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Agronomic aspects of wetland rice cultivation and associated methane emissions

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Abstract. Wetland rice cultivation is one of the major sources of atmospheric methane (CH_4). Global rice production may increase by 65% between 1990 and 2025, causing an increase of methane emissions from a 92 Tg CH_4 y^{-1} now to 131 Tg in 2025.

Methane production depends strongly on the ratio oxidizing: reducing capacity of the soil. It can be influenced by e.g. addition of sulphate, which inhibits methanogenesis. The type and application mode of mineral fertilizers may also affect methane emissions. Addition of organic matter in the form of compost or straw causes an increase of methane emissions, but methane production is lower for materials with a low C/N ratio.

High percolation rates in wetland rice soils and occasional drying up of the soil during the cultivation period depresses methane release. Water management practices aimed at reducing emissions are only feasible during specific periods in the rice growing season in flat lowland irrigated areas with high security of water availability and good control of the water supply. Intermittent drying of soils may not be possible on terraced rice lands.

Assuming a 10 to 30% reduction in emission rates per unit harvested area, the global emission may amount to 93 Tg CH_4 y^{-1} in 2025. A reduction of global emissions seems very difficult. To develop techniques for reducing CH_4 emissions from wetland rice fields, research is required concerning interactions between soil chemical and physical properties, and soil, water and crop management and methanogenesis. Such techniques should not adversely affect rice yields.

Introduction

Methane is a chemically reactive and radiatively active atmospheric trace gas. Its concentration has showed an accelerated increase during the past 300 years to about 1.7 ppm today (Steele et al. 1987; Khalil & Rasmussen 1990), almost double that in the pre-industrial era (Rasmussen & Khalil 1984). Its current annual rate of increase is ~ 1% (Cicerone & Oremland 1988). This increase is mainly caused mainly by an excess of sources over sinks (Khalil & Rasmussen 1985), which amounts to 38–48 Tg (Tg = Teragram; 1 Tg = 10^{12} g) (Cicerone & Oremland 1988). The total annual source of atmospheric methane (CH_4) is 400 to 640 Tg (Cicerone & Oremland 1988). About 20% of the total global emission is from fossil sources (Wahlen et al. 1989), the remainder stems from wetland rice fields (92 [60—140] Tg, Aselmann & Crutzen 1989), natural wetlands (40—160 Tg; Aselmann & Crutzen 1989; this source includes amounts of 'old' or fossil methane), landfills (30—70; Bingemer & Crutzen 1987), ruminants 66—90 Tg; Crutzen et al. 1986), termites and other insects (10—100; Cicerone & Oremland 1988), oceans and other minor sources. These global estimates are highly uncertain.

Rice cultivation may contribute significantly to future increases in atmospheric CH_4. To meet the demand for rice, the production has to increase from its current level of 460 million tons per year to 556 million tons in 2000 and 758 million tons in 2020 (IRRI 1988). Most of the increases will have to be achieved on the existing irrigated wetland rice fields (Neue 1990), through intensification and yield increases. The associated methane emissions from wetland rice fields may increase to 131 Tg $CH_4\ y^{-1}$ compared to the current annual emission of 92 Tg CH_4 (Fig. 1).

Research efforts aimed at reduction of emissions and implementation of the developed techniques at farm level is, therefore, required. Methane emissions per unit area of harvested rice may be reduced by 10 to 30% (EPA 1990). Assuming that 30% reduction can be achieved on irrigated rice fields, where levels of soil, crop and water management are high, and 10% reduction on the rainfed wetland rice lands, with somewhat lower levels of management and water control, the global emission from rice fields may stabilize at the current level (Bouwman et al. 1992).

Table 1 shows that the current harvested area is 149 million ha and that about 90% of the global rice production is in Asia. About half of this area is covered by irrigated wetland rice fields, 30% by rainfed wetland rice fields, about 8% deep water rice and 15% is upland rice. Globally 60% of the harvested area is managed under a triple cropping system, 15% is double cropped and 25% is planted once a year (Matthews et al. 1991).

Methane production is negligible in aerobic upland rice soils, and emissions are probably very low in the deep water rice fields with floating rice. In floating rice the roots in the soils and lower parts of the stem are physiologically dead, so that the pathway for escape of methane through the plants is blocked (Neue et al. 1990).

The advantages of growing rice in an aquatic milieu are several. Their relative importance is locale specific, depending on factors such as soil physical and chemical conditions, climate, hydrology, and biotic factors. Some advantages seem to operate under most conditions:

