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Long-term effects of lowland *sawah* system on soil physicochemical properties and rice yield in Ashanti Region of Ghana

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Abstract

Lowland *sawah* is viewed as a sustainable alternative to traditional rice culture in West Africa. *Sawah* (a bund-demarcated, puddled, leveled, and water-regulated rice field) has received growing research attention lately, but no data exist yet on the system's long-term agronomic impact. In a clayey inland-valley soil in southern Ghana, 10-year-old *sawah* plots (OSP), fresh *sawah* plots (FSP), and non-*sawah* plots (NSP) were maintained under both ponded and non-ponded conditions in 2007. The OSP enhanced soil status of exchangeable nutrients compared to NSP. There were relative improvements in soil bulk density, total porosity, and field moisture content (OSP ≥ FSP > NSP), with clear benefits of ponding over non-ponding in OSP. The NSP was so unsustainable that it showed less favourable values of these variables than an adjacent fallowed plot. These soil variables deteriorated with time, with significant differences in FSP. Soil moisture retention data for tension range of 0-300 kPa depicted the importance of puddling and ponding. During 2001-2009, OSP consistently out-yielded NSP by five times on average. During 2007-2009 when all three plots co-existed, grain yields averaged 5.80, 4.80 and 1.10 Mg ha^{-1} in OSP, FSP and NSP, respectively. In 2007 yields, OSP minus FSP was higher than NSP; in 2008/2009, the opposite prevailed. These results highlight the agronomic benefits of continuous *sawah*-based rice production. Although the positive effects of puddling on the soil hydrophysical properties were largely responsible for the wide margin in yield between *sawah* and traditional systems, other yield-enhancing factors, particularly bunds for water control, were also lacking in the latter.

Additional key words: age of *sawah*; moisture retention; *Oryza sativa*; ponded *sawah* plot; rice grain yield; seasonal puddling; soil bulk density.

Resumen

Efectos a largo plazo de las tierras bajas del sistema *Sawah* en la región Ashanti de Ghana sobre las propiedades fisicoquímicas del suelo y el rendimiento del arroz

Las tierras bajas del *sawah* (campos de arroz encharcados y delimitados por lomos de inundación, dotados de una buena nivelación del terreno y regulación del agua) constituyen una alternativa sostenible al sistema tradicional de producción de arroz en África Occidental. El *sawah* ha despertado una creciente atención, pero aún no existen datos concretos sobre su impacto agronómico a largo plazo. En el año 2007, bajo un suelo arcilloso de valle interior, se llevaron a cabo unos ensayos de cultivo de arroz tanto bajo condiciones de inundación permanente como temporal, para comparar parcelas de *sawah* de 10 años de antigüedad (OSP) con otras de nueva implantación de *sawah* (FSP) y con parcelas no sometidas al *sawah* (NSP). Se observó un incremento de la fertilidad del suelo bajo OSP en comparación con NSP. Otras propiedades del suelo, como densidad aparente, porosidad total y contenido de agua a capacidad de campo mostraron únicamente mejoras relativas (OSP ≥ FSP> NSP), indicando los beneficios derivados del encharcamiento sólo en OSP. En NSP se obtuvieron peores resultados que en el caso de los barbechos adyacentes. En FSP,

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Abbreviations used: FSP (fresh *sawah* plot); NERICA (New Rice for Africa); NSP (non-*sawah* plot); OSP (old *sawah* plot); SOC (soil organic carbon); WARDA (West Africa Rice Development Association).

los atributos de suelos analizados presentaron diferencias significativas con el tiempo. El contenido de humedad alcanzado a la tensión 0-300 kPa expresa la importancia de la práctica de la inundación y del establecimiento de lomos en la delimitación de las parcelas. Entre 2001 y 2009, la producción de arroz en OSP fue 5 veces mayor que en NSP. Entre 2007 y 2009, cuando los tres sistemas coexistieron, la producción de grano fue 5,80, 4,80 y 1,10 Mg ha^{-1} en OSP, FSP y NSP, respectivamente. En 2007 la producción fue OSP menos FSP >NSP. Sin embargo, en 2008/2009 resultó al contrario. Estos resultados ponen de manifiesto las ventajas agronómicas del *sawah* en la producción de arroz.

Palabras clave adicionales: densidad aparente del suelo; edad del *sawah*; encharcamiento estacional; *Oryza sativa*; parcelas estancadas de *sawah*, rendimiento del grano de arroz; retención de humedad.

