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Soil & Tillage Research 56 (2000) 37–50

Soil & Tillage Research

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The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops

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Abstract

Changes in soil physical properties due to traditional methods of puddling for lowland rice (*Oryza sativa* L.) production and post-rice legumes was investigated in field experiments conducted on three sites in Indonesia and two in the Philippines over a 3-year period. Puddling treatments used in the field were, in increasing order of puddling intensity, dry cultivation prior to submergence, one and two plowing and harrowing treatments using a draught animal and associated implements, and two cultivations using a mechanical roto tiller. Rice was followed by mungbean (*Vigna radiata* (L.) Wilzek) on all five sites, and in addition soybean (*Glycine max* L. Merr.) at Ngale and peanut (*Aracis hypogaea* L.) at Jambegede were also grown. All puddling treatments were followed by post-rice treatments of surface drainage (with and without surface drains) for the Indonesian sites and sowing technique (zero-till-dibble versus plough-broadcast-harrow) for the Philippine sites. Rice yields were highest under the traditional puddling techniques using draught animal traction. Results suggested that puddling with a roto tiller reduced yield because of insufficient depth of puddling, while dry cultivation may have reduced yield due to increased soil strength of the puddled layer; both are thought to limit root development. Puddling had no significant effect on post-rice mungbean and peanut production. However, results showed that increasing puddling intensity tended to reduce soybean yield. Dry cultivation of lighter textured, well drained soils such as at Manaoag, tended to require more intensive weed control in both rice and dryseason crops compared to higher puddled treatments. Weed infestation was thought to be the largest contributing factor for reduced mungbean yield at Manaoag. Increasing soil puddling intensity at Ngale and Jambegede appeared to reduce root growth. Soil water depletion tended to be smaller in the plough layer that was cultivated under wet conditions compared to pre-rice dry land preparation. Soil water extraction was small and root proliferation was upto 40 cm depth under wet conditions where plant water requirements were met from seasonal rainfall. Root proliferation was deeper and soil water use greater under dry climatological conditions. Small amounts of subsoil water use resulted in substantial yield increases ranging from 3–24 kg mm^{-1} of soil water used, reinforcing the important role of subsoil water storage and use by the dry season crop in this farming system.

Keywords: Soil puddling; Soil structure; Rice; Legumes; Crop establishment

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0167-1987/00/$ – see front matter
PII: S0167-1987(00)00121-5

1. Introduction

Rice in tropical Asia is mostly grown under lowland conditions with one to three crops per year, depending on the rainfall or the availability of irrigation water and the use of modern, short season varieties. Rainfed lowland rice based cropping systems represented approximately two-thirds of all rice cropping systems in the countries of south and southeast Asia (Huke, 1982). Wet cultivation or puddling is synonymous with rice culture in Asia and is used to assist in transplanting of rice seedlings, to reduce water and nutrient loss and to control weeds (Sharma and De Datta, 1985). Puddling breaks down and disperses soil aggregates into micro-aggregates and individual particles. The degree of dispersion for a given puddling effect is dependent on the structural stability of the soil. It is likely to affect the regeneration of soil structure after rice, which in turn, will affect the growth of a dry season crop.

In conventional rice growing systems, land preparation is usually done by two plowings and two harrowings under submerged conditions and is the accepted practice of land preparation for lowland rice (Sanchez, 1976). Puddling is also required to reduce the loss of water and nutrients through excessive percolation, to reduce weeds and the reduced conditions enhance nutrient availability (Ghildyal, 1978; Sharma and De Datta, 1985). Despite these beneficial factors, the effect of puddling on rice yields is not clear. Puddling has been reported to increase the yield of rice (Van de Goor, 1950; Sakanoue and Mizunuma, 1962; Sanchez, 1973; DeDatta and Kerim, 1974). However, other reports have shown that puddling may not be necessary as it did not affect rice yields (Mabbayard and Buencosa, 1967; Scheltema, 1974; Utomo et al., 1985).

Most farmers in rainfed lowland areas do not grow secondary crops after rice. When they do, the yields of these crops are usually very low (Pasaribu and McIntosh, 1985; Adisarwanto et al., 1989) and well below the potential yield of these crops (So and Woodhead, 1987). These low yields are commonly associated with the adverse effect of soil physical conditions induced by puddling during land preparation for the rice crop (Pasaribu and McIntosh, 1985; Adisarwanto et al., 1989). Root growth into the subsoil is generally limited, resulting in low plant available water for post-rice crops. Reports on plant water requirements vary but generally range from 300–1000 mm (Doorenbos and Kassam, 1979) and depended on crop type, duration of growth, evaporative demand of the atmosphere and crop characteristics. For maximum production where plants are exposed to a minimum amount of stress, the water requirement for a 70-day mungbean crop was estimated to be 375 mm, for a 90-day peanut crop 500 mm and for a 100-day soybean crop 450 mm. However, Zandstra (1982) found that acceptable yields for mungbean, soybean and peanut on a dryland soil at IRRI were achieved with only 198–364 mm of water. Provided roots can access subsoil water during the dry season, moderate to high yields can be expected in the absence of rain and irrigation.

The physical limitation imposed by puddled soil have been recognised as the major cause of poor establishment and yield of post-rice crops in Asia, including soybean in east Java (Adisarwanto et al., 1989) and mungbean in the Philippines and other Asian countries (IRRI, 1984; So and Woodhead, 1987; Mahata et al., 1990; Varade, 1990; Woodhead, 1990). Puddling is associated with dispersion of soil aggregates during wet cultivation (Sharma and De Datta, 1985; Adachi, 1990) and results in a massive structure after rice. The strength of puddled soil increases rapidly upon drying and may restrict root growth of the secondary crop. As a result, these crops cannot access the considerable amount of water that is stored in the subsoil after the prolonged period of inundation during the rice phase. To increase the yield and yield stability of secondary crops after rice, it has been suggested that the effects of adverse soil physical conditions can be minimised by manipulation of soil puddling during land preparation for rice (Sharma and De Datta, 1985; Utomo et al., 1985). Tranggono and Willatt (1988) showed that increasing the intensity of puddling resulted in increased maize yields on a Vertisol but decreased yields in a lighter textured hardsetting Regosol in east Java. It is important that any manipulation of the puddling intensity should not affect the growth and yield of the primary rice crop.

