Wastewater Use in Irrigated Rice Production – a Case Study from the Red River Delta, Vietnam

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Introduction

Wastewater use in irrigated crop production is a highly complex issue, with opportunities and risks and agronomic, economic, ethical and human and ecosystem health dimensions. Wastewater influenced production systems are characterised by an enormous variability in bio-physical and socio-economic conditions and the true complexity is generally poorly understood except for a few reported case studies (eg., Scott et al., 2003). Recognising as a preamble that the agronomic dimension of soil, water and crop management is crucial for understanding and optimizing wastewater irrigation, this study focuses on agronomic aspects of wastewater influenced irrigated rice production systems in Vietnam where wastewater influenced irrigation is common.

From an agronomic perspective, wastewater irrigation represents an opportunity for accessing "free" nutrients which if realised contribute towards the interrelated objectives of productivity maximization, nutrient capture and wastewater reclamation and reuse. However, there are also risks of toxicities and soil degradation, and the nutrient content of wastewater may be unknown to the farmer, excessive and out of balance with changing crop demands. The realization of the nutrient opportunity is therefore constrained by fundamental difficulties and depends on the effectiveness of the overall nutrient management practices combining all major nutrient sources: soil, farm yard manure, inorganic fertilizer and wastewater. However, although integrated nutrient management also for wetland rice has developed considerably in recent years with a focus on site specific nutrient management (eg., Dobermann et al., 2002), the more complex case of wastewater irrigation as a dimension of site specificity has not been analysed. Currently, farmers' management practices and recommendations of advisory services in wastewater influenced areas are therefore likely to be formulated in a partial knowledge vacuum and to reflect more traditional practices in non-wastewater areas which may not be appropriate for wastewater conditions.

The objective of this study is to contribute to the development of a framework for optimising and sustaining overall benefits of peri-urban wastewater irrigation, by describing and analysing the agronomic dimensions of a wastewater irrigated rice production system emphasising on biomass production and nutrient utilization and balances for assessment of nutrient management strategies and wastewater assimilation capacity. A brief summary of the main results are presented with further details in Jensen (2005) and Jensen et al. (2006).

Methods

The study area comprised of 3 sites close to the city of Nam Dinh located in the lower part of the Red River Delta. Field investigations took place during May 2003 – June 2005, with an emphasis on the Spring Crop period, when the field water balance is mainly determined by irrigation water

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management practices, and on nitrogen. A diagnostic analysis of rice production systems were undertaken at three sites contrasting in irrigation water quality and degree of wastewater influence. The field work was mainly of the survey and monitoring type, sampling soil and crop in farmers' fields followed by standard soil and crop laboratory analyses supplemented with farmer interviews. In addition, dedicated experiments were undertaken in 2004 and 2005 with fertilizer omission sub-plots within farmers' plots to evaluate nutrient uptakes and fertilizer practices in more detail. The word fertilizer is in the following used synonymously with inorganic fertlizer.

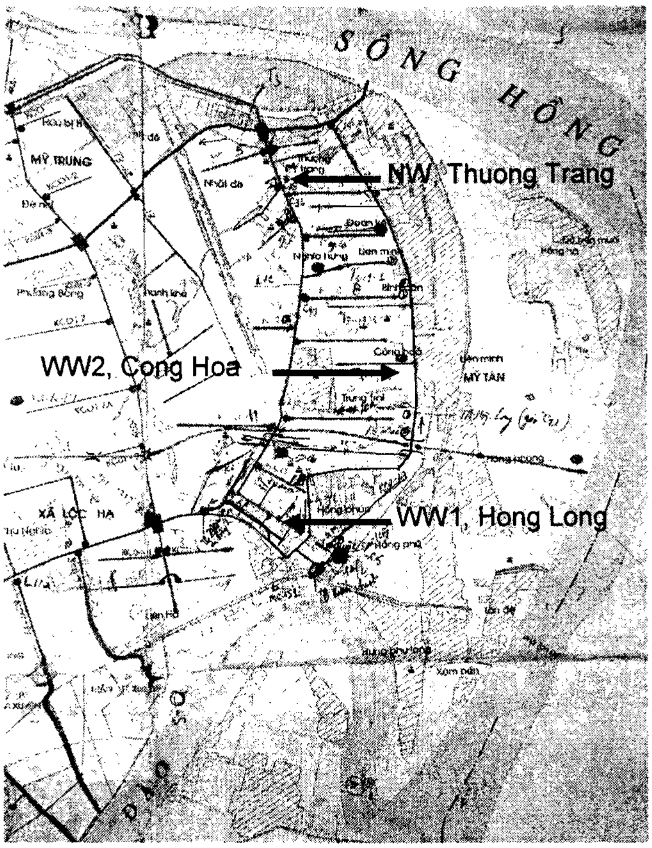

Fig. 1. Location map, Nam Dinh. (Red, irrigation; blue, drainage; Song Hong, Red River).

