and weather conditions were taken with every flux measurement. Plant height was measured weekly. Amounts and types of fertilizer and other soil amendments were recorded when added to the fields.

The site chosen for the intensive field experiment was near JinSa, about 15 km west of Chengdu. Experiments over the entire growing seasons were conducted between 1997-1999. Throughout this period the same fields and plots were used, though not all fields in all years. Six fields were used in 1997, five fields in 1998 (the same as the preliminary work at this site in 1996), and three fields (1, 3, and 5) in 1999. Each field had three sample plots. Results of these experiments will be discussed in later sections.

In 1999, an extensive survey of water use in 60 sample fields in 20 counties was also carried out. Water level in the fields was measured morning and evening throughout the growing season, and local weather information. Soil information was collected where available. In the 2000 growing season, agriculture agents and farmers in 20 counties and municipalities of Sichuan province were surveyed on changes in the use of organic amendments, fertilizer use, and irrigation in the past five years. They were also asked their opinion for the reasons for the changes.

Methane production in the soil was estimated in the 1998 and 1999 growing seasons by taking weekly soil core samples. Samples were taken by pushing a plastic cylinder into the soil until it reached the compressed puddled soil layer about 20 cm deep. The sample cylinder was withdrawn and capped. Each sample cylinder was approximately 25 cm long and 7.5 cm in diameter. Holes were drilled in the side of the cylinder every 5 cm, and sample cores were removed using an open syringe. Each soil sample was placed on a piece of filter in a 250 ml sample jar, and moistened with water from the rice field. The sample jar was sealed and flushed with Nitrogen gas. Samples were removed via syringe every half hour for two to two and one half hours, and measured for methane concentration using the same GC/FID machine as the field emission experiment.

III. Methane Emissions from Rice Fields

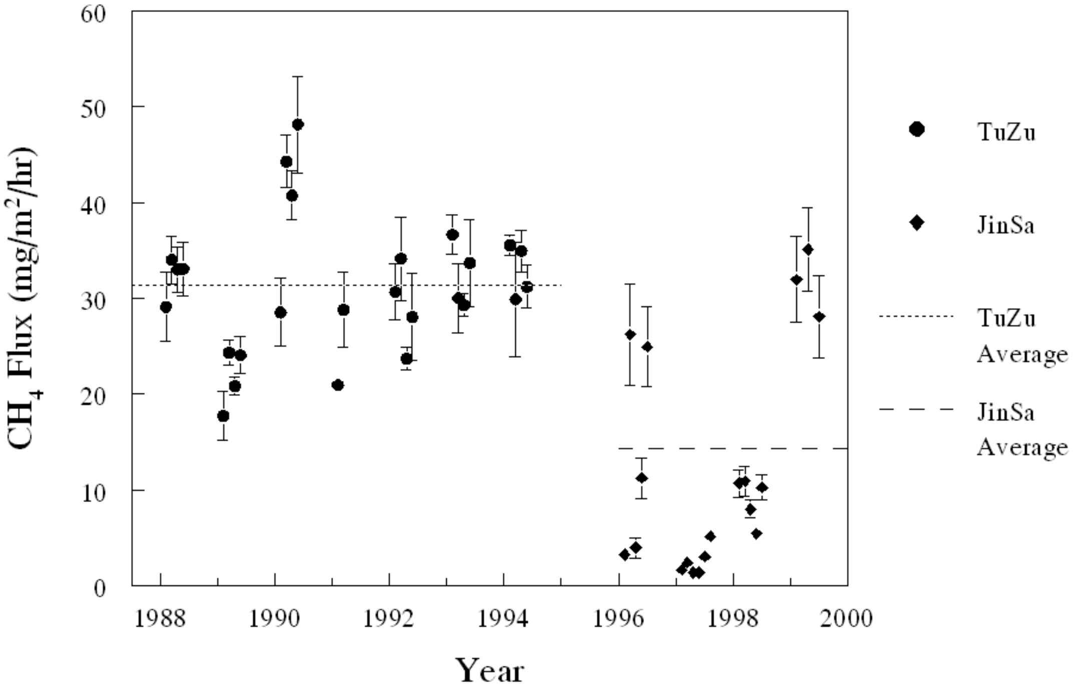

Figure 1. The seasonal average flux of each field for all growing seasons of both the present work in JinSa compared to earlier experiments in TuZu.