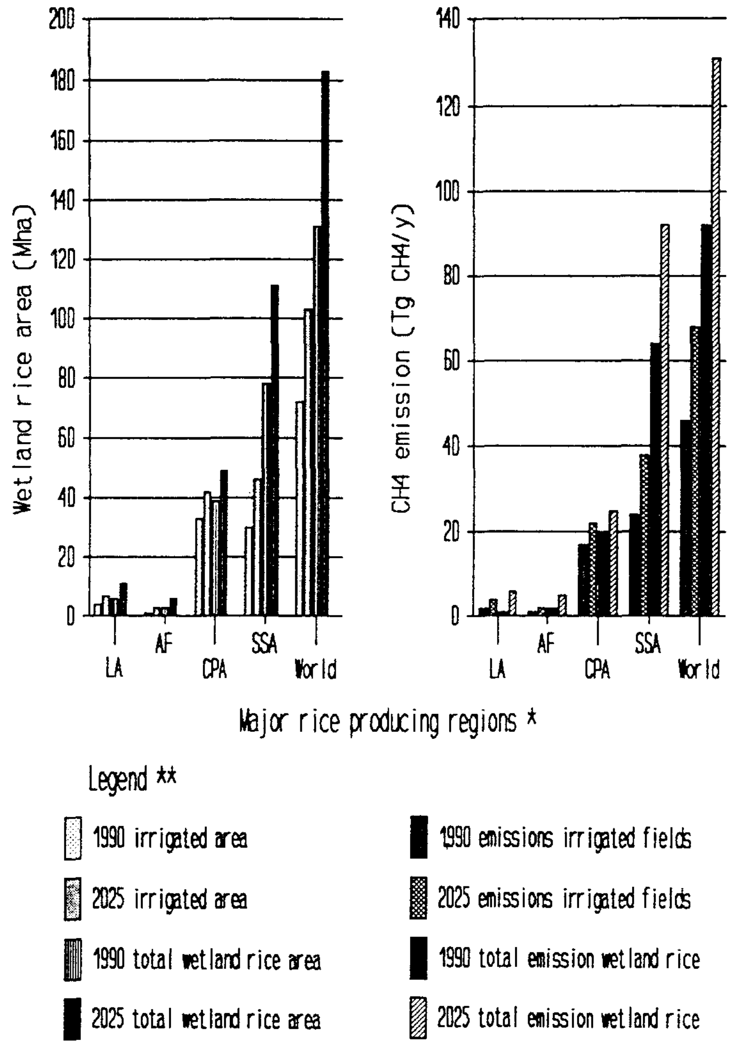

Fig. 1. Projection of areas of wetland rice cultivation, irrigated areas and associated methane emissions adapted from EPA (1990) by Bouwman et al. (1992). *LA = Latin America; AF = Africa; CPA = Centrally Planned Asia; SSA = South and Southeast Asia. **wetland rice included irrigated and rainfed wetland rice fields. The projection is based on (i) the above projections of the demand for paddy; (ii) an overall productivity increase of 25% between 1990 and 2025; this is not unrealistic in view of the admirable yield increases have been achieved in the past decades (see Purseglove 1972; FAO 1962–1990); (iii) an increase of the irrgated and rainfed wetland rice lands by 5% between 1990 and 2025 at the cost of upland rice cultivation; and (iv) on temperature dependent emission rates (from Aselmann & Crutzen 1989).

Table 1. Areas, estimated paddy yields of rice for irrigated wetland, rainfed wetland and upland rice.

Region	Total harvested rice area (1000 ha)	Type (%)			Area wetland rice	Yield (ton ha^{-1})			1990 production (1000 T)
		UP	IR	RF		UP	IR	RF	
Europe[a]	482	0	100	0	482	1.0	4.5		2475
Oceania	114	0	100	0	114	1.0	7.7		876
Japan	2097	0	100	0	2097	1.0	6.2		12938
USSR	654	0	100	0	654	1.0	3.9		2524
North America	1087	0	100	0	1087	1.0	6.5		7011
South America	6857	15	50	35	5828	1.0	3.7	1.5	17211
Central America	728	15	50	35	619	1.0	4.8	1.5	2250
Africa	5532	50	15	35	2766	1.0	5.8	1.5	10511
Middle East[b]	669	0	38	62	669	1.0	4.4	1.5	1746
China	32400	2	93	6	31914	1.0	5.9	1.5	179496
Rest Centrally Planned Asia[c]	8550	13	38	50	7456	1.0	6.1	1.4	26613
South and Southeast Asia	89380	13	33	54	77582	1.0	3.4	1.5	185464
Total	148550				131268				468575

[a] including Turkey; [b] Afghanistan, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Saudi Arabia, Syria, UAE, North Yemen, South Yemen; [c] North Korea, Vietnam, Cambodia, Mongolia

Areas in 10^3 ha, production in 1000 T. Data for 1990. Sources: areas FAO (1990); distribution rice ecologies Neue et al. (1990); Yields: FAO (1990) and Neue (in EPA 1990). UP = upland rice; IRR = irrigated wetland rice; RF = rainfed wetland rice

- sufficient water supply for the rice plants, which is one of the least drought resistant food crops (Doorenbos & Kassam 1986);
- ease in land preparation in moist to wet soils, especially when hand tools or simple animal operated equipment are used. This factor is important in the dominantly clay paddy fields of Asia (Moormann & Van Breemen 1978);
- simplified weed control by wet preparation and flooding. Only a limited number of weed species can grow and compete with rice under flooding. Weed control is a major problem in non-flooded rice lands, e.g. in the phreatic rice lands in West Africa (Moormann & Van Breemen 1978);
- greater availability of plant nutrients. Under flooding nitrogen fixation occurs by aquatic nitrogen fixers in amounts of 13 to 99 kg N/ha (Kawaguchi & Kyuma 1977), while the availability of phosphorous and several minor elements, except Zinc, is improved (Moormann & Van Breemen 1978). This relative high fertility of wetland rice soils compared to upland soils makes continuous cultivation of rice possible (Kawaguchi & Kyuma 1977; Moormann & Van Breemen 1978).

Other advantages relate to soil conservation and the use of periodically flooded lands:

- for wetland rice it is necessary to construct terraces when the terrain is sloping and to make levees to flood it. These practices diminish the erosion hazard;
- rice cultivation has made the utilization of annually flooded lowlands possible. Almost one third of the potentially arable land area in tropical Asia is in alluvial lands (Kawaguchi & Kyuma 1977).

Upland rice has the potential to expand, but continuous rice cultivation may result in serious soil erosion hazards. There is potential for both expansion and intensification of the cultivated area in wetland rice environments, in particular in South and Southeast Asia, where 18 million ha of tidal wetlands and areas with deep water could be used for rice (Neue, in EPA 1990).

An important reduction of the CH_4 emissions from wetland rice lands can be achieved by reducing the harvested area. However, the implicit change from rice consumption to other food is not considered here, but this option merits policy attention.

In this paper an overview will be given of

- the soil processes important for methane formation and oxidation in wet rice fields;

— the role of rice plants in the transport and oxidation of methane in wetland rice soils.

In the last part a number of agronomic aspects of rice cultivation interacting with methane production and oxidation with attention to possibilities for reducing emissions:

— water management in wetland rice cultivation;
— the application of rice straw and other types of manure;
— the application of mineral fertilizers.

Soil reduction processes in wetland rice soils

A review of CH_4 formation, controlling factors and biochemical pathways can be found in Oremland (1988) and Conrad (1989). A number of soil processes and soil conditions important in methanogenesis will be discussed briefly.