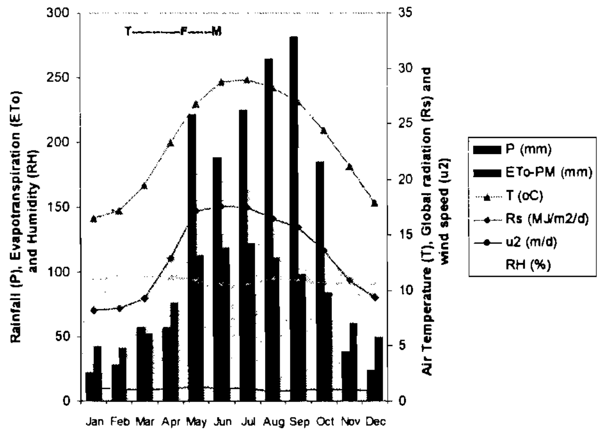

Fig. 2. Climograph, Nam Dinh. Spring crop schedule indicated (T, transplanting; F, flowering; M, maturity) (From Jensen, 2005).

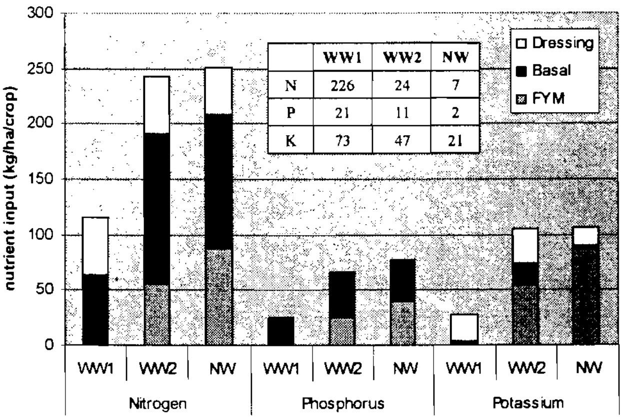

Fig. 3. Nutrient inputs (kg/ha) in Spring Crop by farmer (average) and wastewater (table, median irrigation).

Case study sites: The 3 sub-scheme areas investigated (Fig. 1) cover rice irrigation using raw domestic wastewater (WW1), diluted drainage cum wastewater (WW2) and river water (NW) respectively. **WW1**, Hong Long cooperative served by the Quan Chuot pumping station delivering raw municipal wastewater, with field investigations mainly in a 20 ha area along the main canal. The irrigation distribution practice may be characterised as simultaneous as the entire scheme is irrigated on each irrigation event. **WW2,** Cong Hoa in Tan Tien cooperative 1.5 km north of WW1, served by the Cong Hoa pumping station delivering water from the main drainage canal. The drain water is a mix of diluted wastewater, area wide field runoff and groundwater. Some river water may have entered the drainage canal in early 2005 as a result of sand pumping for land development in a nearby area. The water distribution practice in the scheme is rotational with different sections irrigated on different days, and the agronomic field studies took place mainly in sections 5A (~ 25 ha) and 5B (~ 13 ha) located along the lower part of the main irrigation canal of the scheme. **NW**, Thuong Trang hamlet in Tan Tien cooperative, 1.5 km north of WW2 and adjacent to the main canal of an irrigation scheme served by a pump station delivering water from the Red River upstream of the Nam Dinh city drainage canal outlets.

The climate is sub-tropical with a main rainy season from May to October, year round high humidity and low wind speed, and relatively low global radiation and air temperature during Nov – Mar (Fig. 2). The typical cropping pattern in the prevailing heavy textured alluvial soils is double cropping of wetland rice with a main Spring Crop (Feb-Jun) and a Summer Crop (Jul-Oct). The climatic conditions during the experimental period may be summarised relative to the long term average condition as (with the probability of exceedance for rainfall in parantheses): **2003**, high global radiation and air temperature, low rainfall (88 %), high irrigation requirement; **2004**, low global radiation after flowering and near normal air temperature, high rainfall (22 %), low irrigation requirement; and **2005**, low global radiation, air temperature low during vegetative period but relatively high after flowering, low rainfall (95 %), high irrigation requirement Thus, the experimental data covers both very dry and relatively wet spring seasons.