A different pattern of methane emissions was observed at JinSa from our previous work in China, because the key environmental conditions are not the same as at TuZu. First, the soil type is different (sandy loam at TuZu, silty loam at JinSa), although it is not clear how much of a role this plays in the difference of emission rates observed between Jin Sa and Tu Zu. Perhaps the most important differences are in the agricultural practices. At JinSa there is little use of organic fertilizers, and nitrogen-based chemical fertilizers are prevalent. Farms in the area around TuZu area were mixed agriculture with pigs and other livestock as well as the grain crops. The manure was disposed of in the rice fields. At JinSa, the only crops were spring wheat followed by rice. The wheat stubble was burned before the fields were plowed and flooded for rice in the 1996-1998 growing seasons. Moreover, intermittent flooding is common in JinSa, compared to continually flooded fields at TuZu. The data from 1997 show the effect most dramatically when the water levels were low throughout the growing season due to drought. In 1998, the opposite weather occurred, with rain and flooding throughout late July and August. In 1999, field burning of wheat stubble was banned to control air pollution near Chengdu, and again continued rainfall kept the fields flooded (foiling the intended experimental design). When both water and organic fertilizers are present, emission rates of Jin Sa are comparable to those at TuZu. Figure 1 shows the variable annual emissions at JinSa compared to the earlier data from TuZu.

Figure 2 shows the full season data from JinSa. In 1997 and 1998, the highest fluxes were in the middle to late growing season, after the plants were mature, and the principal carbon source was root exudates and decaying plants (70 to 80 days after transplanting). In 1999, the first peak in emissions is very shortly after transplanting (10 to 40 days), suggesting that the carbon source is the wheat stubble from the preceding crop.

The agricultural practices at JinSa are a consequence of irrigation control of available water and availability of chemical vs.organic fertilizer. The data show the possibility of reducing methane emissions from rice fields by modifying the agricultural practices to include intermittent flooding and reduced use of organic fertilizers. These modifications call for adopting acceptable and clearly successful agricultural practices, instead of making changes that have not been tried before. However, as the data from 1999 indicate, methane emissions can immediately return to a high level with both the addition of organic matter and flooded fields.

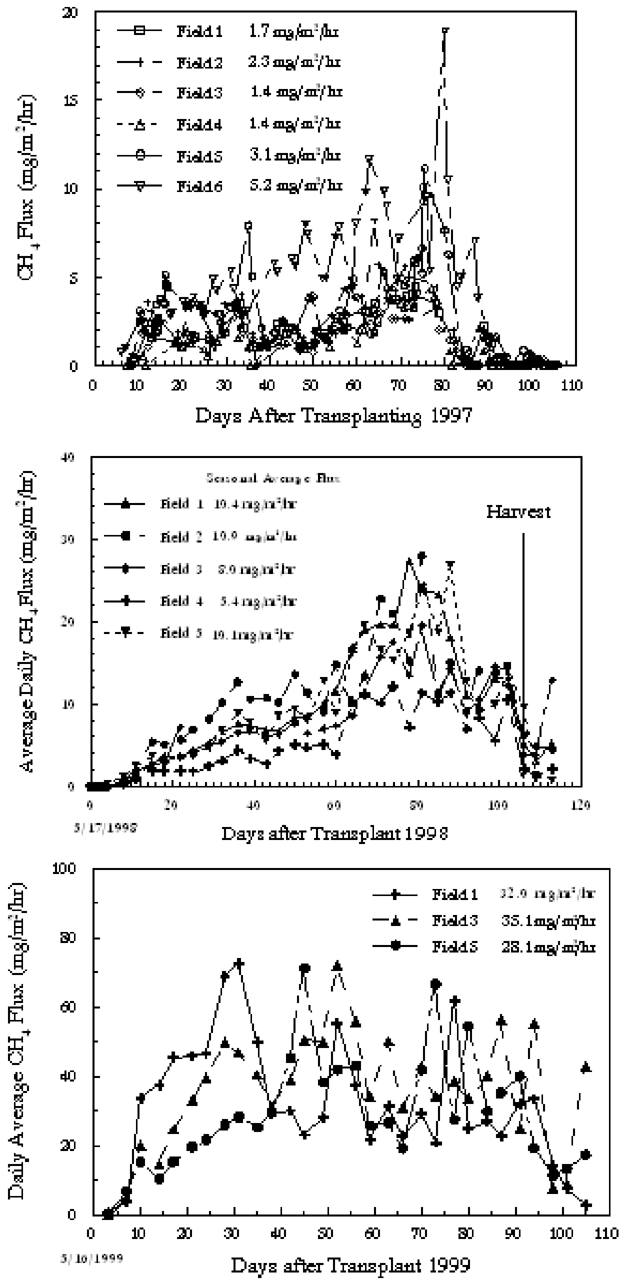

Figure 2. Daily average methane fluxes for each field for three growing seasons at JinSa, Sichuan Province. Calculated seasonal average fluxes are from transplant to harvest. In 1998, methane measurements continued for another week after harvest. Note: flux scales differ by year.