Organic matter in anaerobic soils is decomposed by microbes in consecutive steps in which the hydrogen acceptors (= oxidizing agents) are used up one after the other in a thermodynamically determined sequence of the following processes: aerobic respiration, nitrate reduction, general fermentations, sulphate reduction, methane fermentation. The redox potential of a soil decreases after flooding as a consequence of sequential reduction of oxidized compounds by organic matter (Table 2). When the inorganic hydrogen acceptors have been consumed, the remaining organic matter will continue to be degraded by microbial oxido-reduction processes that ultimately lead to formation of a mixture of CO_2 and CH_4, the ratio of the two gases depending on the degree of oxidation of the initial organic material. One of the main pathways in CH_4 formation in nature

Table 2. Sequential reduction of oxidized soil compounds in a soil after inundation.

Redox-reaction		pE_0^7 #
$O_2 + 4H^+ + 4e$	$\Leftrightarrow 2\,H_2O$	13.8
$NO_3^- + H_2O + 2e$	$\Leftrightarrow NO_2^- + 2OH^-$	12.66
$MnO_2 + 4H^+ + 2e$	$\Leftrightarrow Mn^{2+} + 2H_2O$	6.8
$Fe(OH)_3 + 3H^+ + e$	$\Leftrightarrow Fe^{2+} + 3H_2O$	−3.13
$SO_4^{2-} + 10\,H^+ + 8e$	$\Leftrightarrow H_2S + 4H_2O$	−3.63
$CO_2 + 8H^+ + 8e$	$\Leftrightarrow CH_4 + 2H_2O$	−4.14

$pE_{07} = -\log(E_0)$; E_0 in V, corrected for pH = 7
Source: Moormann & Van Breemen (1978)

proceeds via acetic acid (Cappenberg & Prins 1974; Reddy et al. 1986; Strayer & Tiedje 1978; Takai 1970).

A positive correlation exists between the soil's reduction potential and methane emissions (see e.g. Yagi & Minami 1990). For the equilibrium:

$$\mathrm{Ox} + ne + m\mathrm{H}^+ \Leftrightarrow \mathrm{Red}$$

the relation which describes the redox potential E_h (selecting a temperature of 25 °C) is (from Ponnamperuma 1972, 1985):

$$E_h = 0.059/n \log(\mathrm{ox})/(\mathrm{red}) - 0.059\ m/n\ \mathrm{pH}$$

For the Fe^{3+}/Fe^{2+} redox reaction the E_h will be low at increasing Fe^{2+} activity or at higher pH. Higher initial levels of Fe^{3+}, organic matter, low NO_3^-, MnO_2 and O_2 and high temperatures favour E_h decrease (Ponnamperuma 1981). The type of organic matter added to a soil may also have an effect on the magnitude of the fall of E_h (Swarup 1988) and on methane production (Nouchi et al. 1990; Yagi & Minami 1990).

Temperatures have a marked effect on CH_4 development, giving diel and seasonal patterns (Schütz et al. 1990). Temperature effects may also be reflected in regional differences caused by climatic variation (Kimura et al. 1991; Parashar et al. 1991).

Generally methanogenesis has an optimum pH range around 7 (Williams & Crawford 1984; Conrad 1989). In surface soils with an initial pH between 5 and 6 the increase in alkalinity (HCO_3^-) due to flooding associated with reduction of Fe^{3+} to Fe^{2+} implies an increase in pH, normally to values of 6.5 to 7 (Moormann & Van Breemen 1978). In calcareous soils less dissolved Fe^{2+} and hence less HCO_3^- are formed during the inundation period; there the acidifying effect of accumulated carbon dioxide is more important, causing a fall in pH to between 6.5 and 7 (Moormann & Van Breemen 1978). Strongly alkaline soils as frequently used for rice cultivation in semi-arid areas in northern India and Pakistan, are normally low in organic matter (Kawaguchi & Kyuma 1977) and they show little reduction after flooding (Moorman & Van Breemen 1978). Hence, in most soils the ratio oxidizing: reducing capacity may be more important than the initial soil pH.

In steady sate methanogenic ecosystems show a characteristic stratification (Conrad 1989):

- a thin aerobic surface layer of 0.5 to 10 mm thickness (Moormann & Van Breemen 1978); in this layer consumption of the methane produced in the reduced zone may occur;
- the second layer is reduced with Fe^{3+}, Mn^{4+} and NO_3^- still present;
- a layer of sulphate reduction;

— and finally a zone of methane generation is found. This layering coincides with values of the redox potential specific for the redox couples present as given in Table 2 (Conrad 1989).

The importance of the various redox systems varies from one soil to another, which has been illustrated by Takai (1961) who showed for a range of Japanese soils that the ratio of CO_2 to CH_4 released depends strongly on the ratio of oxidizing capacity to reducing capacity. Any effect on the water content and distribution of oxygen in the paddy soil, and on the availability of organic matter, electron acceptors (nitrate, iron, manganese, sulphate) and nutrients (N, P, S, K and trace elements), also influences CH_4 production and emission (Conrad 1989).

Apart from these short term changes in soil chemistry induced by flooding, permanent changes may occur, such as migration of iron and manganese, and changes in base status and soil mineralogy. Implications of these processes are discussed in Moormann & Van Breemen (1978).

Transport and oxidation of methane and the role of rice plants

The seasonal variation of CH_4 emission seems to depend on many factors, but some patterns seem to be characteristic. In the period shortly after inundation the CH_4 emission from rice fields is similar to emissions from unplanted fields (Holzapfel-Pschorn & Seiler 1986; Sass et al. 1990). In that period the CH_4 flux is related to mineralization of available soil organic matter. Methane emission maxima were observed in planted fields immediately prior to panicle differentiation and just before heading (Holzapfel-Pschorn & Seiler 1986; Schütz et al. 1989; Minami & Yagi 1988; Yagi & Minami 1990). These peaks may be attributed to increased efficiency of gas transport through the root system of the rapidly growing rice plants during tillering and to the supply of easily decomposable organic substrates in the form of root exudates (Sass et al. 1990). These exudates consist mainly of carbohydrates, organic acids and amino acids, and they are preferentially released during the vegetative stage of rice growth (Boureau 1977; Schütz et al. 1989). Another peak which may occur in the latest stage of the rice crop (Schütz et al. 1989; Sass et al. 1990) may be related to the decay of roots (Schütz et al. 1989). Yagi & Minami (1990) observed another methane emission maximum after the paddy field was left to dry out, possibly due to release of captured methane.