Introduction

According to FAO (2007), paddy production in Africa has gone up for the sixth consecutive year, reaching 21.6 million tons in 2006, 6% above the 2005 total. The FAO (2007) attributes the progress in West Africa to favourable weather conditions and to the positive signs of the adoption of NERICA (New Rice for Africa) varieties developed by the AfricaRice (formerly WARDA – West Africa Rice Development Association). The share of total rice (*Oryza sativa* L.) area in rainfed lowlands in West Africa is put at 38%, and this share is rapidly increasing (WARDA, 2008). It has been shown that the use of high-yielding varieties in these promising lowlands (that are more suited for rice growth than the uplands) without the appropriate ecological engineering offered by the *sawah* technology cannot alone sustain high yields of rice (Wakatsuki *et al.*, 1998, 2005; Wakatsuki & Masunaga, 2005). The term *sawah* is of Indonesian origin but has been adopted in West Africa as corresponding to paddy in Asia. *Sawah* refers to a bunded, puddled and levelled rice field, with inlets and outlets for irrigation and drainage, respectively. Advances have been made in adapting this technology to the peculiarities of West African lowlands, where site-specific management strategies are largely absent. Since its introduction, this technology has been gaining popularity in West Africa, especially in Ghana and Nigeria.

Although the *sawah* system equally has as one of its working hypothesis the use of high yielding varieties, the ecological engineering aspect of the technology is another major factor whose contribution to the system's performance may surpass that of improved rice varieties. This basically involves soil puddling, using a hand-operated power tiller. Apart from assisting in weed control and facilitating transplanting operations, the major agronomic benefits of puddling include reduction in water infiltration and percolation rates in a paddy field and enhancement of yield (Kirchhof & So, 1996; Singh *et al.*, 2001). Puddling aims at completely destroying the soil structure under a saturated field condition, thereby reducing the soil hydraulic conductivity so as to enhance water retention. Normally, the macropores are reduced, but the total porosity of puddled soils is either enhanced or not affected or slightly decreased due to an increase in micropores (Sharma & Bhagat, 1993; Bhagat, 2003). The operation is accompanied by settling down of the soil particles at a speed commensurate with their relative density, such that the less dense particles occupy the topsoil, resulting in a reduced bulk density. Rice is such sensitive to especially topsoil compactibility that the crop's field performance has been shown to have a direct relationship with the soil bulk density (Kirchhof *et al.*, 2000; Bockari-Gevao *et al.*, 2006; Kukal *et al.*, 2008).

The little available information from Nigeria on the effects of puddling on bulk density, total porosity and moisture content of lowland soils at rice harvest show that these soil properties can be similar for puddled and non-puddled plots, or deteriorated in the latter compared to the former (Lal, 1986; Ogunremi *et al.*, 1986). In terms of grain yield, Lal (1986) concluded after a six-year trial that puddling may not be necessary for soils with relatively high clay content. Ogunremi *et al.* (1986), on the other hand, also found no differences in yield between puddled and no-till sandy-loam soil. However, Sharma & Bhagat (1993) reported from India that puddling was effective for reducing water percolation to levels suitable for growing a good rice crop in soils with < 70% sand. The reduction in percolation rate in such soils is of utmost importance if they are permeable and occur in areas with scanty rainfall during the growing season, with the water table remaining well below the soil surface (Kirchhof *et al.*, 2000). All these literature views tend to suggest that the reduction in deep percolation losses in rice fields due to puddling and the associated enhancement of soil moisture and yields are confined to specific textural and hydrological scenarios.

Apart from not conforming to any specific textural attribute, West African lowlands exhibit diverse hydrological conditions. Yet, the *sawah* technology enhances rice yield under such scenarios in the region (Asubonteng *et al.*, 2001; Buri *et al.*, 2008; Nwite *et al.*, 2008). Attempts to edaphologically explain such yield benefits due to the *sawah* system focused only on other beneficial attributes of the system, such as enhancement of soil chemical and fertility properties and good water control (Nwite *et al.*, 2008; Issaka *et al.*, 2009). It has been shown under Asian conditions that paddy soils exhibit a dynamic soil-water system which is driven by puddling, duration of ponding, and age of the paddy (Lennart *et al.*, 2009), but such has yet to be checked for the increasingly popular *sawah* system in West Africa.

The soil puddling aspect of the lowland *sawah* ecotechnology, as well as its submergence (water ponding) aspect, is needed to improve the soil hydrophysical condition for the rice crop. Puddling destroys the soil structure, but instantly lowers (improves) the soil structural index of bulk density, the extent of which is often a test of puddling efficacy. The yield response of *sawah* rice to continuous application of this soil structure-deteriorating puddling is not known. Information is thus needed on the effects of continuous *sawah* system not just on soil fertility but also on soil hydrophysical properties (under both ponded and non-ponded conditions) and rice yield. No other study has been undertaken in this regard in any part of West Africa. This paper reports the effects of 10 consecutive years of the lowland *sawah* system on selected soil fertility parameters, bulk density, total porosity, moisture retention, and rice grain yield.