The alluvial soil profiles are located in the middle of the Red River Delta and derived from river alluvium and categorised as Luvisols (FAO-UNESCO-WRB) or Entisols (USDA). WW1 is a Low Flat location and classified in the suborder Aquent because of a more permanent saturation and reduced matrix in the subsoil. WW2 is a Lower Flat position with a classification indicating that soil saturation is more common here than at the NW site in a High Flat position, reflecting the topographically relatively higher position of NW probably with a more effective internal and surface drainage.

Field experiments: Grid Surveys with a spatial resolution of 50 x 50 m for top soil and crop (1 m^2) sampling were undertaken in June 2003 (WW1, n=41; NW, n=12) and June 2005 (WW2, n=32) with the sample points in WW1 and WW2 spaced along the main irrigation canals. In addition, a number of farmers' plots were selected in each season and scheme for more detailed biomass sampling (transplanting, DAT 40, flowering, and harvest (20 hills)). Soil samples were routinely analysed for pH(H_2O), EC(1:5), C-organic, N-total, and available P and NO_3 , at times supplemented by texture and more detailed soil chemical analyses. Crop samples were analysed for dry matter and N, P and K content of above ground biomass components using standard method. Fertilizer omission sub-plots (-F; IRRI, 2004) were implemented in selected farmers' plots (+F) in 2004 (WW1 and NW) and 2005 (WW2 and NW). The only difference between –F and +F was the inorganic fertilizer application, with zero in –F and according to farmers' practice in +F. Thus, if the farmer used farm yard manure (FYM) in his plot FYM would also be incorporated in the –F sub-plot area.

The irrigation water quality was reported for WW1 in 2004 by DHI (2005; unfortunately excluding organic N forms), and for WW2 and NW in 2005 by Jensen et al. (2006). The water samples in WW1 were taken in the main irrigation canal during irrigations at land preparation (16 Jan 04) and after transplanting (22 Mar 04), while the samples in WW2 and NW were taken 3 places in the main irrigation canal on the day after irrigation at land preparation (18 Feb 05), 40 days after transplanting (08 Apr 05) and at flowering (14 may 05). The seasonal inputs of elemental N, P and K (Fig. 3) were estimated from average concentrations and simulated irrigation deliveries during land preparation and field crop periods. Clearly, these numbers are associated with a considerable uncertainty as also discussed in Jensen and Tuan (2006; this issue). The BOD and COD values were high in WW1 and in excess of a critical level for decreasing rice yields found in a Japanese experiment with wood pulp wastewater (cited in EPA, 1980).

Results and Discussion

Nutrient inputs: Nutrient inputs and other management practices were estimated from farmer interviews (Fig. 3). The data illustrate the generally high level of nutrient inputs including FYM used by farmers in the Red River Delta. The nutrient input practices were quite similar in NW and WW2 whereas in WW1 the dosage of fertilizer was less and of FYM nearly zero. Basal applications are very high, especially in NW and WW2, and only one or two splits are used. Adding farmer and wastewater inputs (Fig. 3), the nutrient input level in WW1 becomes very high at eg., about 350 kg-N/ha/crop, even when excluding the likely substantial organic N input which was not measured in WW1. Generally, nutrient inputs are poorly coordinated, without considerations for the complementarity between nutrient sources (FYM, fertilizer, wastewater, soil) and plot specific requirements.