De Bont et al. (1978) showed that rice plants in the ripening stage release 20 times more CH_4 than 2 week old plants. Seiler (1984) and

Holzapfel-Pschorn et al. (1986) reported that more than 95% of the total CH_4 release is through diffusive transport through the aerenchyma system of the rice plants, while transport by rising bubbles is only important in unplanted fields.

The balance between methane formation and consumption controls methane concentrations near the surface and thus in large part the flux to the atmosphere (Bartlett et al. 1985). About 42% (Sass et al. 1990) to 67% (Holzapfel-Pschorn et al. 1986) to over 90% (Schütz et al. 1989) of the methane produced may be oxidized. In the absence of rice plants 35% of the total methane production is emitted, but the methane production was much lower than in planted fields (Holzapfel-Pschorn et al. 1986). The processes of production, consumption and transport of CH_4 to the atmophere may all be expected to depend on properties of the root system of the rice plant (Sass et al. 1990). Nouchi et al. (1990) found no correlation between methane release and transpiration. Apparently, stomata do not play a major role and roots can absorb methane independent of water uptake. The methane flux rates in planted fields appear to be proportional to the total amount of methane in the paddy soil profile, whereby its vertical distribution is very important (Nouchi et al. 1990).

The depth of the water layer in the fields controls methane fluxes. Sebacher et al. (1986) observed that emission rates were linearly related with water depths to about 10 cm. Water depths greater than 10 cm do not promote CH_4 emission, which is caused by microbial CH_4 oxidation in aerobic water columns deeper than 10 cm (De Bont et al. 1978; Delaune et al. 1983).

Agronomic aspects of CH_4 emission from wetland rice fields

1. *Water management*

Water management practices may affect CH_4 emissions (e.g. Yagi & Minami 1990; Minami 1990), but they may also have consequences for crop growth and farm management. These techniques include manipulation of percolation rates, temporary drainage and reduction of the period of inundation.

— Water losses through percolation depend on the physical characteristics of the subsoils. A dense subsoil to minimize water percolation losses is obtained by wet tillage or puddling. In addition, the pressure exerted by human feet or animals during tillage, transplanting and weeding causes a compacted layer (plow pan or traffic pan) between 10 and 40 cm depth, characterized by higher bulk density and less medium-to large-sized pores (Leung & Lay 1973). Optimal conditions for compaction are found in fine loamy soils, while traffic pans may be absent or only weakly developed in very sandy soils, and pan formation is less pronounced in soils with high clay contents (Moormann & Van Breemen 1978). Puddling causes a stratification of the soil material with sandy materials settling first, followed by finer silt and clay. Medium textured soils show a clear stratification upon puddling. In sandy soils the clayey cover may be absent or very thin. In very fine soils stratification may be difficult to observe. The presence of fine clay layers and algae at the surface causes trapping of gases and contributes to the development of a vesicular structure (Moormann & Van Breemen 1978).

In moderately permeable freely drained soils permanent use for wet rice cultivation causes a gradual formation of a slowly permeable subsurface layer, whereby percolation rates may decrease from 60 mm d^{-1} to 12 mm d^{-1} in about 4 years (Moormann & Van Breemen 1978). In more permeable freely drained soils percolation rates may decrease to about 20 mm d^{-1} in about 6 years (Moormann & Van Breemen 1978).

In East Asia percolation rates of 10 to 20 mm d^{-1} are considered essential for high production (Kawaguchi & Kyuma 1977: 55). Percolation and good drainage are necessary for leaching of toxic substances, such as organic acids and excess CO_2 and H_2S, and to restore nutrient imbalances related to Fe, Mn, P, Zn, S and Na (Neue et al. 1990). Methane emissions may be reduced by removal of organic substrate and CH_4 consumption may be increased by introducing fresh dissolved oxygen into the system with the percolating water. A remarkable variation of the CH_4 emissions was observed with different rates of percolation in a lysimeter experiment. Average emission rates were 9.25, 4.79 and 0.34 g CH_4 m^{-2} d^{-1} for percolation rates of 0, 5 and 20 mm d^{-1}, respectively (Minami 1990).

— Temporary drainage of rice fields during parts of the growing season or between crops may increase CH_4 consumption and decrease methane production. In rice usually basin irrigation is applied, whereby different irrigation schedules are used. Details on these schedules can be found in Doorenbos & Kassam (1986); a brief description will be given here. The length of the growing period is usually between 90 and 150 days, depending on the rice variety, temperature and sensitivity to day-length. In the description below a length of 120 days is used.

— in 'continuous submergence' the water depth is 10 cm during a week after transplanting to secure good growth of the seedlings. In the following tillering period submergence is shallow (3 cm maximum).

Drainage and drying of the topsoil is practiced during this period, when rice can tolerate water shortage and root development is stimulated. Drainage must be completed 30 days prior to heading and from this time on (~50 to ~70 days after transplanting) adequate water supply during head development through flowering is essential. During the ripening period fields should gradually be drained to facilitate harvest operations. Usually fields are completely drained 30 to 45 days after heading, or ~90—105 days after transplanting. Untimely drainage adversely affects yields;

— in the 'intermittent irrigation' schedule water contents are maintained at saturation by intermittent shallow submergence;
— with the 'heading stage submergence' schedule the soil is kept at saturation level or lightly submerged during almost the complete growing period, except for a period of 25 days prior to 10 days after heading (from ~55 to ~90 days after transplanting) when the fields are submerged to a depth of about 10 cm;
— in 'water saving' schedules the soil is maintained at water contents of >75% of saturation throughout the growing period. Moderate submergence is only practiced during a period of 30 days starting at head initiation till the end of flowering (from ~60 to ~90 days after transplanting). On soils with high percolation rates water savings of up to 50% can be achieved.

In intermittent irrigation the water use is 80% of that in continuous submergence, and yields only 50%; relative water use and yields for heading stage submergence 60% resp. 75%, and for water saving schedules 75%, resp. 110% (Doorenbos & Kassam 1986).