Material and methods

Location and characteristics of the study area

The study was conducted at Adugyama in the Ahafo-Ano South District of the Ashanti Region of Ghana. The area falls within the semi-deciduous agro-ecological zone of Ghana, and is located at latitude 6°53'N and longitude 1°52'W. It is on an altitude of about 270 m above sea level. Detailed characteristics of the natural environment (including the soil) at the initiation of the study have been reported elsewhere (Wakatsuki *et al.*, 2001). In summary, mean seasonal annual rainfall is about 1,350 mm, with a bimodal distribution pattern. About 75% of this occurs during the major sub-season, usually between March and mid July with the peak in June; the rest occurs in the minor sub-season, between late September and November. The mean monthly temperature is about 26°C whereas the range for daily relative humidity is 63-88% during the cropping season. The soil in the study site, a hydromorphic inland-valley bottom for rice production on a mean slope of 0.5%, is classified as a Eutric Gleysol in the FAO system. By the mean particle size distribution (sand-35%, silt-37%, clay-28%) in the topsoil, the soil is a clay loam in the USDA classification system. The depth of water table fluctuates between the surface level and 25 cm soil depth from June to November, after which it falls gradually to sometimes a depth of about 150 cm in January.

Field operations

The *sawah* system of rice cultivation involves bunding, as well as soil puddling and levelling of the plot, which are not done in the traditional system. The study was initiated in 1998 and continued till 2009. By 2007, three plots differing in *sawah* and puddling status coexisted in the site: i) a 10-year old *sawah*-rice field, referred to as old *sawah* plot (OSP); ii) a newly established *sawah* field, referred to as fresh *sawah* plot (FSP); and iii) a traditional farmer-managed rice field, referred to as non-*sawah* plot (NSP).

The plots were contiguous in the order they were listed. Land preparation and water control methods were the major differences among the three plots. The OSP has been puddled for 10 consecutive years and FSP (established in 2007) for the first time, and both were properly secured and demarcated into basins with bunds (before puddling) for ease of water control. Each of the *sawah* basins was of approximate dimension 25 m × 25 m. The NSP, being a non-*sawah* production system, had never been subjected to puddling and was an 'open' field (without bunds) and, thus, served as the control. As at the time of setting up OSP and FSP for the 2007 growing season, NSP was already in its 6th week of rice growth.

After puddling in each cropping season, four-week old rice seedlings were transplanted into OSP and FSP. The transplanting was done in rows at a plant spacing of 25 cm × 25 cm, whereas the plant stands in NSP were randomly distributed at a spacing range of 20-30 cm. Both OSP and FSP had, in addition to rainfall, a nearby spring as a source of water. A canal and its distributing channels led water from the spring to the *sawah* basins in OSP and FSP. Irrigation and drainage in the basins were through manually controlled inlets and outlets, respectively on the bunds. The only source of water for NSP was rainfall.

Sampling strategies

In 1998, 2001 and 2007, samples were collected in triplicate from the top-(0-20 cm) soil of OSP and NSP for chemical analyses. Having established the FSP in 2007, top-(0-10 cm) soil of the three plots (OSP, FSP and NSP), as well as an adjacent fallowed plot, were sampled in the first two weeks after puddling for determination of selected soil hydrophysical properties. First, the benchmark OSP and FSP were drained from few hours after puddling to ensure non-ponded conditions. This is the usual practice before transplanting. With no intervening rain events, soil samples were collected in triplicates in October 2007, two days after puddling. Sampling was done with both metal cores (size, 5 cm × 5 cm) and a scoop (collecting about 250 g of the wet soil) from the surface layer (0-10 cm) in all the three plots, after which water was re-introduced into the plots. Infiltration characteristics of the soil were measured only in the fallowed plot using a mini-disk tension infiltrometer, with an internal diameter of 4.4 cm (2006, Decagon Devices Inc., Pullman) and applying a tension of 2 cm.

Thereafter, ponding treatments were superimposed on the three plots. To do this, about 225-m^2 sub-basins were demarcated from one end of selected three OSP and three FSP basins and were maintained at a hydraulic head of zero (*i.e.,* negligibly ponded) for two weeks after puddling. These were designated 'non-ponded'. Similarly demarcated sub-basins at the other end of the basins were submerged to a depth range of 5-10 cm for the same interval and were designated 'ponded'. Corresponding assessment of the effect of ponding status on the soil hydrophysical condition in NSP was done in naturally non-ponded and ponded portions in the 'open' field, as validated by visual observations 2-3 h after rainfall. Soil sampling was repeated after the two weeks in both the non-ponded and ponded sub-basins. In both sampling events, all soil samples were immediately wrapped in black polythene bags and conveyed to the Soil Physics Laboratory of the Soil Research Institute, Kumasi.

Although the study was initiated in 1998, measurement of grain yield was started in 2001 and continued till 2009. Starting from 2007 when FSP was established, the yield measurement, then involving the three plots, was done regardless of their ponding status. Three-row border plants were left out in the yield assessment, which was also done in triplicate.