The objective of the experiments described in this paper was to determine the effect of soil puddling intensity on the growth and yield of lowland rice and post-rice food legumes on different soils and under different climatic conditions. It was assumed that the different puddling methods used would result in a range of different puddling intensities which can be ranked.

2. Materials and methods

2.1. Field trial sites and design

Five sites were selected in Indonesia and the Philippines. In Indonesia, the experimental sites were at Ngale and Jambegede, both in east Java, and Maros in south Sulawesi. In the Philippines, the experiments were conducted at Manaoag, Pangasinan and Bulacan, San Ildefonso, both north-northeast of Manila. The soils and climatic conditions of these sites have been described by Schafer and Kirchhof (2000).

In Indonesia the rice crop and post-rice food legumes were grown in and after the rainy seasons of 1991–1992, 1992–1993 and 1993–1994, and in the Philippines they were grown in seasons of 1992, 1993 and 1994. The rainy seasons in the two countries differ by approximately 6 months associated with the different monsoon seasons.

Rice cv. IR 64 was used in east Java and the Philippines, and cv. Ciliwung (progeny of IR 64) in south Sulawesi. In all locations, rice was planted at a spacing of 20 cm×20 cm. Hand weeding was done at 30 and 60 days after transplanting. The post-rice crops used were mungbean on all sites and additionally soybean at the site in Ngale and peanut in Jambegede.

The puddling treatments comprised four degrees of puddling: T1, dry cultivation before submergence, approximately at the plastic limit of that soil; T2, one wet ploughing and harrowing using draught animals; T3, two wet plowings and harrowings using draught animals; and T4, two wet cultivations using roto tiller/hydro tillers.

The intensity of puddling increased from T1 to T4 and attempts were made to control the depth of puddling to 15–20 cm. Post-rice treatments included drainage versus no drainage in the Indonesian sites, both using zero-till-dibbling as the sowing technique. In the Philippines no drainage treatments were superimposed on the puddling treatments, but zero-till-dibble versus plow-broadcast-harrow (PBH) was compared. These additional treatments corresponded to locally used practices. These treatments were arranged in a randomised block design with four replications. The main block factor was 'soil puddling', selected from sufficiently large rice bays which were level and have been under rice cultivation for at least 20–30 years prior to these experiments. For the dry season crop, plots were split to include the subplots factor 'post-rice soil management'. Other details of the trial, were similar to the experiments described under E2 by So and Ringrose-Voase (2000). Soil types at the experimental sites are described by Kirchhof and Schafer (2000).

Following standard recommendations for rice production, uniform applications of 300 kg urea, 150 kg triple superphosphate (TSP) and 100 kg potassium chloride (KCl) per ha were made before the last harrowing or cultivation for the rice crops. A second fertiliser application of 100 kg urea ha^{-1} was made at 30 days after transplanting.

2.2. Measurements

Measurements were made for soil properties and crop yield. Soil properties include determination of the mean weight diameter of water stable aggregates using the wet sieving technique, depth of puddling/tillage and the water infiltration rates. The strength of the submerged puddled layer was determined through measurement of the soil sinkage capacity. The apparatus used is identical to a penetrometer except a metal plate (10 cm×2.5 cm) is pushed into the soil instead of a cone. Due to limited resources, not all measurements were made at all sites.

On the sites in east Java, soil water contents were monitored during the post-rice cropping phase using a Wallingford neutron probe type IH-III/DIDCOT in the 1993 growing season. The probe was calibrated at both sites but a common calibration equation to determine volumetric water content from count ratio, independent of depth of measurement, was derived. Depths for measurement was taken at 20, 30, 40, 60 and 100 cm depth. Soil water content in the topsoil at 0 and 15 cm was determined gravimetrically. The total soil water used during the growth of plants (evapotranspiration) was calculated from the difference in total soil water stored between planting and harvest.

Root samples were collected from mungbean plots only. Soil cores, of 10 cm diameter and length, were collected upto a depth of 1 m. Root lengths were determined after soil and roots were separated and roots scanned using a hand scanner to record digital images. These images were analysed for root length (Kirchhof and Pender, 1992).

3. Results and discussion

3.1. Changes in soil properties due to soil puddling

As discussed earlier, soil puddling is considered necessary to soften the soil for transplanting of rice seedling and to reduce water loss through excessive percolation (Ghildyal, 1978). The measurement of the depth of tillage/puddling conducted at Maros, showed that the different puddling intensities resulted in different depths of puddling and were not significantly different between the 3 years of measurement. The depths of puddling were 14, 17, 17 and 9 cm for treatments 1 to 4, respectively (LSD 5%=0.4 cm). Although the two wet cultivations with the rototiller were considered to have a greater puddling intensity, the floating nature of the machine restricted puddling to a shallow depth of only 9 cm. The sinkage capacity measurement made at Jambegede showed a similar trend with the rototiller resulting in a depth of puddling of 10 cm (Fig. 1). At Jambegede the depth of puddling from the dry and wet cultivations using the draught animals were uniform at 20 cm. Strength of the wet surface soil and sinkage capacity decreased with increasing degree of puddling except with the rototiller treatment which has a higher strength than the other two wet cultivations. The reason for this discrepancy is not clear at this stage. The sinkage capacity of all treatments were well below 100 kPa which imposes no restriction on transplanting rice seedlings. Transplanting is commonly done to a depth of 10 cm, therefore the rototiller treatments had adequate depth of puddled soil.