Soil characteristics: Wastewater irrigation is likely to have influenced soil characteristics, although this investigation can not conclusively distinguish the influence of soil genesis and water management on soil properties. The soil surveys in 2003 revealed highly significant differences between WW1 and NW, with soil pH lower in WW1 (5.4 v. 5.7) and with WW1 having higher levels of: soil organic Carbon (2.3 v. 1.7, %), high compared with normal expectations for alluvial soils in the Red River Delta (Bo et al., 2003; Son et al., 2005); total Nitrogen (about 0.3 v. 0.2, %); Electrical Conductivity (1.6 v. 0.5 cS/m); and exchangeable Na^+ (0.76 v. 0.27, cmol+/kg). The data remains to be finally analysed, but the C-org. and N-tot. seem also very high in WW2. The soil chemical differences probably reflect accumulation of wastewater related inputs in WW1 and WW2 of organic matter and electrolytes including sodium, although the topographically lower position of WW1 and WW2 could also explain higher concentrations of organic matter because of spatially variable sedimentation during soil formation. A considerable spatial variability in soil properties was found in WW1. Summarising on soil fertility and combining the data from the various soil surveys of this study with the critical values for available nutrients suggested by Bo et al. (2003), it appears that the main soil nutrient limitations are K (all sites) and N at NW. The EC-level suggests a mild salinity stress at early vegetative growth in WW1, potentially with yield implications, and the relatively high Na in WW1 could adversely influence K-uptake.

Rice crop development: The main varieties grown in the area are Tap Giao (hybrid) and Khang Dan (inbred) and varietal differences have not been found in this study (which was not designed to consider this factor either). The typical crop development pattern in terms of days after transplanting (DAT) was: seeding, -16, flowering 76 and harvest 107. However, the field duration (i.e., days from transplanting to harvest) was significantly longer in wastewater sites than in the NW site, on average by 7 days in 2003 (WW1; prolonged ripening), 10 days in 2004 (WW1; delayed flowering) and 6 days in 2005 (WW2; delayed flowering). On average, the field duration was significantly ($P < 0.001$) longer by 8 days in wastewater areas. This is in accordance with farmers' general perception on the differences between wastewater and non-wastewater areas. This is likely induced by a combination of the high N-availability in wastewater areas promoting vegetative growth and the wetter hydrological regime in WW1 and WW2 delaying maturation.

Rice crop biomass components: Analysing differences at the level of grain, panicle, hill and unit field area, a number of statistical significant differences between WW1 and NW emerge: The hill density in WW1 (44/m^2) was 14 % lower but with similar number of panicles per hill; grain moisture-% and filled grain weight were higher in WW1; number of filled grain per panicle was smaller in WW1; weight of filled grain per hill was similar, but number of filled grain per hill was smaller in WW1 while straw weight per hill was higher in WW1; and the harvest index and grain yield were smaller in WW1 but total dry matter yield was nearly similar. These differences can not conclusively be ascribed to wastewater effects although several of the differences observed could probably be explained by the well-known N-induced excessive vegetative growth in WW1 and the likely associated higher pest pressure. However, the differences in planting density and field wetness may mask wastewater quality effects.

Table 1. Yields of grain and straw (dry matter, Mg/ha; Y_G, grain; Y_S, straw; Y_B, total above ground biomass; HI = Y_G/Y_B, harvest index; P, t-test probability; Plot grain and straw yields in Sp-03 are probably erroneous).

Crop survey		site	n	Y_G	P	Y_S	P	Y_B	P	*HI*	P
Sp-03	Grid	NW	12	6.9	0.009	5.9	0.590	12.8	0.366	0.54	0.038
		WW1	41	5.9		6.2		12.1		0.49	
	Plots	NW	4	9.2	0.926	9.1	0.585	18.3	0.749	0.51	0.381
		WW1	8	9.3		8.1		17.4		0.54	
Sp-04	Plots	NW	4	8.4	0.012	6.8	0.015	15.2	0.996	0.56	0.000
		WW1	9	6.2		9.0		15.2		0.41	
Sp-05	Plot	NW	6	8.5	0.199	8.2	0.157	16.6	0.619	0.52	0.014
		WW2	12	7.8		9.5		17.3		0.45	
	Grid	WW2	32	6.6		7.6		14.1		0.46	
Su-03	Plots	NW	2	5.3	n.a.	8.5	n.a.	13.8	n.a.	0.38	n.a.
		WW1	4	5.1		10.7		15.8		0.32	

Grain yields in the Spring Crop (Table 1) were apparently similar at NW and WW2 but higher in NW than in WW1 by 17 % (2003) and 35 % (2004), on average by 26 %. The yield of the summer crops were similar but as expected lower than that of the Spring Crop (on average 50 % for the NW site). The total biomass was generally not different so the harvest index (HI) was on average significantly higher in NW as compared with WW1 (23 %) and WW2 (14 %). It is noted that the mass of filled grain per hill was not different, suggesting that differences in hill density may explain (part of) the difference in yield. Peters and Ngai (2004) found a considerable yield response to plant density in a wastewater irrigated rice system with a highest yield at a plant density of 60 hills/m^2.