Data analyses

All soil physicochemical analyses were done in line with standard laboratory procedures (Sparks, 1996; Dane & Topp, 2002). Briefly for the soil physical properties, the core samples were saturated by desorption for 48 h and used for the determination of moisture retention. First, the saturation weights were recorded. Moisture retained at the matric potential (or soil moisture tension) of 6 kPa was determined using the conventional device of tension table with a hanging column of water. Soil moisture retention from 10 to 300 kPa was determined in a pressure chamber using plates with porous membranes. Thereafter, the core samples were used to determine soil bulk density using the core method, with the samples oven-dried at 105°C for 24 h. Soil total porosity was calculated based on the principle of intrusion porosimetry for non-swelling soils. Additionally, the total porosity was estimated as:

{[1 – (the ratio of bulk density and an assumed particle density of 2.65 Mg m^{-3})]100}%

The soil samples collected with a scoop were partitioned into two. One part was used for determination of field moisture content while the other part was used for chemical analyses after drying at room temperature and passing through a 2-mm-mesh sieve. Where applicable, moisture content of the soil was expressed on volumetric basis by multiplying its gravimetric moisture content by the pre-determined bulk density. For the infiltration test, data on cumulative infiltration and time were fitted with the Philip's infiltration model ($I = Ct + St^{1/2}$) that relates cumulative infiltration (I) to transmissivity (C), sorptivity (S) and time (t). To obtain an equation in this form, a relationship of the polynomial order was established between I and square root of time ($t^{1/2}$). The unsaturated hydraulic conductivity was computed for the applied tension by the method proposed by Zhang (1997):

$$K = C/A$$

where K is the unsaturated hydraulic conductivity (LT^{-1}), C is the transmissivity term of the Philip's model (LT^{-1}) and is the slope of the curve for I versus $t^{1/2}$, and A is a value relating van Genuchten parameters for a given textural class to applied tension and disk radius. For the clay-loam texture of the soil under investigation and the 2-cm tension applied to the 2.2-cm-radius disk, A corresponds to 6.8 (Decagon Devices Inc., 2006).

Analysis of variance and descriptive statistics were used to compare the soil data as well as the grain yield data among the rice production systems and the soil ponding status. The analysis incorporated all three replicates of the soil and yield data. Differences were deemed significant within the limit of 5% probability level. The statistical analysis was done using the software SPSS 15.0 for Windows Evaluation Version (2006, SPSS Inc., Chicago).

Results

Dynamics of soil fertility indices in the study site

The soil pH, soil organic C (SOC) and some nutrient elements in the top-(0-20 cm) soil at the time of the initiation of the *sawah* trials in 1998, later in 2001 and just before the 2007 growing season are summarized in Table 1. In 1998 when it was first cultivated, the NSP showed generally lower soil pH but higher values of SOC, total N and available P compared to the 10-year-old OSP. Notably, the negative change in SOC status in OSP between 1998 and 2007 was not significant. The soil total N in OSP also showed a tendency of gradual decline over the years. However, the *sawah* system was able to maintain the exchangeable bases at favourable levels.

Bulk density, total porosity and field moisture status

Table 2 shows the soil bulk density, total porosity, and field moisture content as influenced by the different treatments. Relative to NSP (control), OSP generally maintained the most favourable levels of these parameters, followed consistently by FSP. These soil hydrophysical parameters were even deteriorated under NSP when compared with the fallowed plot. Although there was a clear trend of the positive effects of time lapse since initiation of the *sawah* systems in the study site, the effects were significant only for the gravimetric moisture content (*i.e.,* OSP > FSP).

The data in Table 2 also show that water ponding enhanced the measured soil physical parameters under all three plots differing in *sawah* status. Hence, the ponded plots indicated lower soil bulk density but higher values of the other parameters than the non-ponded plots, irrespective of *sawah* status. The highest soil bulk density was observed under the non-ponded FSP. The percent difference in total porosity was higher in the non-ponded plots than ponded plots of FSP; the reverse was true in FSP. In OSP, the difference in total porosity in the ponded plots was similar to the corresponding difference in the non-ponded plots. The relative increment

Table 1. Mean (±std. dev.) topsoil chemical properties in the *sawah* and the non-*sawah* plots

Plot/Year	pH (H_2O)	SOC[1] (g kg^{-1})	STN[2] (g kg^{-1})	AvP[3] (mg kg^{-1})	K^+	Na^+	Ca^{++}	Mg^{++}
					cmol$_c$ kg^{-1}			
NSP[4] 1998 (n = 22)	5.7 ± 0.1	18.0 ± 1.4	2.00 ± 0.14	4.40 ± 0.79	0.27 ± 0.04	0.16 ± 0.02	5.1 ± 0.6	1.8 ± 0.2
OSP[5] 1998 (n = 30)	7.5 ± 0.1	15.3 ± 1.2	1.50 ± 0.11	ND[6]	0.17 ± 0.02	0.29 ± 0.02	7.6 ± 0.4	1.7 ± 0.1
OSP[5] 2001 (n = 25)	ND	13.2 ± 1.1	1.30 ± 0.90	3.80 ± 0.33	0.16 ± 0.01	0.26 ± 0.02	7.3 ± 0.6	1.7 ± 0.2
OSP[5] 2007 (n = 25)	6.2 ± 0.1	12.7 ± 0.7	1.09 ± 0.06	3.31 ± 0.20	0.33 ± 0.02	0.23 ± 0.03	13.6 ± 0.8	2.6 ± 0.3
CV[7] (%)	13.4	10.1	15.8	9.8	43.4	11.5	37.4	26.0

[1] SOC: soil organic carbon concentration. [2] STN: soil total nitrogen. [3] AvP: soil available P. [4] NSP: non-*sawah* plot. [5] OSP: old *sawah* plot. [6] ND: not determined. [7] For comparing among years in the OSP.