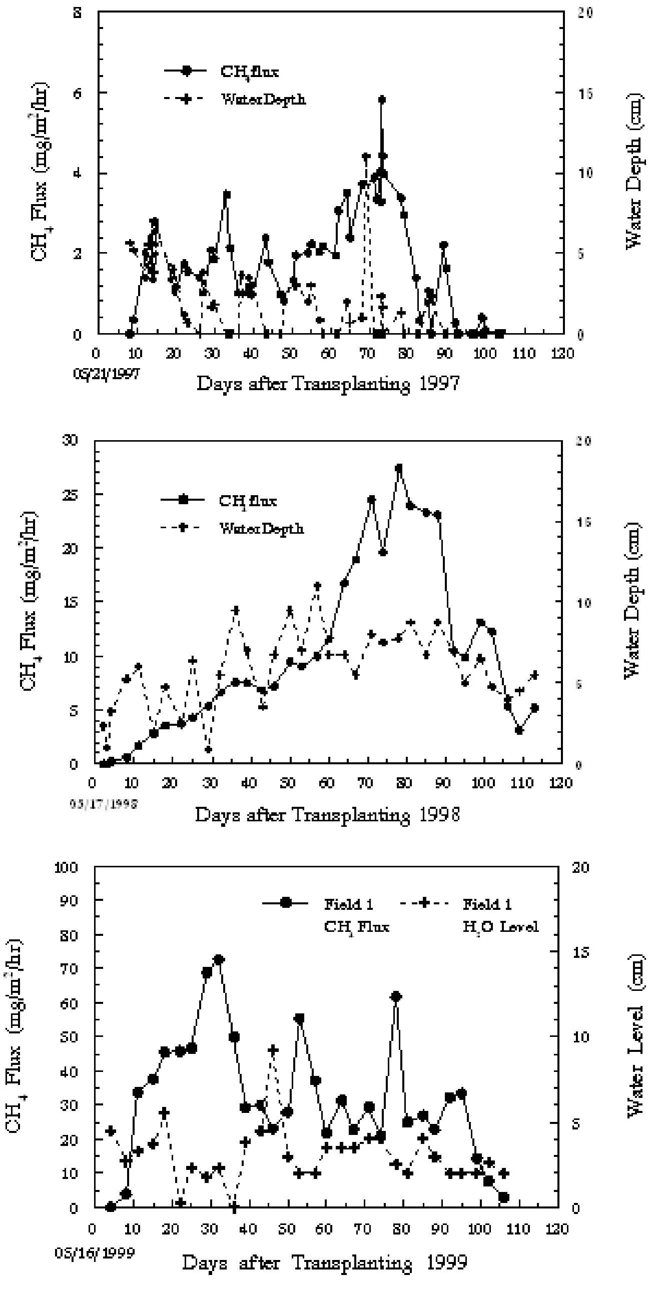

Figure 3. Average water level in field 1 for all three years of the methane emission measurements at JinSa. Drought in 1997 led to restricted irrigation. Flooding in 1998 led to relatively high water levels in the second half of the growing season. In 1999, sufficient rain kept the fields from ever draining completely.