Nutrient concentrations in biomass: Nutrient concentrations were generally lower in NW than in wastewater areas. The median grain N-concentration from the grid surveys was highest in WW1: 1.53 % (WW1), 1.39 % (WW2) and 1.11 % (NW), implying a 40 % higher protein content in the grain from the raw wastewater area than in the non-wastewater area. This has potential implications for child nutrition and health. Similarly, the N content of straw is higher in WW-areas with implications for the value as animal fodder and as crop residue for composting. The time course of biomass nutrient concentrations, when compared with generally accepted critical levels, tentatively indicate that N-deficiency occurred at flowering and P-deficiency at panicle initiation in WW2 and NW, whereas K-deficiency only occurred in –F plots of NW. The apparent N deficiency at flowering – if real – implies that short-term nutrient deficiencies may occur even in wastewater systems with a high nutrient load and that there is scope for improved fertilizer scheduling with increased split applications. The apparent P- and K-deficiencies may have been induced by inadequate P and K supply in combination with N excess.

Fertilizer response and use efficiencies: Grain yield responded to fertilizer input in NW, but there was a clear lack of response to fertilizer at the two wastewater influenced sites WW1 and WW2 (Table 2) implying that a considerable underutilization and waste of fertilizers must be taking place at the wastewater sites. The yields without fertilizer are quite high and indicate a considerable "indigenous" (i.e., non-fertilizer) source of plant available nutrients (Table 3).

Table 2. Grain yield response to fertilizer
(-F, fertilizer omission sub-plots; +F, farmers fertilizer input; standard deviation in ()).

crop	Site	n	*Yg* (Mg/ha)		paired t-test
			-F	+F	P(T<=t)
Sp-04	NW	4	7.0 (1.2)	8.4 (1.0)	0.014
	WW1	3	6.5 (2.1)	6.0 (1.7)	0.463
Sp-05	NW	6	6.6 (0.9)	8.5 (1.0)	0.004
	WW2	5	7.7 (0.4)	7.7 (1.1)	0.490

The level of indigenous supply is by Asian standards classified as very high ($N_I > 50$ kg/ha) and the high values in WW1 and WW2 highlights the potential importance of wastewater nutrient inputs. The main sources were in 2004 FYM and soil in NW and wastewater and soil in WW1, and in 2005 FYM and soil in NW and FYM, wastewater and soil in WW2. The indigenous supply in NW and WW2 appear to be proportional to the content of soil organic Carbon (at transplanting) as also found by Dobermann et al. (2003) for their Hanoi site.

Table 3. Nutrient uptake from indigenous (i.e. non-fertilizer) sources in –F plots.

Year	site	Nitrogen		Phosphorus		Potassium	
		N_I (kg/ha)	c.v. (%)	P_I (kg/ha)	c.v. (%)	K_I (kg/ha)	c.v. (%)
2004	NW	86	15	18	16	107	12
	WW1	154	10	30	13	201	13
2005	NW	108	10	20	12	124	10
	WW2	166	12	29	25	147	18

Nitrogen use efficiency indicators may be defined as: e_A, agronomic efficiency (additional grain yield due to fertilizer input relative to zero-fertilizer); and e_F, apparent fertilizer recovery (increased N uptake relative to zero-fertilizer crop as a percentage of applied N fertilizer). Obviously, the e_A for WW1 and WW2 was close to zero but on average about 10 kg-grain/kg-Nfertilizer for NW, slightly lower than the typical value under farmers' conditions in Asia. The agronomic efficiency could be about 20 to 30 kg/kg in a well managed system, and the low value observed indicates a waste of nutrients through a combination of poor synchrony in demand and supply, excess application, high indigenous supply and considerable losses of applied N to the environment. The apparent N-fertilizer recovery was extremely poor in WW1 (only 7 % of 120 kg-N/ha applied in 2004), whereas the recovery was about 20 to 35 % in NW and WW2 (Asian average of ~ 30 %;

Cassman et al., 2002) which is low compared with a well-managed system where at least 40 to 50 % recovery should be possible.