Table 2. Selected hydrophysical properties of the top-(0-10 cm) soil as affected by the *sawah* and the non-*sawah* systems and length of exposure to puddling

Field/Puddling Status[1]	Bulk density (Mg m^{-3})		Total porosity (%)				Field moisture content (%)		
	1st	2nd	1st Estimated	2nd Measured	2nd Estimated	Difference[2]	1st Gravimetric	1st Volumetric	2nd Gravimetric
Fallowed plot	1.20b	ND[3]	54.9b	ND	ND	–	44.2c	52.5b	ND
Old *sawah* plot (N)	0.94c	0.96c	64.6a	69.4b	63.9b	8.56	70.4a	66.0a	58.2b
Fresh *sawah* plot (N)	1.04c	1.46a	60.6a	50.4e	44.8e	12.50	57.2b	59.6ab	20.7e
Non-*sawah* plot[4] (N)	1.58a	1.38ab	40.4c	50.3e	47.8de	5.23	27.0d	42.4c	24.8e
Old *sawah* plot (P)	ND	0.73d	ND	77.8a	72.6a	7.05	ND	ND	70.2a
Fresh *sawah* plot (P)	ND	1.24b	ND	53.7d	53.2cd	0.96	ND	ND	44.3c
Non-*sawah* plot[4] (P)	ND	1.19b	ND	62.5c	55.2c	13.23	ND	ND	36.4d
Mean for P	–	1.05b	–	64.6a	60.3a	7.08	–	–	50.3a
Mean for D	–	1.27a	–	56.7b	52.2b	8.76	–	–	34.6b

[1] N: non-ponded as the plot was drained reasonably to the level of the soil surface. P: ponded to a depth of about 15 cm for about 2, 2 and 8 weeks for the old sawah plot, the fresh sawah plot, and the non-sawah plot, respectively. [2] The difference between the measured and the estimated total porosity at the 2nd sampling. [3] ND: not determined. [4] Serves as the control treatment. Note: Means within a column not followed by different letters do not differ statistically.

in the ponded plots over their non-ponded counterparts was much lower under OSP (20.8%) compared to NSP (46.8%). However, the corresponding increment under FSP was the highest (114.6%). Overall, the ponded OSP and non-ponded FSP maintained the most and least favourable values, respectively, of the soil hydrophysical parameters considered.

Comparison of the relative changes in the soil bulk density and gravimetric moisture content under the different *sawah* status could be made between the first and the second sampling dates (an interval of two weeks) (Table 2). The comparison is for the non-ponded plots only, since there were no ponding and, hence, no data on the effect of ponding at first sampling. Both bulk density and gravimetric moisture content showed a tendency for a negative change in the puddled plots, but these changes were significant only in FSP.

Soil moisture characteristics and hydraulic properties

Figure 1 shows the soil moisture retention curves as influenced by *sawah* and ponding status, for matric potentials ranging from 0 kPa (saturation) to 300 kPa. Moisture retention was higher under ponded than non-ponded conditions for OSP; the reverse was true for FSP. The moisture release pattern in the treatments was such that the highest drop in volumetric moisture content of the soil occurred between the 0 and 6 kPa. Beyond the 6 kPa, the moisture release was slow, except for the non-ponded OSP in which the highest soil moisture release occurred between the 10 and 33 kPa. The ponded OSP absorbed the highest amount of moisture at saturation, but dropped by the widest margin between saturation and the 33 kPa. However, it still retained the highest volume of water at this matric potential. Across all the matric potentials considered,

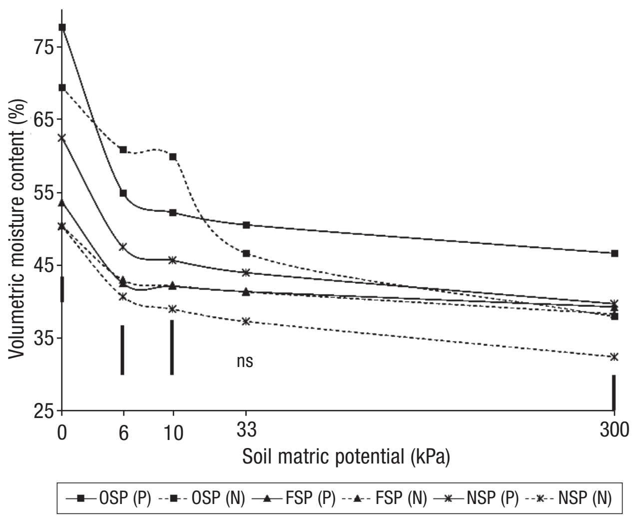

Figure 1. Moisture release curves of the inland-valley soil in the old *sawah* plot (OSP), fresh *sawah* plot (FSP), and the non-*sawah* plot (NSP) under ponded (P) and non-ponded (N) conditions two weeks after puddling. Vertical lines represent the least significant differences (LSDs) among the treatments; ns stands for 'not significant'.