Drainage of inundated rice fields cannot be implemented during the second half of the vegetative stage of rice (~40 to 70 days after transplanting) and during flowering (~70—85 days after transplanting), when the rice plants are most susceptible to drought. In these periods yields begin to decline at water contents below 70 to 80% of saturation; contents of 50% give a 50 to 70% yield decrease; at 30% of the saturated water content zero yields can be expected, while at 20% the rice plants wilt and die (Doorenbos & Kassam 1986).

Drainage of the fields between crops in irrigated systems may cause hazards on terraced hillsides, where drying may cause severe cracking of the soil material and water losses, and in extreme cases a collapse of the terrace construction. In rainfed areas, farmers are very much dependent on the water stored in the bunded field. Drainage of fields may under such circumstances not be feasible.

Intermittent drying and wetting of the paddy field may induce nitrification/denitrification processes, whereby nitrogen losses are accelerated and emissions of nitrous oxide may be higher than under continuously flooding. Maintaining the soil saturated or very wet, instead of flooded, often reduces rice yields because of changes in bulk density, diffusion characteristics, nutrient availability and buffering systems (Neue et al. 1990).

— Broadcasting the rice seeds directly in the field instead of transplanting reduces the period of inundation and CH_4 formation. However, transplanting has a number of advantages over direct seeding, as discussed by Purseglove (1972):

- higher yields, often by as much as 15—25%;
- less seed is used;
- the crop is on the land for a shorter period, allowing extra time for the land to be in a suitable condition with the rains, or for the preceding crop, and permits more crops to be grown annually;
- water saving;
- more effective weed control;
- higher security, since transplanting can be done at the appropriate moment;
- less damage from birds. The main disadvantage of transplanting is a much higher labour requirement than direct seeding.

If the water management practices described prove to be successful in realizing reduction of CH_4 emissions without causing extra risks of yield decrease or crop failure for the rice growers, they may only be feasible in the flat lowland irrigated rice lands with high security of water availability and complete control of the water supply.

2. *Application of organic matter*

It is apparent from the data presented in the Appendix, that addition of organic matter to wetland rice fields, whether or not in combination with mineral fertilizers, causes elevated CH_4 emissions.

To assess the global impact of rice production, the data in the Appendix were used to derive a relation between the amount of organic matter added to the rice soil and CH_4 release. As no yield data are reported in nearly all the studies presented in the Appendix, a paddy production of 3.2 tons ha^{-1} (world average from Table 1) is assumed. Using a shoot: grain ratio of 3:2 (Ponnamperuma 1984) and a root:shoot ratio of 0.17 (Yoshida 1981), the total dry matter production of wetland rice would amount to 8.8 ton ha^{-1}. In addition, aquatic biomass production is about

0.6 ton ha^{-1} per season and weed dry matter production during fallow periods about 2 t ha^{-1} (Roger & Watanabe 1984; Watanabe & Roger 1985), giving a total of 11.4 tons dry matter per ha. The ratio of CH_4 release to the total of organic matter additions calculated with the flux data in Appendix is 13% (standard deviation 10%, excluding straw and compost additions $\geqslant$ 12 tons/ha), based on the following assumptions:

- 15% of all stubble, all root biomass, aquatic biomass and weeds are returned to the soil;
- further soil additions are straw or compost as presented in Appendix;
- and a C content in all materials of 50%.

If all experiments with extra straw and compost additions in the Appendix are excluded the ratio CH_4 release: organic matter added to the soil would be 16% ($\pm$10%). Martin et al. (1983) and Neue (1985) reported that a maximum of 30% may be converted to methane. The difference with this simple calculation may lie in the oxidation of considerable amounts of methane under field conditions.

The 1988 world rice production was 470 million tons, with a contribution of 20 million tons from upland rice fields. With 15% of straw, all root biomass, aquatic biomass and weeds returned to the soil, this would amount to 560 million tons dry matter or 280 million tons C. Combining this number with the 16 $\pm$10% of CH_4 release results in an annual emission from wetland rice soils of about 45 Tg CH_4 y^{-1}. Aquatic biomass, weeds and root exudates also contribute to the CH_4 emissions, and their omission may account for the difference of this estimate with the global emission from wetland rice cultivation estimated from temperature dependent emission rates of 92 Tg CH_4 y^{-1} (Aselmann & Crutzen 1989). Unfortunately, no country statistics on usage of organic matter in rice cultivation are available, but the global trend seems to be decreasing (Neue et al. 1990).

Methane emissions are increased considerably in the early stages of growth after application of organic matter (Schütz et al. 1989); very high applications did not increase CH_4 emission, possibly due to the formation of toxic products of fermentation. Additions of straw increased the CH_4 emissions by a factor of 2 to 3 compared to mineral fertilization only (Yagi & Minami 1990). Schütz et al. (1989) observed less spectacular increases, possibly caused by the difference in percolation rates caused by the soil physical characteristics (Schütz et al. used a light textured soil as compared to Gleysols and peaty soils in the work of Yagi & Minami).

There seems to be a relationship between the C/N ratio of the organic matter applied and the CH_4 emissions, whereby composted material with low C/N causes lower emissions than e.g. uncomposted rice straw with high C/N ratios (Tsutsuki & Ponnamperuma 1987; Nouchi et al. 1990; Yagi & Minami 1990). Compost did not significantly increase CH_4 emissions in the studies by Yagi & Minami (1990) and Tsutsuki & Ponnamperuma (1987), but Schütz et al. (1989) found remarkable increases in the fields where compost was applied. Unfortunately no exact data on the composition of the materials used were reported.

In many areas the use of organic fertilizers is a major and cheap source of nutrients to the rice crop (Ponnamperuma 1984). A 5 ton crop of paddy rice (rice in the husk) removes from the soil, in paddy + straw, about 150 kg N, 20 kg P, 150 kg K and 20 kg S. Almost all the K and about 30% of the N, P and S remain in the straw (Ponnamperuma 1984). Straw is especially beneficial for K and S deficient soils, it may be useful in iron-toxic soils and organic matter additions may help restoring soil structure when previously puddled soils dry up (Ponnamperuma 1984). Straw has been shown to markedly increase nitrogen fixation (Matsuguchi 1979). Further advantages of straw are its on the spot availability, in amounts of 2—10 ton ha^{-1} per season, and elimination of disposal problems. The usage of straw as fertilizer may cause net immobilization of N, which may be avoided by adding mineral fertilizer or delaying planting (Broadbent 1979).