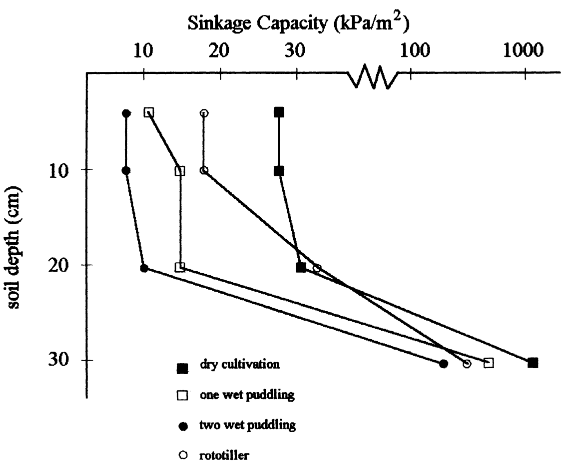

Fig. 1. The effect of puddling methods on sinkage capacity at Jambegede.

The measurement of mean weight diameter (MWD) of the wet puddled surface soils for the Ngale and Jambegede soils showed that all treatments gave a similar range of water stable aggregates. MWD at Ngale and Jambegede were significantly different (p=0.005). The averages were 0.072 cm for Ngale and 0.062 cm for Jambegede, probably reflecting the higher clay content and associated stronger structural stability of the heavy clay soil at Ngale. Dry cultivation on both soils resulted in a small but significantly higher MWD (p<0.0001) on both soils, 0.065 for the wet cultivation treatments compared to 0.073 for the dry cultivation treatment (T1). Although differences were small, they clearly showed that wet cultivation had a greater detrimental effect on soil structure than dry cultivation. The small size of the water stable aggregates of the submerged puddled layer probably represented those aggregates that remained stable against the long history of wet cultivation prior to the establishment of this trial.

Wet cultivation significantly reduced infiltration rates only at Jambegede. Dry cultivation treatments had 0.104 and wet cultivation 0.040 cm h^{-1} (p=0.0004). On the Jambegede soil this clearly showed that wet puddling was necessary to minimise percolation losses. Infiltration rates at Ngale were too low to be determined accurately and hence no significant differences were observed between puddling treatments. It is interesting to note that percolation rates at Maros were always just below 0.1 cm h^{-1}, irrespective of tillage method used. Such high infiltration rates are normally considered too high for the maintenance of surface water during the wet season in rainfed rice production, generally considered to be approximately 0.025 cm h^{-1} or 6 mm per day. However, the hydrology of the Maros area with its surrounding limestone ridges and high subsoil water conductivities resulted in high ground water levels which reach the soil surface after rainstorms and during much of the rainy season. This clearly showed that the decision to puddle the soil in order to reduce percolation losses, needs to take the broader landscape hydrology into account. Although measurements were not made in the Philippines, the Vertisol with low clay content (340 g kg^{-1} clay) at Bulacan site and the silty loam at Manaoag appeared to behave similar to Jambegede with sufficiently high permeability after pre-rice cultivation, in particular under dry soil conditions (T1).

3.2. Rice yields

Rice yields varied significantly between the five sites (Table 1). Despite the large differences in soil type, there were no differences in average yields at Ngale and Maros. The Philippine sites, Manaoag and Bulacan had the lowest average yields and Jambegede in east Java, intermediate yields. Since agronomic management techniques were similar on all sites, differences were most likely associated with soil–climate interactions. Conditions for rice production were probably most favourable at Ngale, on a soil with low permeability and high rainfall. The high permeability of the Maros soil was probably compensated for by high rainfall coupled with the high water tables associated with the hydrology of the landscape which provided a non-limiting supply of water. Lower rainfall and the more permeable soils in a reasonably well drained terrain, probably resulted in occasional water stress on the Philippine sites. Jambegede can be ranked as intermediate, a relatively well structured soil in well drained terrain but in a high rainfall area.

Puddling intensity affected rice yields significantly (Table 1). Yields were lowest on the dry cultivation treatment (T1) and the roto till treatment (T4). Treatments using the more traditional animal traction had the highest yields. It is reasonable to assume that the depth of puddling and sinkage capacity of the soils were similarly affected on all sites. This suggested that yield differences were due to a low depth of puddling on the roto-tiller treatments and high sinkage capacity on the dry cultivated treatment. Both of these could result in reduced root growth to depth and hence lower rice yields.

The interaction between soil puddling and location of the experiments was not significant, except for some treatments at Manaoag and Maros. The low yield on the dry cultivation treatment at Manaoag was associated with visually observed higher weed infestation. Although infiltration measurements were not carried out, the high weed infestation was most likely due to drainage of surface water from the high percolation losses that occurred several times during the season. The yield differences observed in Maros between the average of treatments T2 and T4 with treatment T3 remained unclear.

3.3. Food legume yields

Legume yields for the five sites over the 3 years of experimentation are given in Table 2. These averages gave some indication of the production potential for the different soils and climates, despite the low plant

Table 1
Average rice yields over three field seasons at five different sites[a] and the four puddling intensities treatments[b]

Location	Treatments				Mean
	T1	T2	T3	T4	
Rice yield (Mg ha^{-1})					
Bulacan	4.7	4.9	4.8	5.0	4.8
Jambegede	4.9	5.3	5.0	5.2	5.1
Manaoag	3.3	3.8	4.2	3.7	3.8
Maros	5.5	5.4	6.1	5.4	5.6
Ngale	5.3	5.7	5.7	5.5	5.6
Mean	4.75	5.02	5.14	4.95	4.97

[a] $Pr > F$=0.0001, S.E.= 0.1 Mg ha^{-1}.
[b] $Pr > F$=0.0361, S.E.= 0.09 Mg ha^{-1}.