OSP retained more moisture than NSP in general, and under non-ponded conditions in particular. Notably, the differences among the treatments were not significant at the 33 kPa. Although the non-ponded NSP consistently maintained the least values, these differed significantly from those for the ponded and non-ponded FSP only at the 300 kPa. The trend (ponded OSP > others > non-ponded NSP) at the 300 kPa is striking.

A plot of the cumulative infiltration (I) against square root of time ($t^{1/2}$) under a fallow soil condition is shown (Fig. 2). The soil attained a cumulative infiltration of only 0.63 cm in 7 min. When Y and x in the polynomial equation in the figure are substituted with I and $t^{1/2}$, respectively, the equation takes the form $0.0017t – 0.0047t^{1/2} – 0.0010$, which conforms to the Philip's model. From this equation, the unsaturated hydraulic conductivity of the soil was 2.50×10^{-4} cm s^{-1}, which translates into 9 mm h^{-1} or 216 mm day^{-1}. This value represents very slow soil conductivity, even with the non-puddled condition of the fallowed plot, indicating that the soil was of very low permeability.

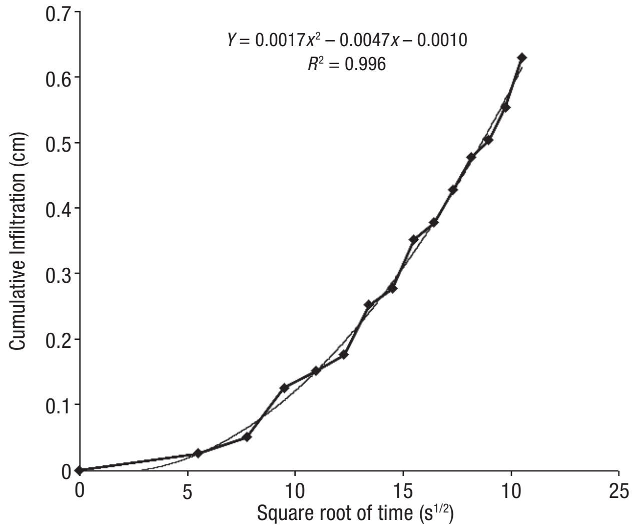

Figure 2. Cumulative infiltration as measured *in-situ* on a fallowed plot of the inland-valley soil in 2007.

Grain yield response to the *sawah* and non-*sawah* systems

Table 3 shows the grain yield of rice under the *sawah* systems (OSP and FSP) and the non-*sawah* systems (NSP) for the period 2001-2009. The OSP, apart from tremendously out-yielding NSP on a regular basis, showed a trend suggesting gradual increment in yield as it advanced in age. For instance, for the period 2001-2005, the extent by which grain yield in OSP was greater than that in NSP ranged from 344 to 370% (except for flood-disaster years); the corresponding extent for the period 2006-2009 was 408-450%. This tendency for an increase in yield with time under the *sawah* system was also evident in the newly established FSP. Furthermore, the increment in rice grain yield with *sawah* age is confirmed by the fact that OSP significantly out-yielded FSP in 2007 (when the latter was first initiated) by a margin (1.4 Mg ha^{-1}) greater than the absolute yield in NSP. In the subsequent two years of 2008 and 2009, the differences between OSP and FSP were not significant, although mean values were marginally higher in the former than the latter in both years.

Discussion

The drop in soil pH below the neutral values expected of *sawah*-managed soils was probably due to severe weathering and leaching associated with high rainfall in the area (Issaka *et al*., 1996). Having been under fallow for years, the NSP must have had its fer-

Table 3. Rice grain yield (Mg ha^{-1}) under the old *sawah*, the fresh *sawah* and the non-*sawah* plots over the study years

Sawah status	2001	2002	2003	2004	2005	2006	2007	2008	2009	Mean[1]	
										A	B
Old *sawah*	4.0a	4.7a	3.8a[2]	5.0a	4.5a[2]	5.3a	5.5a	5.8a	6.1a	4.97a	5.80a
Fresh *sawah*	–	–	–	–	–	–	4.1b	5.0a	5.3a	4.80a	4.80a
Non-*sawah*	0.9b	1.0b	1.0b	1.1b	1.1b	1.0b	1.0c	1.1b	1.2b	1.04b	1.10b
Increase (%)[3]	344.4	370.0	280.0	354.5	309.1	430.0	450.0	427.3	408.3	377.9	427.3