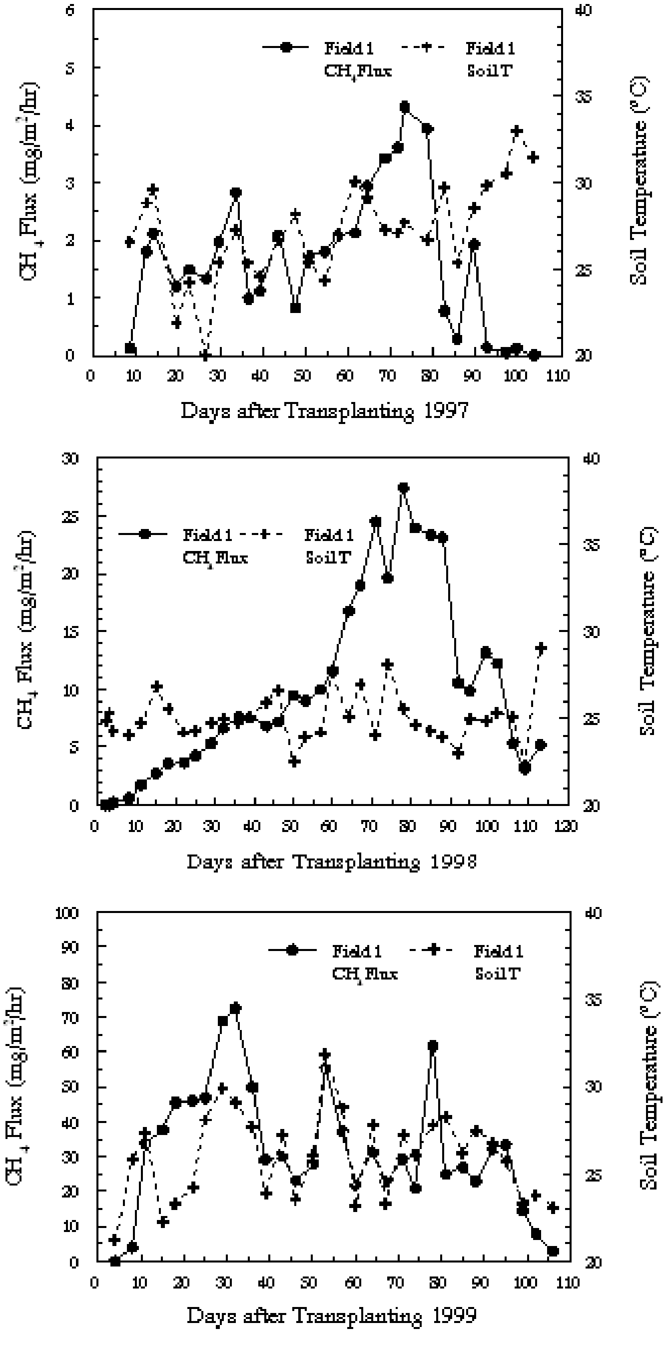

Figure 4. Soil temperature as it affects methane flux, throughout three growing seasons at JinSa

Figure 3 and figure 4 show field 1 as an example of the interaction of methane emission and water level, and soil temperature. Field 1 was intended as a control field for all three years of the experiment. The water level mainly affects the seasonal emission (Figure 3). Without water, the soil becomes aerated and methanogenic bacteria die or go dormant. In 1997, a drought led to intermittent irrigation in all fields, as water was restricted throughout the summer. In 1998, the opposite problem occurred, with so much rain that the fields could not be completely drained even for harvest. The difference in seasonal average flux was 3 to 5 times higher in 1998 than 1997. In 1999, frequent rains also kept the fields flooded, though in that year all fields had additional organic matter from the previous crop (about 5 tonnes/ha). With adequate water and the additional carbon source, the seasonal average emission increased another 3 times over 1998.

With adequate water and a source of organic matter for food, the activity of methanogens is also influenced by soil temperature (Parashar et al., 1993). Figure 4 demonstrates that some of the peaks in emissions throughout the growing season correlate with the soil temperature. However, soil temperature is partially dependent on water level depth. At times during growing season when soil temperature shows no correlation with methane emissions, usually either the soil has dried so methane is oxidized before it can escape (e.g. late 1997), or deep water and cool weather keep the temperature variation low (e.g. 1998).

IV. Methane Production and Oxidation in Rice Soils

Most of the methane that is produced below the soil is oxidized by methanotrophic bacteria in the rhizosphere of the rice plants. The emissions measured are therefore the difference between two large numbers, namely, the production rate and the oxidation rate. Since the oxidation rates are generally high, relatively small differences in oxidation at one location compared to another can lead to large differences in the observed emissions. For instance, all else being the same, if the oxidation rate decreases from 90% to 70%, it would lead to an increase in flux of a factor of three. The differences of methane flux observed in various experiments may be caused by the different efficiencies of the oxidation processes in the soils.

The measurement of the oxidation rates is not normally carried out in the field and is generally difficult to determine accurately. For our experiments at TuZu we used an indirect method to estimate the oxidation rate (Khalil et al., 1998d). These results show that the oxidation rates at Tu Zu were about 45-60%, which is much less than reported in other experiments (Schütz et al., 1989; Sass et al., 1990; Denier van der Gon and Neue, 1996). The lower oxidation rate may have contributed to the high fluxes observed.

At JinSa, we designed new experiments to measure the oxidation rates more directly. These measurements consist of incubating soil from various depths under anaerobic conditions to measure the production rates of methane, as described earlier. A mass balance model relates the measured production of methane in the incubation studies and the directly measured flux to the rate of oxidation. Figure 5 shows the estimated oxidation rates calculated from the experiments carried out during the 1998 and 1999 growing seasons.

In the early part of the growing season, the plants are not effective at transporting methane and the root zone is small so that neither root exudation nor oxidation processes are effective; the emission of methane is mostly controlled by ebullition (Schütz et al., 1989). In the next phase of growth, as the plants tiller and grow vigorously, all the processes mentioned above may be active. There could be enhanced production of methane because of root exudates from more plants and faster transport that reduces the net oxidation. In the next stage, as the plants mature and flower, there is no further increase of transport efficiency and root exudation is greatly reduced as the roots are then fully grown (Hale and Moore, 1979; Minoda et al., 1996). Other substrates for methane production may also be exhausted. At this stage, therefore, the number of plants per unit area does not affect methane emissions as much as before because the flux is limited by production and not the transport. The presence of fast transport after tillering keeps the concentration of methane in the soil low enough that bubbles are not formed, and plant mediated transport is the major pathway for transferring methane to the atmosphere (see Khalil et al., 1998d).