Table 2
Average food legume yields on three field seasons at five different sites[a]

Location	Treatments				Mean	
	T1	T2	T3	T4		
Mungbean yield (Mg ha^{-1})						
Bulacan	0.19	0.20	0.25	0.22	0.22	
Jambegede	0.47	0.53	0.42	0.48	0.48	
Manaoag	0.82	0.94	0.94	0.93	0.91	
Maros	0.45	0.39	0.42	0.43	0.42	
Ngale	1.04	1.04	1.02	1.04	1.03	
Mean	0.59	0.62	0.61	0.62	0.61	
Soybean yield (Mg ha^{-1})						
Ngale	1.14	0.99	0.92	0.85	0.95	p=0.023
Peanut yield (Mg ha^{-1})						
Jambegede	1.99	1.95	1.88	1.78	1.88	NS

[a] Pr > F = 0.0001, S.E. = 0.01 Mg ha^{-1}.

population densities (200,000–300,000 plants ha^{-1}) in these trials. These densities were deliberately selected to avoid the situation where soil water becomes limiting in the higher rainfall areas and not limiting in the low rainfall areas. The highest yields were obtained on the Vertisol in Ngale and the silty loam soil in Manaoag. The high production potential in Ngale was probably associated with high plant available water under conditions where the rainy season tapers off relatively slowly into the dry season (Schafer and Kirchhof, 2000). In contrast, in Manaoag the rainy season stops rather abruptly, but the soil is reasonably well drained, resulting in adequate crop establishment and adequate root growth into the subsoil. In Maros and Bulacan, waterlogging generally follows mungbean sowing due to the frequency of heavy rainstorms during the late rainy season resulting in poor establishment. The soil surface is poorly drained and poor soil structure leads to high soil strengths following dry spells.

The subfactors investigated, drainage versus no-drainage, and zero-till dibble versus plow-harrow-broadcast (PBH) were not significant. The lack of a drainage effect however was not consistent with local expectations and it is possible that the surface drains installed were inadequate. Further research will be needed to assess if drainage will have an effect and the effect of different soil drainage techniques. In the Philippine sites, the lack of a tillage effect (i.e. zero-till-dibble versus plow-broadcast-harrow) indicated that sowing method may not have a large effect on yield on these sites, consistent with the farmers' experience and choice of the simpler and less costly PHB method.

Puddling intensity in general had no significant effect on mungbean yield, except treatments 2 and 3 were statistically different in Jambegede, and dry cultivation significantly reduced mungbean yields on the Manaoag site. The latter observations were in contrast with earlier findings of Willatt and Trangono (1987) and IRRI (1988) where legume yields were reduced on lighter textured soils due to high pre-rice soil puddling intensity. Rice harvest at the Manaoag site tended to occur at the start of the dry season when the soil surface was already dry. Excessive weeds within the rice crop could have reduced the amount of residual water stored in the root zone resulting in lower mungbean yields. Experiments by IRRI (1988) and Willatt and Trangono (1987) were conducted under conditions when the soil was still submerged during rice harvest, thus still relatively wet when post-rice legumes were sown. Under those conditions, poor soil structure induced by soil puddling, probably resulted in aeration problems leading to yield reduction. These contrasting findings emphasise the importance of soil water conditions, which are affected by climatological conditions towards the end of the rice phase and at the start of the legume phase. The relatively large difference at Jambegede between one and two plowing and harrowings using animal traction remained unexplained.

Although mungbean yields were not affected by soil puddling in Ngale, soybean yields tended to be increased with decreased puddling intensity. Using 'year' as a covariate, yields decreased from 1.14, 1.00, 0.92 and 0.85 Mg ha^{-1} for treatments T1, T2, T3 and T4, respectively (p=0.023). These trends agreed with the findings by IRRI (1988) and Willatt and Trangono (1987) on the heavy clay soils. The lack of response to soil puddling on mungbean may be due to the different lengths of the cropping cycle of approximately 2 months for mungbean and 3 months for soybean and peanut. Species with a longer growing season appeared to exhibit a larger reliance on subsoil water use, which assumes greater importance as the dry season continues. Peanut had a similar length in growing period compared to soybean. However, no significant puddling effect was observed at the site in Jambegede. It is possible that the mechanism described by Willatt and Trangono (1987) in their experiments, i.e. faster soil structural regeneration of cracking clay soils if puddled with high intensity versus massive structure formation on lighter textured soils if puddled intensively, resulted in improved and restricted root growth to depth on the heavy clay and a restricted root system on the loamy soil. Subsequent growth during the latter part of the growing season was therefore restricted due to roots being less able to tap subsoil water reserves.

3.4. Soil water use and root growth

Rainfall during the growing season of mungbean and soybean in Ngale 1993 was uniformly distributed with a total of 363 mm for the mungbean crop and 377 mm for the soybean crop. Rainfall in Jambegede was 143 mm, considerably lower than Ngale. Differences in soil water extraction were related to pre-rice puddling intensity. There was a consistent trend of larger soil water use for the treatments with the lower puddling intensities (T1 and T2, Table 3). Therefore, soil puddling under submerged conditions appeared to potentially limit soil water use and reduce yields of the following dry season crop, where soil strength of the puddled layer restricted root growth into the subsoil.

Total soil water use from the Vertisol in Ngale was small compared to the rainfall during the growing period of soybean and mungbean (Table 3). The high rainfall during the growing season resulted in relatively shallow root proliferation. Most roots were observed in the top 20 cm depth and root growth was not detected with the sampling procedure used beyond 40 cm depth (Figs. 2 and 3). This was probably associated with anaerobic conditions of the soil in combination with high rainfall. The plant water requirement was almost entirely met by rainfall and the use of subsoil water stored was limited.

Under the drier conditions in Jambegede however, subsoil water use was higher and a similar situation can be expected if sowing is delayed at Ngale and the

Table 3
Rainfall, soil water depletion, and grain yield of legumes in 1993 for Ngale and Jambegede sites

Location	Crop	Water	Puddling treatments				Yield (Mg ha^{-1})
			T1	T2	T3	T4	
Ngale	Mungbean	Rain (mm)	363	363	363	363	0.88
		$\Delta\theta^{a}$ (mm)	39	48	36	36	
		Rain $+\Delta\theta$	402	412	399	399	
	Soybean	Rain (mm)	377	377	377	377	0.63
		$\Delta\theta$ (mm)	128	94	90	80	
		Rain $+\Delta\theta$	505	471	467	457	
Jambegede	Mungbean	Rain (mm)	134	134	134	134	0.32
		$\Delta\theta$ (mm)	122	110	102	108	
		Rain $+\Delta\theta$	256	244	236	242	
	Peanut	Rain (mm)	134	134	134	134	1.31
		$\Delta\theta$ (mm)	213	212	183	194	
		Rain $+\Delta\theta$	347	346	327	328	

[a] $\Delta\theta$=difference in soil water storage sowing to harvest.