Nutrient balances: Two forms of input–output nutrient balances are calculated (with N as an example): N-bal, including farmer managed inputs (N in FYM, N_{FYM} and in fertilizer, N_F) and outputs (N in crop harvest, N_C); and N-Tbal, including also wastewater inputs (N_{WW}). The balances are partial, disregarding eg., atmospheric inputs:

Farmer balance, N-bal: $N_{bal} = (N_{FYM} + N_F) - N_C$ kg-N/ha (1)

Total balance, N-Tbal: $N_{Tbal} = N_{bal} + N_{WW}$ kg-N/ha (2)

The average nutrient balances for the Spring Crop are summarised in Table 4, with a considerable variation among the sites and among farmers/plots within sites with a typical range of say +/- 100 kg-N/ha (Fig. 4). The balance implies where positive an accumulation and/or losses in/from the root zone, and where negative a soil depletion and/or supply from non-soil sources not considered by the balance. The 3 sites have positive N balances, especially when also including wastewater inputs, and imply N excesses and likely substantial losses with economic and environmental implications (eg., denitrification, leaching etc.). The potential value of the wastewater input is highlighted when comparing farmer and total balances, but soil K reserves are likely to be depleted widely and particularly in WW1.

Table 4. Spring crop average nutrient balances, farmer and total (ref text; kg/ha).

Site	Nitrogen		Phosphorus		Potassium	
	N-bal	N-Tbal	P-bal	P-Tbal	K-bal	K-Tbal
WW1	-83	143	-10	11	-152	-79
WW2	57	81	41	52	-60	-13
NW	96	103	37	39	-37	-16

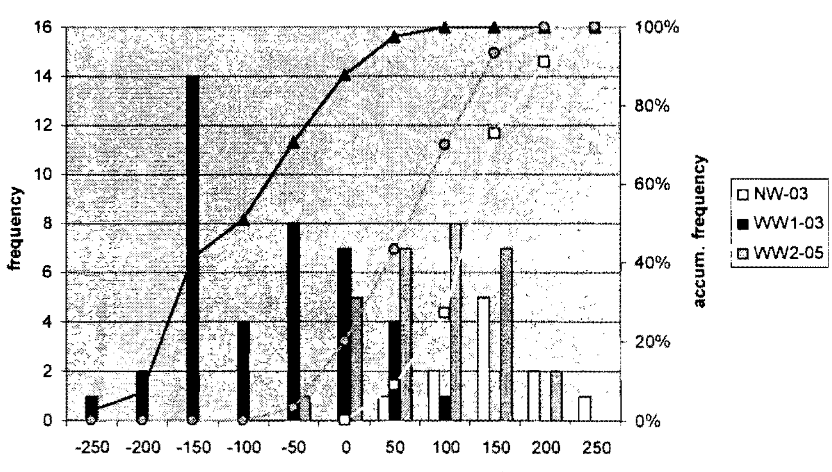

Fig. 4. Distribution of farmer N balances in grid and plot surveys 2003 (NW and WW1) and 2005 (WW2).

Improved nutrient management: The results imply a considerable scope for improving the nutrient management in the schemes studied. Thus, N fertilizer inputs should be reduced considerably in the wastewater influenced areas and the timing of N fertilizer application should be improved in all areas. The very high basal applications should be discouraged in view of the substantial supply/uptake from non-fertilizer sources and split application techniques should be more widely adopted. An improved typical N-fertilizer practice is tentatively suggested for the NW site in Fig. 5, comparing farmers' practices with general recommendations emanating from The International Rice Research Institute (IRRI) when considering also indigenous N supply (assuming optimal management, a yield target of 9 ton/ha at 40 kg-N per ton yield more than –F yield, and no basal application as indigenous supply is high; hybrid may need basal (~20%) and higher N_F). Apparently, the total application may on average be reduced to nearly 50 % of the current average, mainly by omitting the basal application, and N dressings should be given as 3 to 4 splits during vegetative and early reproductive periods.

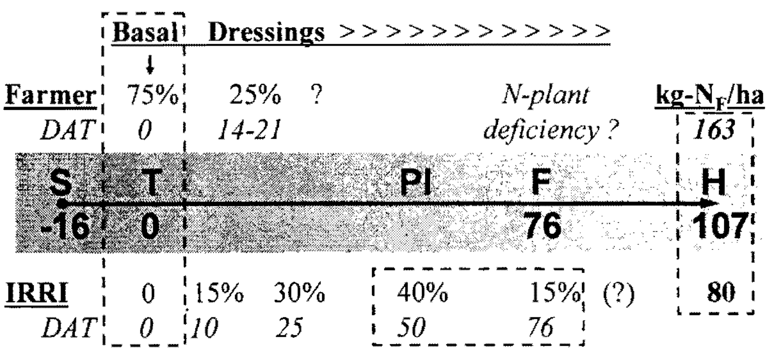

Fig. 5. Average N-fertilizer inputs by farners in non-wastewater area (NW) from transplanting (T) to harvest (H) compared with "best practice" (IRRI, ref text).