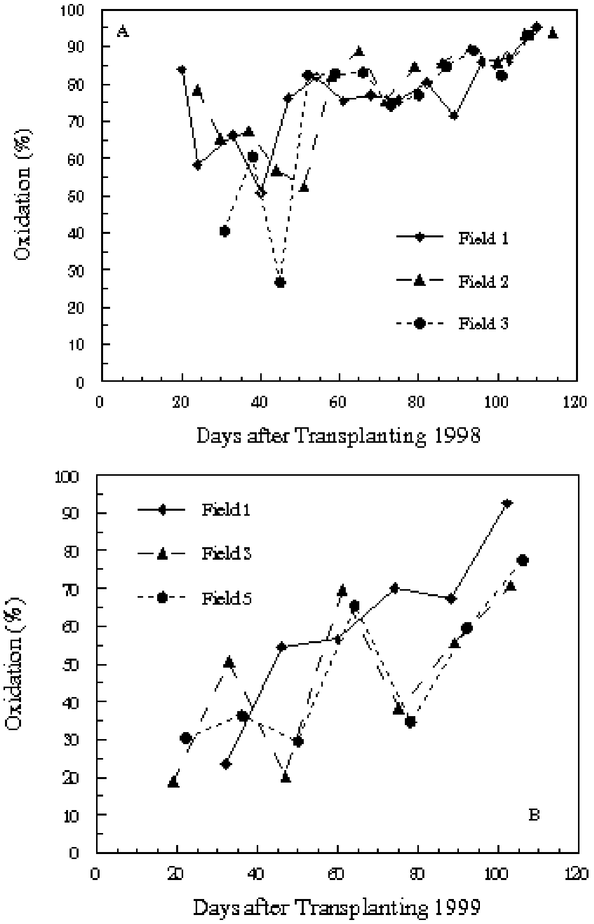

Figure 5. Estimated percent oxidation from three rice fields in: A) 1998 and B) 1999.

As discussed in section III, average seasonal methane emission in 1999 was three times higher than in 1998. As the emissions are closer to those measured at TuZu, so the oxidation fraction is very similar to the oxidation rate modeled from TuZu. This suggests that aerobic bacteria react more slowly than methanogenic bacteria to an increasing food supply. If the soil stays flooded (anaerobic) throughout the growing season, the aerobic bacteria would be limited to the plant root zone and unable to expand if methanogens increase production.

V. Ambient Measurements

There were two types of ambient measurements that were taken in this experiment, each fulfilling a different objective. One type consisted of taking samples at the sides of the rice fields around the same time as the flux measurements. The other type of ambient samples was collected at a continental background site at Minqin in the Gansu Province of China. Triplicate flask samples were collected at Minqin once a week and sent back to our laboratory for analysis. These data represent atmospheric composition in the clean continental background at middle latitudes.

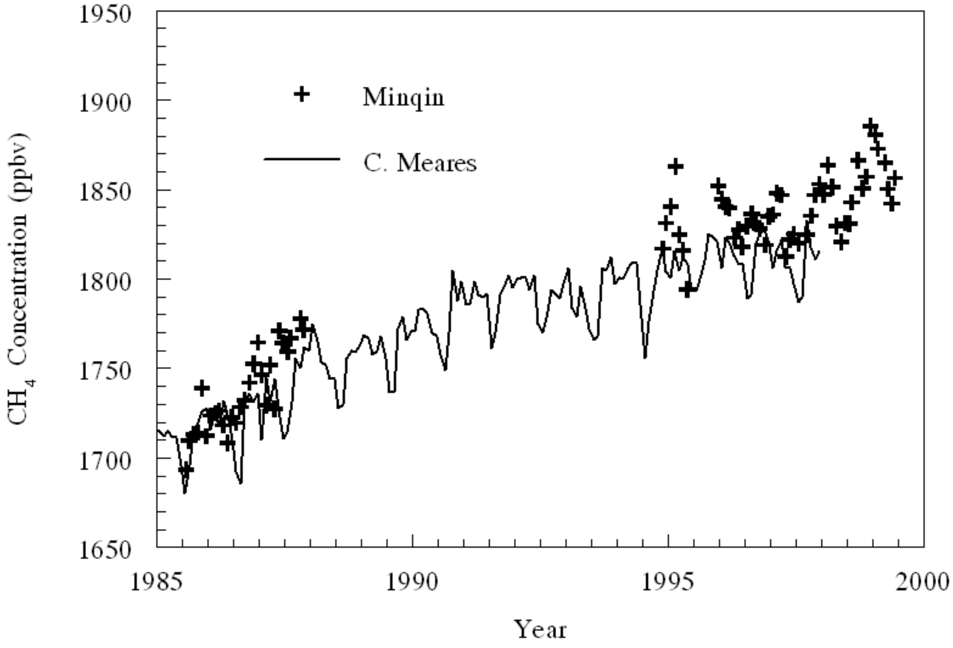

Figure 6. Methane concentrations at a continental clean air site: Minqin, China, Latitude 38.4° N, Longitude 103.1° E; and at a comparable site representing the marine boundary layer, Cape Meares, Latitude 45.3° N, Longitude 123.6° W.