Alternative uses of straw include the removal for use as fuel, piling or spreading in the field, use as animal feed and bedding, substrate for composting, burning or use as mulch for succeeding dryland crops.

Compost may be easier to apply due to its reduced volume compared to straw but the amount of labour required for composting is higher than simple incorporation of residues (Ponnamperuma 1984). Compost is a poor indirect source of nitrogen, as most of its N is in the form of nitrate, which may easily be lost be denitrification in inundated fields (Ponnamperuma 1984).

Burning of straw — a major method of straw disposal in many countries (Ponnamperuma 1984) — causes release of CH_4, CO and many other polluting species (Hao et al. 1990). About 675 million tons (or 340 million tons C) of the 1240 million tons of dry matter produced in rice fields is in shoot material. Use of this material as fertilizer would cause an emission of 54 Tg CH_4 ($\sim$410 kg CH_4 ha^{-1}, corresponding to a daily emission of $\sim$0.3 g $m^{-2}d^{-1}$ for a 120 day growing season; compare the Appendix), assuming that 16% of the carbon is released as CH_4. During burning of all this material 4 to 7 Tg CH_4 ($\sim$28 to 55 kg CH_4 ha^{-1}), 60 to 100 Tg CO ($\sim$450—750 kg CO ha^{-1}) and various other air pollutants such as NO_x (0.4 Tg N), N_2O (0.02 Tg N) and volatile organic compounds would be emitted using emission factors presented by Hao et al. 1990. Hence, CH_4 emission caused by burning of rice straw is considerably lower, but burning causes considerable emissions of other pollutants.

3. *Mineral nitrogen fertilizers*

In inundated soils denitrification may be a serious problem. Therefore, reduced forms of nitrogen are widely used in rice cultivation. The ammonium yielding fertilizers ammonium sulphate ($(NH_4)_2SO_4$) and urea $(NH_2)_2CO$) account for 84% of the total nitrogen fertilizer consumption in South and Southeast Asia including China (Bouwman et al. 1992, based on FAO 1990); ammonium phosphate ($(NH_4)_3PO_4$) makes up 4%. The first two types are discussed in more detail.

— Ammonium sulphate has an N content of about 20.5%. Its global consumption amounted to 5.5 Tg N y^{-1} in 1989, about 7% of the total nitrogen fertilizer consumption. About 55% of the consumption of $(NH_4)_2SO_4$ is in South and Southeast Asia (Bouwman et al. 1992, based on FAO 1990).

In general electron acceptors such as sulphate (and also nitrate) are preferred over bicarbonate and thus inhibit CH_4 production by competition (Conrad 1989; Jakobsen et al. 1981; Takai 1980; Winfrey & Zeikus 1977). This explains the observed low methane emissions in the presence of sulphate (see e.g. Bartlett et al. 1985, 1987).

Recent research shows that $(NH_4)_2SO_4$ may affect CH_4 emissions from wetland rice fields in various ways: Schütz et al. (1989) observed a decrease when the ammonium sulphate was incorporated, while fluxes were much higher for surface applied $(NH_4)_2SO_4$. Yagi & Minami (1990) reported no significant difference in the CH_4 flux between non-nitrogen and $(NH_4)_2SO_4$ plots. Combination of straw and $(NH_4)_2SO_4$ may increase CH_4 emissions compared to application of straw alone, and similar results were obtained for urea (Schütz et al. 1989). The amount of sulphate added with 200 kg ha^{-1} of $(NH_4)_2SO_4$ seems to be insufficient to explain the observed prolonged inhibition of CH_4 formation; re-oxidation of the sulfide formed to sulphate in the rhizosphere may be responsible for maintaining a high redox potential in the reduced layer (Schütz et al. 1989).

The above experimental results show that the interactions of $(NH_4)_2SO_4$ with methanogenesis are not clearly understood. From the sequence of soil reduction processes one would expect that this effect may be attributed to the sulphate ions. However, the ammonium ions may also be involved since NH_4^+ is rapidly oxidized to nitrate in the rhizosphere. Nitrate may cause inhibition of methanogenesis, and this may explain the observed reduction of CH_4 emission caused by incorporation of reduced N-forms (see Appendix). Surface applied ammonium may even enhance CH_4 emissions (see Appendix) by inhibiting CH_4 oxidation (Conrad & Rothfuss 1991). Moreover, NH_4^+ influences the soil pH at least temporarily and locally, and may thus interact with the complex system of methanogenesis. The NH_4^+ may volatilize as NH_3 particularly at high pH, or exchange with cations at the soil cation exchange complex. Part of these cations may be leached with the percolating water. The NH_4^+ at the soil's exchange complex will eventually be taken up by the plant roots, and this uptake is balanced by a release of H^+. Although the acidifying effect of ammonium fertilizers is in practice seldom observed (H. U. Neue, personal communication), local and temporal effects may be important in this respect.

— The global consumption of urea is 34 Tg N, which is 40% of the global N-fertilizer consumption. In South and South-East Asia 70% of the N fertilizer use of about 32 Tg N is in the form of urea (estimated from FAO 1990).

Urea is hydrolyzed in soils by the enzyme urease to ammonium carbonate ($(NH_4)_2CO_3$), whereby the alkalinity near the fertilizer grain is increased. This may lead to the volatilization of NH_3, especially in soils with a low cation exchange capacity. Volatilization losses may be reduced by incorporation of the fertilizer.

Cicerone et al. (1983) observed a slight decrease of CH_4 emissions in fields which received an extra dosis of urea in addition to the ammonium phosphate-ammonium sulphate and urea in other plots (see Appendix). In other experiments urea applications have been shown to reduce CH_4 emissions when it was incorporated in the soil (Schütz et al. 1989). In fact, the latter experiment consisted of two simultaneous treatments (fertilizer and incorporation), whereby the act of incorporation itself may be important in this respect. Bronson & Mosier (1991) used urea in combination with the nitrification inhibitor encapsulated calcium carbide (ECC), and found a significant reduction of CH_4 release rates compared to the control. Calcium carbide in coated grains slowly releases amounts of acetylene. It has been shown that this may also reduce N_2, N_2O and also CH_4 emissions (Bronson & Mosier 1991). The mechanism responsible for this phenomenon is not fully understood and requires further research. For other ammonium yielding fertilizers such as $(NH_4)_2SO_4$ the use of ECC and other nitrification inhibitors may also offer possibilities for reducing CH_4 emissions in addition to reductions of N-losses and rice yield responses.