Wastewater assimilation capacity: Assessing the performance of the wastewater irrigation system as a wastewater reclamation activity is difficult, as the origin of the nutrients taken up by the crop or lost to the environment is not known. However, assuming that typically 50 % of the N taken up by the rice crop originates from soil resources (possibly enhanced by long term accumulation of wastewater inputs), the data for WW1 2004 indicates that a maximum of about 40 % of the N input from the wastewater may be assimilated by the rice crop under zero-fertilizer conditions, while only about 25 % would be recovered by the crop under high inputs of N fertilizer as currently practised (+F). Furthermore, considering that organic N-forms were unfortunately not measured in WW1, the real recovery is likely to be considerably less.

Thus, farmers' practices and soil N resources are the main factors currently limiting the recovery of wastewater Nitrogen by the crop to < 25 %. However, there appears to be a scope for improving the recovery of nutrients in the wastewater through a combination of reduced nitrogen inputs and increased planting density. Furthermore, this is likely to result in improved yields and profitability.

Conclusion and Perspective

Wastewater irrigation with high levels of nutrients influences the rice crop in several ways. Under the conditions studied, the high nutrient loads – especially nitrogen – enhance vegetative growth, delay crop development and reduce the economic fraction (grain yield) of the total biomass produced. Furthermore, a considerable plant available nutrient reserve is probably accumulating in the soil. The nitrogen excess in the wastewater irrigated areas results in high N concentrations in the grain and the protein content is consequently considerable higher than in conventionally irrigated rice. This has positive implications for child nutrition and health.

The study reveals a high level of inefficiency and nutrient waste under farmers' practices. There was no yield response to farmers' fertilizer inputs in the two wastewater influenced areas studied. Furthermore, nutrient inputs from various sources – soil, water, organic and inorganic fertilizers – are not seen as complementary, and wastewater as well as non-wastewater systems are characterised by excess and poorly timed N fertilizer applications under conditions of high indigenous nutrient supply resulting in a very low recovery of applied nitrogen. There is a significant scope – also in the non-wastewater area – for reducing and improving the timing of nitrogen inputs, with implications for financial and environmental sustainability and wastewater assimilation capacity. Currently, if seen from a wastewater reclamation perspective, the efficiency of the raw wastewater irrigated system is environmentally unattractive with a recovery of wastewater N by the rice crop of less than 25 %.

The study demonstrates that appropriate field level nutrient management is the key to enhance and sustain both economic and environmental benefits of wastewater influenced irrigation. While recognising that farmers and sites differ considerably in crop management and environmental conditions and that site and farmer specific solutions are needed, recommendations for specific actions in the studied areas include: (i) reduce N fertilizer inputs in wastewater influenced areas and improve the synchrony between crop demand and N supply with split applications especially in the reproductive period; (ii) reduce/cancel the substantial basal applications of N fertilizer which are likely not needed in view of the high uptake from non-fertilizer sources (FYM, soil and irrigation water); (iii) increase the K fertilizer input to improve K nutrition of the crop and avoid long term depletion of soil K; and (iv) increase the hill density in the raw wastewater area (WW1) to improve productivity and assimilation capacity. Additional simple field tests by farmers and advisory services may be needed to support the implementation of these recommendations.

In a wider perspective, the study brings out a fundamental scientific and management challenge for farmers, advisory services, water managers and agricultural scientists: to develop and apply integrated nutrient management principles and practices specific for wastewater influenced conditions. Synchronizing nutrient supply and availability with crop demands is a fundamental objective of farmers, and established principles and practices of plant nutrition and fertilizer management focus on alleviating nutrient deficiencies assuming that farmers may be in full control over inputs. However, wastewater influenced production systems are generally characterised by externally imposed asynchrony with temporal nutrient excesses and unbalances partly beyond the control of farmers. Established principles and practices of nutrient management – and of the interrelated field level water management – should therefore be more rigorously reanalysed in the context of wastewater irrigation to enable farmers to cope more optimally with wastewater situations.

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