[1] A: For all years, 2001-2009; B: For only three years, 2007-2009. [2] Partially destroyed by late flood. [3] For old *sawah* plot relative to non-*sawah* plot. Note: Fresh *sawah* plot was initiated in 2007. Differences between the *sawah* and the non-*sawah* plots were not due to puddling alone; general field management and rice variety also differed.

tility rejuvenated, hence the higher SOC, total N and available P under it in the first year compared to the 10-year-old OSP. The negative change in the SOC status of OSP was not significant, in spite of the sharp decline in SOC commonly observed upon cultivation of hitherto fallowed land in the tropics. This suggests a possibility of controlling excessive organic matter decomposition in tropical soils with the *sawah* system (Kyuma, 2001). Although enhanced N-fixation in soils is one attribute of paddies (Wakatsuki & Masunaga, 2005), the soil total N was rather declining with time in OSP probably due to high volatilization rates of topsoil N in the tropics. That the system could not enhance the soil available P was attributed to its inherently low status in most West African inland valleys (Wakatsuki & Masunaga, 2005).

In spite of the low K^+, Ca^{2+} and Mg^{2+} status of inland-valley soils in West African region (Issaka *et al.,* 1996; Wakatsuki & Masunaga, 2005), the *sawah* system was able to maintain them at favourable levels. This may be attributed partly to puddling-mediated increase in topsoil clay content (Lal, 1986) and the associated reduction in conductivity and deep percolation (Bajpai & Tripathi, 2000), and hence reduction in leaching. The magnitude of such a reduction in conductivity due to puddling has been shown to be pronounced in fine-textured inland-valley soils (Obalum *et al*., 2011), as the one under study. The *sawah* systems could thus be a means of coping with the low fertility status of inland-valley soils. Nwite *et al*. (2008) also reported higher soil exchangeable bases under *sawah* compared to non-*sawah* systems in a lowland soil in southeastern Nigeria. Owing to the positive correlation between SOC and exchangeable bases in West African inland valleys (Issaka *et al.,* 1997), the NSP would by virtue of its high SOC content be expected to also be rich in exchangeable bases. However, unlike OSP, most of such nutrients released in NSP would be lost through leaching.

The improvements in the soil hydrophysical properties in the *sawah*-managed plots are usual effects of puddling (Guidi *et al*., 1988; Bhagat *et al*., 1994; Bajpai & Tripathi, 2000). Puddling reduces hydraulic conductivity not only through increasing the topsoil clay content (Lal, 1986), but also through the mechanism of clay dispersion, particularly in clayey soils (So & Cook, 1993). So, the enhanced soil moisture in OSP over FSP could be a reflection of both the relative content of clay in the topsoil and the relative plucking of the hydraulic pores by the clay dispersed during puddling. The higher moisture content in OSP than FSP means that continuous application of puddling could enhance the moisture content of lowland soils under field conditions. The highest soil bulk density under the non-ponded FSP was attributed to the compaction during puddling with the power tiller, more so as the treatment was introduced to the heavy traffic of the machine for the first time. The percent difference in total porosity was meant to serve as an index of the capacity to amass water following puddling; therefore, the higher the value, the better the treatment. That the value was higher in non-ponded plots than ponded plots of FSP could be due to sealing off of the surface soil pores by the clay particles dispersed after puddling (Kirchhof & So, 1996), a situation that did not prevail in NSP where the reverse was the case. This percent difference in total porosity for the ponded plots was comparable to the corresponding difference for the non-ponded plots of OSP, a pointer to the possibility of narrowing down the differences in hydrophysical conditions of ponded and non-ponded lowland soils with aging of the *sawah* system.

The enhanced moisture content with water ponding signifies that, in addition to the dispersion-mediated retention of water in a puddled soil, progressive consolidation process and sedimentation of clay particles with long period of submergence under water could equally enhance water retention in a paddy field (Kirchhof & So, 1996). The least relative increment in moisture status due to ponding in OSP suggests that a fairly high level of the 'desirable' soil structure for optimizing water retention had been achieved in OSP due alone to the long-term puddling, such that the effect of puddling masked that of submergence. At least three important inferences are implicit from the observed effect of ponding on soil moisture content. First, amply long ponding time on a newly puddled soil can improve soil physical parameters relative to a non-ponded condition. Second, time since lowland cultivation with the *sawah* system must be sufficiently long for puddling alone to always improve soil physical condition over ponded NSP. Third, the hydrophysical status of a puddled and ponded *sawah* field improves as the *sawah* system gets older.

The tendency for a negative change in soil bulk density and moisture content in FSP at just two weeks after puddling may be viewed as highlighting the fleeting nature of the puddling-induced improvements in soil hydrophysical conditions. Several studies have shown that puddled soils normally revert to their original conditions or may even deteriorate at harvest (Guidi *et al*., 1988; Bhagat *et al*., 1994; Bajpai & Tripathi, 2000). It appears, however, that such temporal loss of soil attributes desired by rice crop may not be evident in aged *sawah* systems. The agronomic implication of this observation is that, for the rice crop to benefit maximally from the reduced bulk density and enhanced soil moisture after puddling, transplanting should immediately follow puddling, mainly in newly developed *sawah* fields.