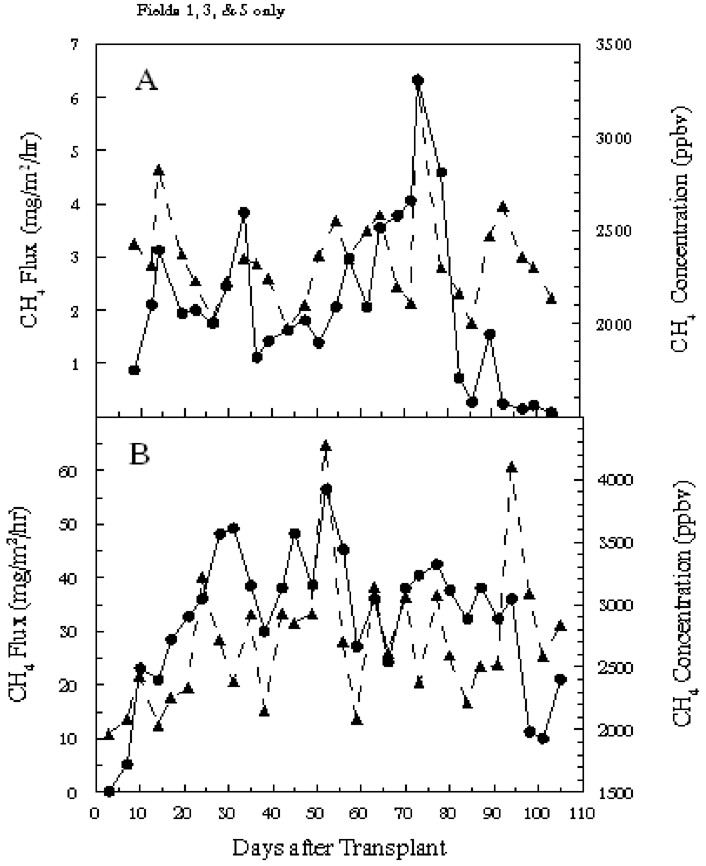

Figure 7. Comparison of daily average methane flux (●) with average ambient methane concentration (▲) for: A. 1997, and B. 1999. The different water regimes and organic matter in the fields in those years led to a 10-fold higher CH_4 flux in 1999, and a higher average background CH_4 concentration of about 500 ppbv.

Although there are established networks for the measurements of greenhouse gases and other environmentally important trace gases, most of the sites represent the marine boundary layer. Our site at Minqin is one of the first and still one of the few clean air continental sites. The site is located at the edge of the Gobi desert in an area of relatively low population density mostly subsisting on reclaimed desert lands. There are no identifiable sources that could contribute significantly to the concentrations of the gases of our interest: methane, nitrous oxide, carbon monoxide, carbon dioxide, CFCs, and other greenhouse gases or ozone-depleting compounds. In Figure 6, methane measurements from Minqin are shown along with similar measurements from Cape Meares in Oregon. These data are being applied to constraining the sources of methane using mass balance models.

The measurements near the rice paddies contain a signal of the flux from the nearby fields. We established that the ambient concentrations could be used to estimate the flux of methane (Khalil and Rasmussen, 1998). The different agricultural management, and topography at Jinsa leads to greater air mixing in the vicinity of the test fields than at Tuzu. Still, the lower average fluxes are reflected in lower daily average concentrations as shown in Figure 7.

VI. Survey of Irrigation and Soil Amendments in Sichuan Province

In 1999, extensive measurements of water use were taken in twenty-four counties and municipalities, at 60 different sites. Water level in each field was measured morning and evening, and weather, and irrigation data were recorded daily. In 2000, farmers and farm agents from the same areas were interviewed about changing agricultural practices in rice cultivation, and information on area planted to rice, and amounts of irrigation water, manure, and nitrogen based chemical fertilizers applied annually for each year from 1981 to 2000 (estimated). Since rice is the predominant crop in the sample regions, the change in resource use, particularly irrigation water, was presumed to be representative of rice agriculture.

Over half the areas sampled still use flood irrigation in the rice fields. The areas most likely to use flood irrigation are located in the hilly perimeter of the principal rice growing areas of Sichuan Province. One site was upland rice, where the fields were dry except after the heaviest rains. Most of the rest of the sites use some form of intermittent irrigation. Where irrigation is highly controlled, the fields are flooded for about a month until the rice plants are established, then irrigated only when rain is inadequate (about 10 sites). Another pattern was “field baking” where the rice fields are allowed to dry for a period of about 2 weeks in the middle of the crop cycle to facilitate root growth, then re-flooded (about 7 sites). The remaining sites had no recognizable pattern.