4. *Soil properties*

Soils that are sandy or silty in texture or soils having high contents of kaolinitic clays are difficult to puddle. The bulk density of these soils often increases upon puddling, resulting in increased speed of changes in redox potential and pH, increased concentrations and residence time of organic acids and retarded organic matter decomposition. To overcome these adverse conditions the aeration may be increased through higher percolation rates, drainage or by maintaining the soil moisture content close to saturation. Under such conditions redox potentials hardly become negative, which is not optimal for methanogenesis (Neue et al. 1990).

Soils low in active iron with high organic matter contents, attain redox potentials of −200 to −300 mV within 2 weeks after submergence (Ponnamperuma 1972); in soils with high contents of iron and organic matter, the redox potential falls to −50 mV and may then slowly decline over a period of a month to −200 mV. Redox potentials of −150 to −190 mV (corrected to pH = 7) are required for methanogenesis (Table 2). Methane production depends on the ratio of oxidizing: reducing capacity (Takai 1961), whereby the amounts of oxygen, NO_3^-, Mn^{4+} and Fe^{3+} were termed oxidizing capacity and ammonium produced during incubation corresponded to the soil's reducing capacity. Addition of amorphous iron in anaerobically incubated soils depressed the formation of volatile fatty acids and methane (Asami & Takai 1970). However, addition of amorphous iron may cause iron toxicity, as commonly occurs in acid sulphate soils and in soils with upwelling groundwater (Moormann & Van Breemen 1978).

Soil conditions not likely to show high methane production are (Neue et al. 1990):

- electric conductivity (EC) > 4 mS cm^{-1} while flooded;
- acidic soil reaction;
- ferritic, gibbsitic, ferruginous or oxidic mineralogy;
- > 40% of kaolinitic or halloysitic clays;
- < 18% clay in the fine earth fraction if the water regime is epiaquic.

These conditions are usually met in Oxisols, most of the Ultisols and some of the Aridisols, Entisols and Inceptisols (Neue et al. 1990; soil classification terms USDA 1975). Rice soils which may be expected to be good habitats for methanogenesis belong to the orders of Entisols, Inceptisols, Alfisols, Vertisols and Mollisols. Generally soils which in their natural state have hydromorphic properties, have the highest potential for methane production (Minami & Yagi 1988; Yagi et al. 1990; Kimura et al. 1991).

Conclusions

Many measurements of methane emissions from wetland rice fields are available. An important gap is the understanding of the process of methanogenesis and methane oxidation in soils at the field level. From the literature data presented in this paper, the positive effect of organic matter additions on CH_4 emission rates is apparent. Rice straw and other organic manures are important sources of N, P, K, S and other minor elements. These nutrients could also be supplied by mineral fertilizers. However, straw has other advantages: it is cheap and on the spot available, and in addition, it adds to the pool of soil organic matter and to its soil physical (structure restoration after drying of puddled soil) and chemical qualities.

The peak in methane emissions observed in the period when plants reach their reproductive stage is related to the high activity of the rice plants providing soil bacteria with organic root exudates or root litter (Holzapfel-Pschorn & Seiler 1986; Schütz et al. 1989; Minami & Yagi 1988; Yagi & Minami 1990). Varietal adaptation may offer possibilities to reduce emissions which could be rather easily implemented at farmers level, provided that rice yields are not affected or even increased.

The effects of mineral fertilizers on CH_4 emissions are not well understood. Sulphate, when incorporated in the soil, may suppress CH_4 emissions. To understand the effects of other types of fertilizers, such as urea and ammonium yielding fertilizers and of nitrification inhibitors, more research is required. Since the processes may differ between soil types, much attention has to be paid to the role of soil properties in the processes of methane formation/oxidation.

Intermittent drainage of rice fields to reduce methane emissions would only be practicable in flat irrigated systems with high levels of security and control of the water supply. Direct seeding as an alternative to transplanting to reduce the period of inundation is an option, but it may under certain circumstances have a number of important agro-economic disadvantages.

On the basis of the available data it is not clear to what extent methane emissions can be reduced by the various agronomic measures discussed. Moreover, it is not clear in how far these techniques influence production. Techniques to reduce emissions are only acceptable if they do not affect or increase paddy yields.

It has been hypothesized that methane emission rates per unit area of harvested rice may be decreased by 10—30% (EPA 1990) and this would result in a global emission in 2025 from wetland rice fields equal to the current emission. If, in addition to reductions of emission rates, no other policies to reduce this source are implemented, and if the other methane sources are not reduced, the current rise of 1% per year in atmospheric concentrations will be maintained or may even increase.

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Appendix. Methane emissions from various types of wetland rice fields and with different fertilizer treatments