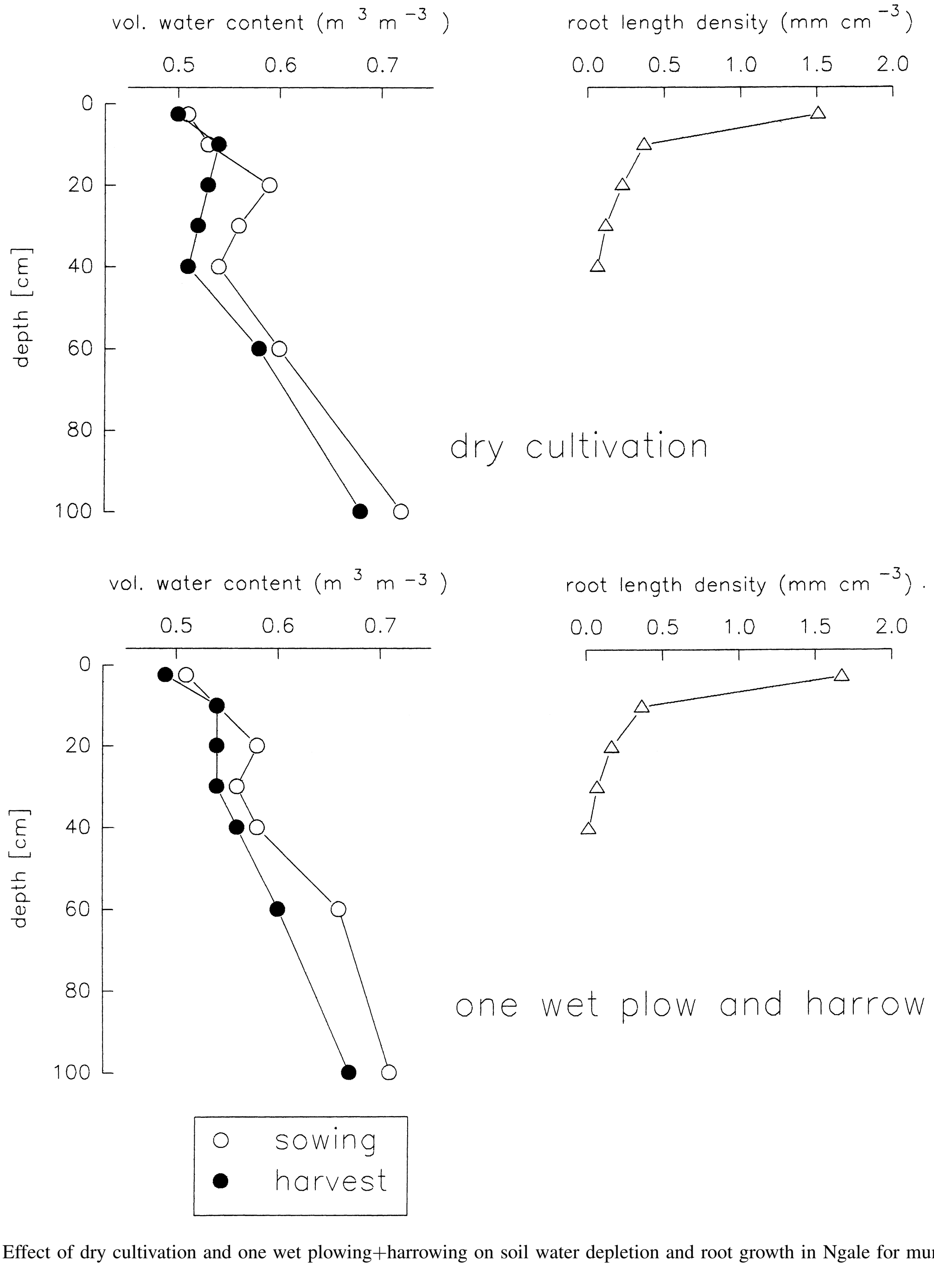

Fig. 2. Effect of dry cultivation and one wet plowing+harrowing on soil water depletion and root growth in Ngale for mungbean.

legumes forced to rely more on subsoil water. This was reflected in the higher root length densities and root growth to greater depth at Jambegede (Figs. 4 and 5). However, root growth could not be detected beyond 60 cm depth with the method used in these experiments.

A comparison of the climates at the two sites suggested that roots used subsoil water reserves under