The last decade has caused major changes in rice agriculture in Sichuan Province. As central control of agriculture has relaxed, the area planted to rice has declined, starting about 1993. Irrigation water use has also declined, mainly linked to rice area. Manure use per hectare has decreased and chemical fertilizer per hectare has increased.

VII. Data

Data are in preparation. The final data set will include: methane fluxes from JinSa for 1996 through 1999, with all metadata; methane production and estimated oxidation; Minqin background concentrations for all trace gases; and summaries of the extensive surveys on water use and agricultural practices in Sichuan province.

Acknowledgments

Major financial support for this project was provided by grants from the U.S. Department of Energy (DE-FG03-97ER62401). Financial support was also provided by the College of Liberal Arts and Sciences (CLAS) of Portland State University. Additional support was provided by the Biospherics Research Corporation and Andarz Co.

Literature Cited

Bouwman, A.F. Agronomic aspects of wetland rice cultivation and associated methane emissions, *Biogeochemistry 15*:65-88, 1991.

Chen Z.L., Li D.B., Shao K.S., and Wang B.J. Features of CH_4 emission from rice paddy fields in Beijing and Nanjing. *Chemosphere 26*, 239-245, 1993.

Cicerone, R.J., C.C. Delwiche, S.C. Tyler, and P.R. Zimmerman. Methane emissions from California rice paddies with varied treatments. *Global Biogeochemical Cycles, 6(3)*: 233-248, 1992.

Denier van der Gon, H.A.C. and H.-U. Neue. Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global Biogeochemical Cycles 9*, 11-22, 1995.

Denier van der Gon, H.A.C. and H.-U. Neue. Oxidation of methane in the rhizosphere of rice plants. *Biology and Fertility of Soils 22*, 359-366, 1996.

Hale, M.G., and L.D. Moore. Factor affecting root exudation II, 197-1978. In: *Advances in Agronomy 31*, 93-124, Academic Press, San Diego, Calif., 1979.

Husin, Y.A., D. Murdiyarso, M.A.K. Khalil, R.A. Rasmussen, M.J. Shearer, S. Sabiham, A. Sunar, and H. Adijuwana. Methane flux from Indonesian wetland rice: The effects of water management and rice variety. *Chemosphere 31*(4), 3153-3180, 1995.

IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2001, The Scientific Basis*. Cambridge University Press, Cambridge, U.K., 2001.

Khalil M.A.K., and R.A. Rasmussen. Constraints on the global sources of methane and an analysis of recent budgets. *Tellus 42B*, 229-236, 1990.

Khalil and R.A. Rasmussen. Using ambient concentrations as proxy for methane flux measurements from rice fields. *Chemosphere 37*(6), 1197-1205, 1998.

Khalil, M.A.K., R.A. Rasmussen, M.J. Shearer, R.W. Dalluge, L.-X. Ren, and C.-L. Duan. Measurements of methane emissions from rice fields in China. *Journal of Geophysical Research 103*(D19), 25,181-25,210, 1998a.

Khalil, M.A.K., R.A. Rasmussen, and M.J. Shearer. Flux measurements and sampling strategies: Applications to methane emissions from rice fields. *Journal of Geophysical Research 103*(D19), 25,211-25,218, 1998b.

Khalil, M.A.K., R.A. Rasmussen, M.J. Shearer, R.W. Dalluge, L.-X. Ren, and C.-L. Duan. Factors affecting methane emissions from rice fields. *Journal of Geophysical Research 103*(D19), 25,219-25,231, 1998c.

Khalil, M.A.K., R.A. Rasmussen, and M.J. Shearer. The effects of planting density, oxidation, and root exudates on methane emissions from rice fields. *Journal of Geophysical Research 103*(D19), 25,233-25,239, 1998d.

Khalil, M.A.K., R.A. Rasmussen, M.J. Shearer, Z.-L. Chen, H. Yao, and J. Yang. Emissions of methane, nitrous oxide, and other trace gases measured from rice fields in China. *Journal of Geophysical Research 103*(D19), 25,241-25,250, 1998e.

Khalil, M.A.K. and M.J. Shearer. Sources of methane: An Overview. In: *Atmospheric Methane, Its Role in the Global Environment*, Ed. M.A.K. Khalil, Springer Verlag, Berlin, p. 98-111, 2000.

Lindau, C.W., and P.K. Bollich. Methane emissions from Lousiana first and ratoon crop rice. *Soil Science, 156*:42-48, 1993.

Minoda, T., M. Kimura, and T. Wada. Photosynthates as dominant source of CH_4 and CO_2 in soil water and CH_4 emitted to the atmosphere from paddy fields. *Journal of Geophysical Research 101*(D15), 21,091-21,097, 1996.