Treatment (amounts of fertilizer per ha)	CH_4 ($g\,m^{-2}\,d^{-1}$)	Remarks	Country	Reference
No fertilizer				
Rice	0.27	sandy soil, 2.5% C	Italy	Holzapfel-Pschorn et al. (1986)
Unplanted	0.008–0.022	Typic pelludert, high clay	USA	Sass et al. (1990)
Unplanted	0–0.006	Entic pelludert, high clay	USA	Sass et al. (1990)
Unplanted	0.15	sandy soil, 2.5% C	Italy	Holzapfel-Pschorn et al. (1986)
Weeds	0.14	sandy soil, 2.5% C	Italy	Holzapfel-Pschorn et al. (1986)
	0.12–0.07	rice paddy, early stage	China	Khalil et al. (1990)
	0.38	wet soil	China	Khalil et al. (1990)
No nitrogen application	0.08–0.37	Gleysol; sandy clay loam; 1.4% C	Japan	Yagi & Minami (1990)
No fertilizer application (1984)	0.28	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
No fertilizer application (1983)	0.38	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
No nitrogen; 120 kg P_2O_5; 80+30 kg K_2O	0.03–0.12	humic Androsol; loam; 6% C	Japan	Yagi & Minami (1990)
No fertilizer application (1984)	0.16	Sandy soil, 2.5% C; plant-free	Italy	Schütz et al. (1989)
No fertilizer application (1984)	0.14	Sandy soil, 2.5% C; weeds	Italy	Schütz et al. (1989)
No fertilizer application (1984)	0.15	Sandy soil, 2.5% C; weeds	Italy	Schütz et al. (1989)
No fertilizer application (1986)	0.32	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
No fertilizer application (1985)	0.16	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
No fertilizer application	0.03		USA	Cicerone & Shetter (1981)
No fertilizer application	0.16–0.32	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
Mineral fertilizers				
50 kg N $(NH_4)_2SO_4$; incorporated	0.18	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
50+30 kg N; 120 kg P_2O_5; 80+30 kg K_2O	0.03–0.14	humic Andosol; loam; 6% C	Japan	Yagi & Minami (1990)
60+30 kg N as $(NH_4)_3PO_4$ + 60 kg P_2O_5 + 60+30 kg K_2O	0.07–0.32	Gleysol; sandy clay loam; 1.4% C	Japan	Yagi & Minami (1990)
100 kg N $(NH_4)_2SO_4$; incorporated	0.21	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
100 kg N as urea; raked into soil	0.23	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
70+30 kg N; 100 kg P_2O_5; 70+30 kg K_2O	0.00–0.01	Andosol; loam; 2.2% C	Japan	Yagi & Minami (1990)
120 kg N as $(NH_4)_3PO_4$	0	Andosol; 1st yr of flooding	Japan	Minami & Yagi (1988)
120 kg N as $(NH_4)_3PO_4$	0.00–0.02	Gleysol; 1st yr of flooding	Japan	Minami & Yagi (1988)
140 kg N as $(NH_4)_2SO_4$	0.15		USA	Cicerone & Shetter (1981)
$CaCN_2$ 0 to 140/200 kg N ha^{-1}	0.2–0.58	no fertilizer effect	Italy	Holzapfel-Pschorn & Seiler (1986)
160 kg N as urea + 40 kg N as $(NH_4)_3PO_4$	0.1	sulphate from seawater	Spain	Seiler et al. (1984)
200 kg N urea; incorporated	0.19	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as urea; surface applied	0.38	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as urea; raked into soil	0.23	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $CaCN_2$; raked into soil	0.1	Sandy soil, 2.5% C; plant-free	Italy	Schütz et al. (1989)

Appendix. Methane emissions from various types of wetland rice fields and with different fertilizer treatments

Treatment (amounts of fertilizer per ha)	CH_4 ($g\,m^{-2}\,d^{-1}$)	Remarks	Country	Reference
200 kg N as $CaCN_2$; raked into soil	0.3	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)_2SO_4$; raked into soil	0.16	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)_2SO_4$; incorporated	0.15	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)_2SO_4$; surface applied	0.3	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)_2SO_4$; incorporated	0.12	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
220 kg N as 16-20-0 $(NH_4)_3PO_4$-$(NH_4)_2SO_4$ + 113 kg N as urea	0.28		USA	Cicerone et al. (1983)
220 kg as 16-20-0 $(NH_4)_3PO_4$-$(NH_4)_2SO_4$ + 190 kg N as urea	0.22		USA	Cicerone et al. (1983)
39+59+51 kg N as urea after planting, prior to flooding, at panicle differentiation, resp.	0.19—0.23	Typic pelludert, high clay	USA	Sass et al. (1990)
39+59+51 kg N as urea after planting, prior to flooding, at panicle differentiation, resp.; addition 41 kg after ± 100 days	0.04—0.08	Entic pelludert, high clay	USA	Sass et al. (1990)
Organic fertilizers				
3 T rice straw incorporated	0.23	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
5 T rice straw incorporated	0.58	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
6 T rice straw incorporated	0.31	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
6 T rice straw incorporated	0.34	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
12 T rice straw incorporated	0.68	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
12 T rice straw incorporated	0.38	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
24 T rice straw incorporated	0.45	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
60 T compost incorporated	0.66	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
Mineral + organic fertilizers				
50+30 kg N* + 12 T compost; 120 kg P_2O_5; 80+30 kg K_2O	0.05—0.14	humic Andosol; loam; 6% C	Japan	Yagi & Minami (1990)
60+30 kg N* + 12 T compost; 60 kg P_2O_5; 60+30 kg K_2O	0.09—0.42	Gleysol; sandy clay loam; 1.4% C	Japan	Yagi & Minami (1990)
50+30 kg N* + 6 T straw; 120 kg P_2O_5; 80+30 kg K_2O	0.08—0.24	humic Andosol; loam; 6% C	Japan	Yagi & Minami (1990)
60+25 kg N* + 6 T straw; 60 kg P_2O_5; 60+25 kg K_2O	0.39—1.61	Peaty soil; clay loam	Japan	Yagi & Minami (1990)
60+30 kg N* + 6 T straw; 60 kg P_2O_5; 60+30 kg K_2O	0.23—0.78	Gleysol; sandy clay loam; 1.4% C	Japan	Yagi & Minami (1990)
70+30 kg N* + 6 T straw; 100 kg P_2O_5; 70+30 kg K_2O	0.00—0.02	Andosol; loam; 2.2% C	Japan	Yagi & Minami (1990)
50+30 kg N* + 9 T straw; 120 kg P_2O_5; 80+30 kg K_2O	0.10—0.21	humic Andosol; loam; 6% C	Japan	Yagi & Minami (1990)
37.5 kg N as $CaCN_2$ + 2.5 T straw	0.28	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
75 kg N as $CaCN_2$ + 5 T straw	0.43	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)SO_4$ + 12 T straw	0.52	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as $(NH_4)SO_4$ + 12 T straw	0.47	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as urea + 6 T straw	0.48	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)
200 kg N as urea + 6 T straw	0.6	Sandy soil, 2.5% C	Italy	Schütz et al. (1989)

* as $(NH_4)_3PO_4$