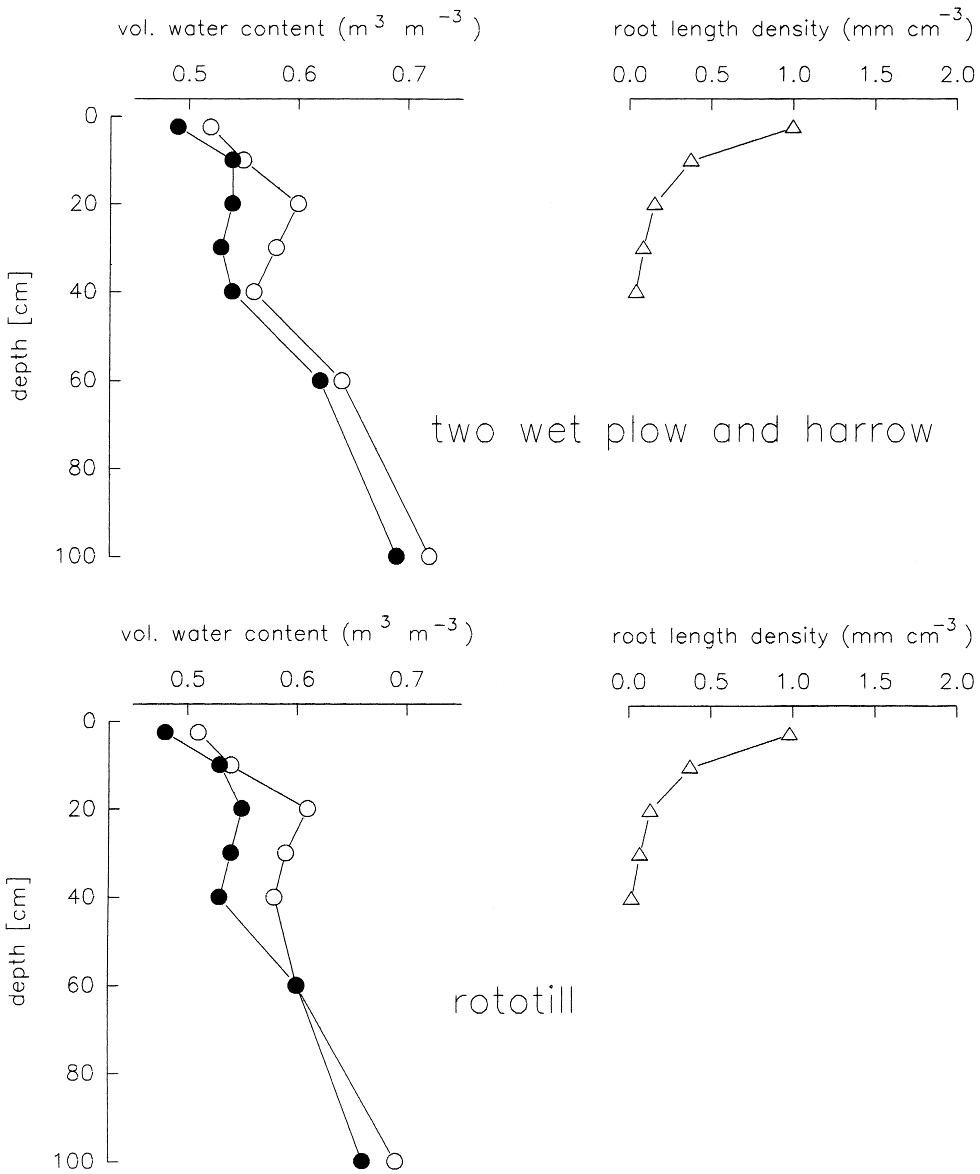

Fig. 3. Effect of two plowing+harrowing and rototiller on soil water depletion and root growth in Ngale for mungbean.

conditions where rainfall was insufficient to satisfy plant water requirements. It emphasised the need to sow early during the rainy season and to create soil conditions with appropriate management techniques that enabled plant roots to penetrate and explore subsoil water reserves under drier conditions. Climatological conditions clearly interacted with soil water content changes. Unfavourable conditions induced by wet cultivation may have restricted root growth and water uptake as indicated by the lower soil water uptake from the puddled layer in Jambegede. The most critical stage for root penetration can be expected at and after the crop establishment phase where roots grow into, and possibly through the puddled layer to tap subsoil water for future growth.