Neue, H.-U., R.S. Lantin, R.Wassman, J.B. Aduna, Ma. C.R. Alberto, and M.J.F. Andales. Methane emission from rice soils of the Philippines, In: *CH_4 and N_2O, Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*, K. Minami, A. Mosier, and R. Sass (Eds.), NIAES Series 2. Yokendo Publishers, Tokyo, Japan, 1994.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner. Methane production and emission in a Texas rice field. *Global Biogeochemical Cycles 4*, 47-68, 1990.

Sass, R.L., F.M. Fisher, Y.B. Wang, F.T. Turner, and M.F. Jund. Methane emission from rice fields: The effect of floodwater management. *Global Biogeochemical Cycles 6*, 249-262, 1992.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund and F.T. Turner. Methane emission from rice fields: Effect of soil properties, *Global Biogeochemical Cycles, 8(2)*:135-140, 1994.

Schütz, H., W. Seiler, and R. Conrad. Processes involved in formation and emission of methane in rice paddies. *Biogeochemistry 7*, 33-53, 1989.

Wang, Z.P., R.D. DeLaune, P.H. Masscheleyn, and W.H. Patrick, Jr. Soil redox and pH effects on methane production in a flooded rice soil. *Soil Science Soc. of America Journal 57*, 382-385, 1993.

Yagi, K., H. Tsuruta, K. Kanda, and K. Minami. Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles 10*, 255-267, 1996.

Publications Supported Wholly or in Part Under This Project.
DOE GRANT DE-FG03-97ER62401 (Chronological Order)
List does *not* include abstracts of presentations at conferences.

Khalil, M.A.K. Earth's Atmosphere. *Encyclopedia of Geochemistry,* Encyclopedia of Earth Sciences Series, Edited by Clare P. Marshall and Rhodes W. Fairbridge (Kluwer Academic Publishers), pages 143-145, 1999.

Khalil, M.A.K. Non-CO_2 Greenhouse Gases in the Atmosphere. *Annual Review of Energy/Environment*, Annual Reviews, 1999, Vol. 24, 245-261, 1999.

Khalil, M.A.K. and R.A. Rasmussen. Soil-Atmosphere Exchange of Radiatively and Chemical Active Gases. *Environmental Science and Pollution Research International*, Vol. 7, No. 2, 79-82, 2000.

Gross, G.W. and M.A.K. Khalil. OH Concentrations from a General Circulation Model Coupled with a Tropospheric Chemistry Model. *Chemosphere: Global Change Science*, Vol. 2, 191-206, 2000.

Khalil, M.A.K., Editor. *Atmospheric Methane, Its Role in the Global Environment.* Springer-Verlag, Berlin, 351 pages, 2000.

Khalil, M.A.K. Atmospheric Methane: An Introduction. In: *Atmospheric Methane, Its Role in the Global Environment*, M.A.K. Khalil, Ed. Springer-Verlag, Berlin, p.1-8, 2000.

Khalil, M.A.K., M.J. Shearer, and R.A. Rasmussen. Methane Sinks, Distributions, and Trends. In: *Atmospheric Methane, Its Role in the Global Environment*, M.A.K. Khalil, Ed. Springer-Verlag, Berlin, p.86-97, 2000.

Khalil, M.A.K., and M.J. Shearer. Sources of Methane: An Overview. In: *Atmospheric Methane, Its Role in the Global Environment*, M.A.K. Khalil, Ed. Springer-Verlag, Berlin, p.98-111, 2000.

Shearer, M.J., and M.A.K. Khalil. Rice Agriculture: Emissions. In: *Atmospheric Methane, Its Role in the Global Environment*, M.A.K. Khalil, Ed. Springer-Verlag, Berlin, p.170-189, 2000.

Khalil, M.A.K., R.A. Rasmussen, and M.J. Shearer. Atmospheric nitrous oxide: patterns of global change during recent decades and centuries. *Chemosphere* 47, 807-821, 2002.

Butenhoff C.L., and M.A.K. Khalil. Correction for water vapor in the measurement of atmospheric trace gases. *Chemosphere* 47, 823-836, 2002.

Khalil, M.A.K. Atmospheric greenhouse gases. *World Resource Review*, 13 (3), 335-355, 2002.

Khalil, M.A.K. and M.J. Shearer. Atmospheric methane. *Handbook of Weather, Climate, and Water: Chemistry, Impacts, and Applications*. Edited by Thomas D. Potter and Bradley R. Coleman. John Wiley and Sons, Inc, NY, pages 89-106, in press.

Visitor Exchanges

Visitors from the U.S.

Drs. R.A. Rasmussen (OGI) and M.A.K. Khalil (PSU). Visits during most years between 1997-2000 to support the field program as needed: Beijing and Chengdu.
Mr. R.W. Dalluge (OGI), visited Chengdu each year 1997-1999, for 1 to 2 months each time to set up equipment at the start of the growing season and carry out special experiments.

Visitors from China

Dr. Xu Li from the CMA visited OGI and PSU for one month, summer 2000.