The soil moisture retention data agree with Bhagat *et al*. (1994) as reported between puddled and non-puddled topsoil in a rice field in northwestern Himalaya. Conversely, Lal (1986) reported, following a six-year study, that moisture retention in the 0-2 cm soil layer was generally higher across all tensions with no-till compared to puddling in a loamy soil in southwest Nigeria. The observation that ponding enhanced moisture retained upon saturation in OSP and vice versa in FSP has been attributed to the effect of ponding on soil structure being dispersive in the former but flocculating in the latter. Regardless of ponding status, the differences between OSP and FSP at almost all the stages highlight the importance of continuous application of puddling. Overall, the gentle slopes of the curves as from the 33 kPa imply a slow moisture release pattern, as first suggested by the extremely slow hydraulic conductivity of the soil under a fallow condition. These slow hydraulic attributes reflected the clayey texture and dominance of micropores in this lowland soil (Obi &Akamigbo, 1981).

In view of the above, the 33 kPa seemingly corresponds to the field capacity of the soil. Since very little water is usually lost between the 300 and 1500 kPa in clayey lowland soils (Obi & Akamigbo, 1981), the gentle slopes observed till the 300 kPa indicates a wide range of available moisture. The trend (ponded OSP > others > non-ponded NSP) at the 300 kPa, a matric potential beyond which soil water becomes difficultly available to plants in most soils, highlights the relative importance of seasonal puddling and a ponded soil condition. These differences, even with the inherently slow hydraulic conductivity of the soil, could be linked to a gradual decrease in hydraulic conductivity of puddled soil as the *sawah* advanced in age (Lennart *et al.*, 2009). The differences across the matric potentials of the present study support the views that the beneficial effects of puddling on soil hydrophysical properties are more pronounced in fine-textured soils (Kirchhof & So, 1996; Obalum *et al.*, 2011).

Because puddling normally disperses soil particles and favours preponderance of micropores, it leads to increased tortuosity and hence reduced hydraulic conductivity. This implies that the *sawah* fields would be expected to show much lower values of unsaturated hydraulic conductivity than the low value of 216 mm day^{-1} recorded under a fallow soil condition, more so with the clayey texture of the soil (So & Cook, 1993). According to one of the authors of the present paper (T. Wakatsuki), a mean percolation rate of 20 mm day^{-1} is considered ideal to sustain ponding and maintain favourable redox processes in *sawah* soils. Therefore, the seasonal puddling of the clay-loam textured soil of the present study is expected to reduce percolation losses in these lowland *sawah* systems by about 11 times under non-ponded, unsaturated conditions.

The grain yield results consistently showed the superiority of OSP over NSP, in spite of the more favourable SOC, total N and available P levels of NSP compared to OSP in 1998 (the first year) and the fact that these fertility parameters of the soil were not improved in OSP over the years (see Table 1). Instead, the yield results portray the effects of puddling and ponding on the soil hydrophysical properties, especially the bulk density and gravimetric moisture content. Rice is a crop that has over 85% of its roots concentrated in the top 20 cm of the soil (Kirchhof & So, 1996). The low bulk densities in FSP and OSP due to puddling compared to NSP must have therefore enhanced the root activity of water and nutrient uptake (Ogban & Babalola, 2003). So, the variations in grain yields would find a partial explanation in the bulk densities that differed under the treatments (Kukal *et al*., 2008). The results of the present study underline the importance of not just favourable soil bulk density but also favourable soil water condition under the *sawah* system.

Although the yield benefits of OSP and FSP over NSP have been largely attributed to the positive effects of puddling on soil bulk density and water retention, other yield-enhancing aspects of the *sawah* technology were lacking in NSP. The complementary roles of good water control with bunds, timely agronomic practices and optimum input levels to strategies aimed at enhancing rice yields in both *sawah* and non-*sawah* production systems in West African lowlands have been well documented (Becker & Johnson, 1999; Ofori *et al.*, 2005; Issaka *et al*., 2009; Toure *et al.*, 2009). For instance, Toure *et al*. (2009) specifically reported that field bunds for water control resulted in a mean increase in rice grain yield of 30-40% in a fine-textured soil in Ivory Coast, by reducing seasonal variations in ponding depth and cumulative weed biomass, and tremendously increasing inputs use efficiency.

As final conclusions, both puddling and early-season submergence enhanced the soil bulk density, total porosity and hence the soil water relations. Although the contribution of submergence would appear to drop with continuous puddling, the results presented suggest that the positive effects of puddling on these parameters be complemented with keeping the continuously puddled soil under submergence early in the growing season. Higher grain yields were mainly due to the more favourable soil physical properties under the entire *sawah* system, whose essential elements include puddling and good water management. The data could not, however, partition the yield benefits of the system into that due to puddling and that due to ponding; further study is needed in that regard. The overall results showed a clear trend of increasing agronomic benefits with the age of the *sawah* system.

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