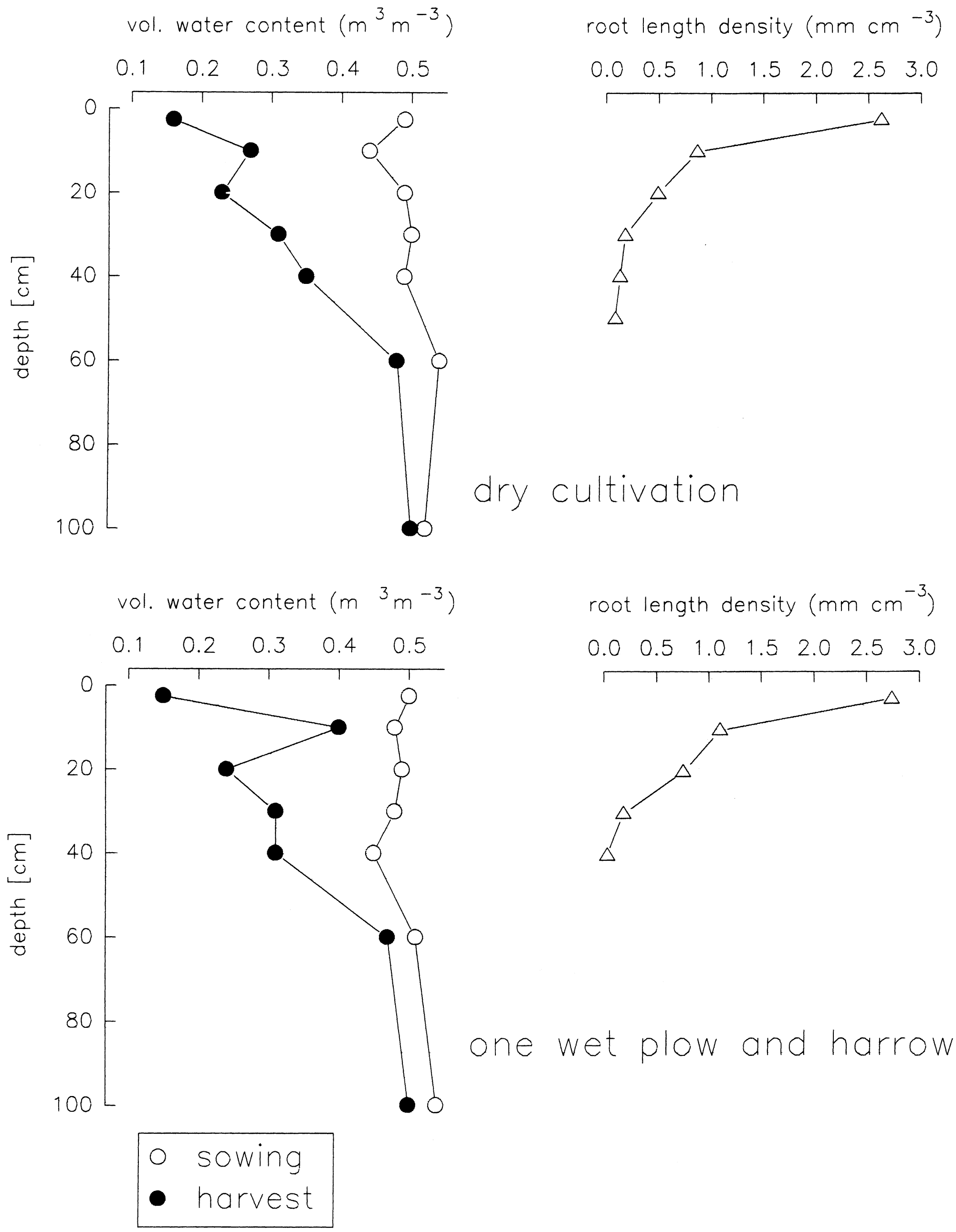

Fig. 4. Effect of dry cultivation and one wet plowing+harrowing on soil water depletion and root growth in Jambegede for mungbean.

3.5. Soil water use and yield

The total amount of soil water used was related to biomass or grain yield produced, for the available data of 1993. At Ngale, mungbean used 399–412 mm of water (Table 3) with an average yield of 0.88 Mg ha^{-1} whereas at Jambegede, water used was 236–256 mm with a mean yield of 0.3 Mg ha^{-1}. At Ngale rain during the growing season maintained reasonably high soil water content near the soil surface which was

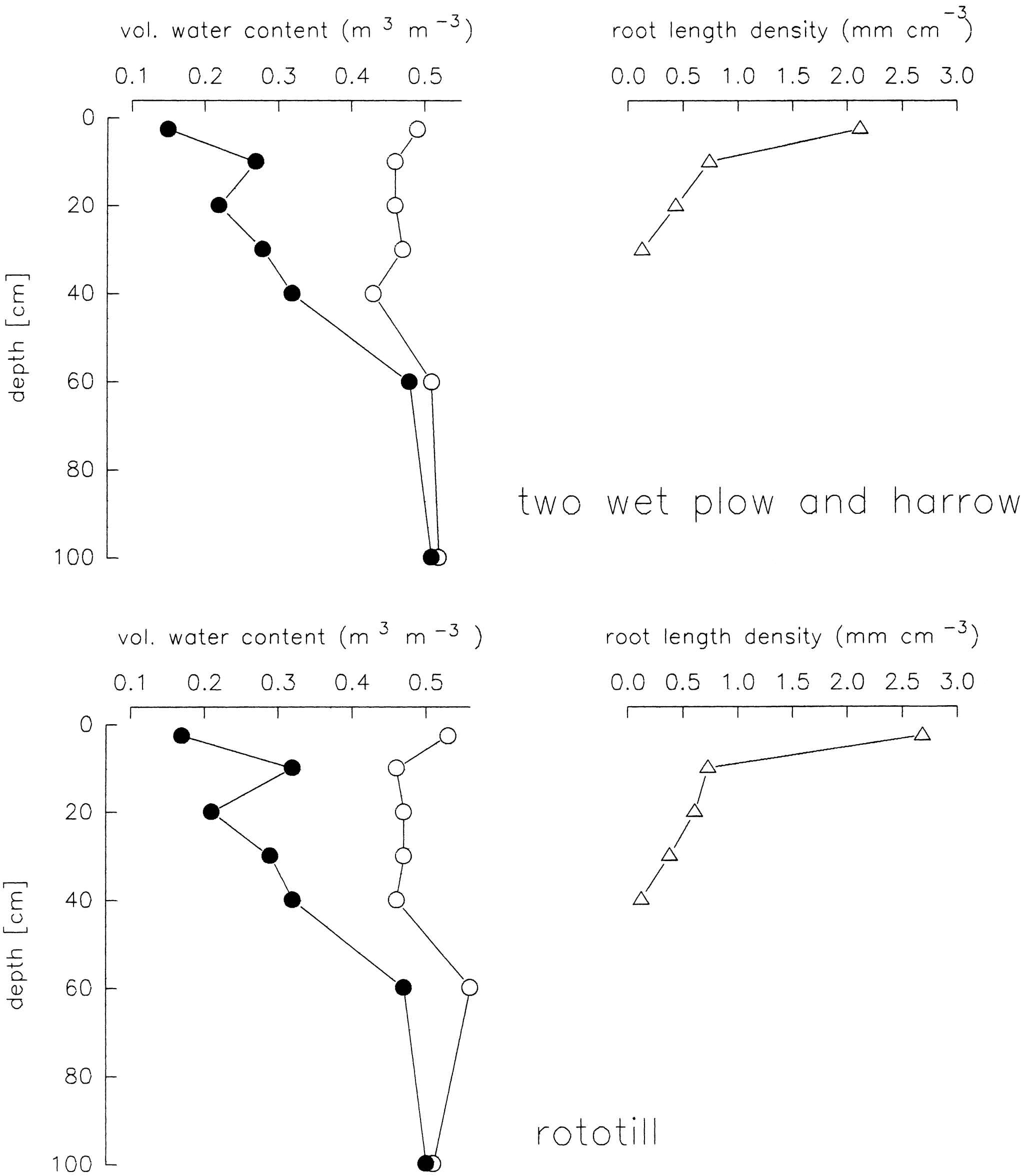

Fig. 5. Effect of two plowing+harrowing and rototiller on soil water depletion and root growth in Jambegede for mungbean.

adequate to supply plant water requirements. At Jambegede, inadequate rain forced the crop to use subsoil water with increasing water stress levels and reduced growth and yield.

Partitioning water used from different depth intervals revealed significant relationships between yield and water use. The relationships gave the highest level of correlation of soil depths 0–65 cm and 65–125 cm were separately related to grain yield (Table 4). However, there was no relationship between mungbean yield and water used in the 0–65 cm depth interval. Soil water contents within this layer were controlled by rainfall events and determined the base level of grain yield (intercept of regression line) while the water from 65–125 cm depth determined the additional yield obtained from subsoil water used.

Table 4
The relationships between water used from different depths and yield of mungbean, soybean and peanut at Ngale and Jambegede in the 1993 season

Location	Crop	Depth (cm)	*r*	Equation
Ngale	Mungbean	00–60	0.15	Y=0.006 X+0.763
		65–125	0.73*	Y=0.024 X+0.430
	Soybean	00–60	0.6*	Y=0.004 X+0.312
		65–125	0.65*	Y=0.008 X+0.484
		0–125	0.63*	y=0.003 x+0.365
Jambegede	Mungbean	00–60	0.03	Y=−0.001 X+0.366
		65–125	0.78*	Y=0.003 X+0.281
	Peanut	00–60	0.75*	Y=0.014 X−0.908
		65–125	0.8*	Y=0.008 X+0.959
		0–125	0.85*	y=0.005 x+0.197

* Indicates significance at $p<0.05$.

However, legumes with longer growth periods, such as peanuts and soybean, grew longer into the dry season when rainfall decreased at the end of the rainy season and the significant relationship between yield and water use from the deeper layers indicated that yields were limited by soil water storage during a significant proportion of the grainfill period.

Subsoil water usage from depth 65–125 cm was significantly related to grain yield for all three legumes on both soil types. The high correlations indicated that changes in soil water contents were associated with root activity and not drainage, although roots could not be detected below 65 cm depth with the sampling method used. It is important to note that yield increases per unit of subsoil water used were substantial despite relatively small absolute changes in soil water contents below 65 cm depth, in particular at the Ngale site. Yield increases were in the order of 3–24 kg ha^{-1} mm^{-1} for the different legumes (Fig. 6), and subsoil water from 65–125 cm was responsible for yield differences between treatments of 13–27% of the mean yield. These figures compared well to reports by IRRI (1985, 1986) where yield increases of 4–7 kg ha^{-1} mm^{-1} for mungbean were observed due to an increase in root exploitable soil depth. These relationships showed the importance of getting roots into the subsoil for increased yields of dry season crops and all soil or agronomic management practices should aim at promoting rooting depth.

Although statistical analysis generally showed that yields were not different between treatments, Table 3 and Fig. 6 indicated that low puddling intensity (T1 and T2) gave small and consistently higher yields, than the high puddling treatments (T3 and T4). These trends support the observation that high puddling intensity was not necessary for rice and minimising cultivation could represent increased farm income through energy savings and potentially higher yields of dry season crops. More work is required to assess the contribution that reduced puddling can make

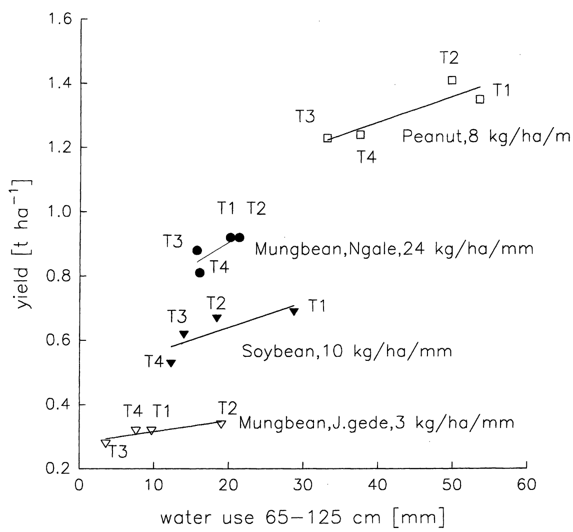

Fig. 6. The effect of soil water usage from the subsoil on grain yield of pulses (T1 to T4 denote puddling treatments).

towards increasing the yield of dry season crops after rice.

4. Conclusion

Puddling intensity influenced rice yield through the strength and depth of the puddled layer. Rice yields obtained using dry cultivation or a roto-tiller under submerged conditions were reduced by about 5% compared to wet tillage using draught animals. These marginal differences indicated that soil puddling can probably be reduced on most soils and that the reduction in cost for soil preparation is most likely to be >5%, as puddling represents a major proportion of the operational cost of growing rice. Puddling to reduce infiltration rates and to avoid water loss may only be necessary on permeable soils where water tables remain well below the soil surface and where rainfall is inadequate during the rainy season. Results from these trials clearly suggest that puddling should be minimised to reduce farm labour and minimise soil structural deterioration.

Across the five sites, different puddling intensities had no significant effect on mungbean and peanut yields. Increasing puddling intensity decreased soybean yield at Ngale. However, within each soil type, there was clear indication that puddling reduced root growth and water uptake from the subsoil. The small amounts of additional water supply from the subsoil resulted in substantial yield increases ranging from 3–24 kg of grain ha^{-1} mm^{-1} of additional water extracted. In areas were rainfall is relatively high, subsoil water use did not contribute greatly to grain yield because plant water requirements were satisfied by rainfall.

The implication of these results is that areas with a sufficiently long rainy periods greater than 4 months, should be able to grow post-rice legumes successfully. It suggest that sowing legumes in the rainy season is not detrimental, on the contrary it will ensure adequate establishment and root growth into the subsoil when the surface soil is moist. The remaining rainfall should be used to supply water through the surface soil, and adequate exploitation of the subsoil water should further contribute to yield. Classification of areas where food legumes can be grown successfully is needed and should take rainfall, soil type as well as the need for soil puddling into account.

Acknowledgements

The project from which these findings were reported was funded by the Australian Centre for International Agricultural Research (ACIAR). Their assistance is gratefully acknowledged. The staff of the experiment stations at Ngale, Jambegede and Bulacan are gratefully acknowledged for their assistance and Mr Severo Arellano from Manaoag for his support and use of his farm.

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