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Water balance and rice growth responses to direct seeding, deep tillage, and landscape placement: Findings from a valley terrace in Nepal

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Abstract

For maximizing water retention and attaining high yields, transplanting into puddled soil (TPR) is often considered the optimal method of rice (*Orzya sativa* L.) establishment. Alternative management techniques like direct seeding (DSR) and deep tillage have been proposed as mechanisms to improve soil physical properties for subsequent dry-season crops, but the risks to rice are uncertain. In this full factorial study on a valley terrace in Nepal, the influence of tillage (shallow—T_1, deep chisel—T_2, deep chisel + moldboard plough—T_3) and establishment practice (TPR, DSR) on the field water balance and rice performance were evaluated in two adjacent landscape settings (terrace edge ''upland'', central terrace ''lowland''). Although deep tillage had only modest influences on seepage and percolation (SP) rates in both years (Y_1, Y_2), landscape placement and establishment practice had significant implications for the water balance (e.g. Y_2 SP cm day^{-1}: TPR-lowland = 1.6, DSR-lowland = 2.3, TPR-upland = 4.1, DSR-upland = 6.1). During low rainfall periods, however, soil water potential and drought vulnerability were governed solely by landscape placement. Despite water balance differences, there was little evidence that rice rooting behavior was substantially modified by landscape or establishment method. Weed biomass was higher in DSR, but was uncorrelated with water balance and productivity trends. In Y_1, lower SP rates and more days with continuous flooding were positively associated with rice productivity. DSR yields were significantly lower than TPR in both landscape positions, with the lowland outperforming the upland (Y_1 mt ha^{-1}: TPR-lowland = 6.4, DSR-lowland = 5.2, TPR-upland = 5.7, DSR-upland = 4.7). To determine if N dynamics were contributing to productivity differences, fertilizer nitrogen was increased from 120 to 150 kg N ha^{-1} in Y_2. Results suggest that DSR performance is comparable – and landscape less important – if nitrogen is non-limiting (Y_2 mt ha^{-1}: TPR-lowland = 6.9, DSR-lowland = 6.5, TPR-upland = 7.0, DSR-upland = 6.5); no aspect of the field water balance was associated with yield variability in Y_2. For direct seeding in N-deficient farming systems, landscape criteria may prove useful for minimizing production risks by identifying field areas with lower SP rates.

Keywords: Transplanted rice; Water relations; Water balance; Drought stress; Root distribution; Weed competition; Nitrogen dynamics

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1. Introduction

In Nepal, Upadhyaya (1996) estimates that over 90% of the land area devoted to rice cultivation is seasonally inundated and the dominant establishment technique in these areas is transplanting into puddled soil (TPR). Most experimental evidence suggests that TPR is valuable for resource use efficiency, yield stability, and high productivity, primarily by conserving water and nutrient resources while reducing weed pressure (e.g. Sanchez, 1973; DeDatta and Barker, 1978; Naklang et al., 1996; Surendra et al., 2001). For areas with mono-modal precipitation distribution where dryland crops like wheat are cultivated after rice, direct seeded rice (DSR) may create favorable soil physical conditions for subsequent crops, thereby optimizing total system productivity (Hobbs et al., 1994; Timsina and Connor, 2001). DSR also can reduce the labor requirement for establishment by transferring field activities to periods when labor costs are comparatively low (Pandey and Velasco, 1999), providing additional impetus for adoption. The site-specific appeal of unconventional rice cultural practices is contingent not only on the growth benefit accrued to subsequent crops but also the risks posed to rice. Rice evolved as a semi-aquatic species with facultative root aerenchyma that facilitate aerobic respiration in flooded soils (Norman et al., 1995). Consequently, rice is significantly more sensitive to water deficit than other grain crops (e.g. Angus et al., 1983; Tanguilig et al., 1987; Inthapan and Fukai, 1988). During the summer monsoon, the confluence of shallow groundwater and surface flow elements periodically create the inundating conditions that define the prime rice growing areas in Nepal; less than a quarter of these areas are serviced by irrigation from assured sources, and drought stress during low rainfall periods is identified as a primary production constraint (Upadhyaya, 1996). Hence, water conservation is considered essential for yield stability and optimization.

In preparation for rice transplanting, wet tillage (i.e. soil puddling) reduces macropore volume in the upper portion of the soil profile while increasing bulk density in a compacted horizon that is alternately termed the plough sole or tillage pan (Ghildyal, 1978; Sharma and DeDatta, 1985; Adachi, 1990; Aggarwal et al., 1995; Bhagat et al., 1999). Tuong et al. (1994) demonstrated the importance of these changes to the soil's hydraulic properties by keeping small portions (ca. 1.5%) of a rice field unpuddled; uniformly puddled companion fields had lower seepage and percolation (SP) rates by a factor of five (2.7–15 mm day^{-1}). At a different site, DeDatta et al. (1973) report SP increases from 3.4 to 9.3 mm day^{-1} with the adoption of non-puddled establishment methods. On coarse textured soils, other findings suggest that wet tillage has less significant consequences, decreasing SP rates on the order of 50% (Kukal, 2002).

Limiting percolation losses and retaining a saturated soil profile may confer several advantages to rice. Ponding water increases in situ storage capacity, hedging against periods of limited rainfall. Consistent flooding also inhibits the establishment and growth of many weeds (DeDatta et al., 1973; Sahid and Hossain, 1995). Perhaps most importantly, consistent flooding can have substantial consequences for nutrient form, availability, and loss (Wade et al., 1998). Maintenance of reducing conditions prevents oxidation of ammonium (NH_4^+) and this form of N is largely retained against leaching (DeDatta, 1981; Kirk et al., 1994); although a fraction of this N pool can volatize as NH_3, especially when pH is high (Loomis and Connor, 1992). Some evidence suggests that chemical transformations in flooded soil increase phosphorous availability (Ponnamperuma, 1978; Neue and Bloom, 1987; Willet, 1991), but this may not hold beyond the first days after submergence (Kirk et al., 1998). Persistent flooding can also increase the plant-available stocks of potassium, calcium, silicon, and iron in the soil (DeDatta, 1981). Further, losses of soluble nutrients from the root zone are inhibited by the lowered floodwater export rates achieved with TPR (Kudeyarov et al., 1989).

Despite these advantages, TPR systems do entail uncertainty. If the main monsoon rains arrive late or fail altogether, timely crop establishment is often compromised and older seedlings demonstrate poor resilience to the stress of transplantation with reduced tillering and delayed maturation ((DeDatta, 1981; Torres and Liboon, 1994). Lagged development increases the damage probability from drought if anthesis and grain fill extend beyond the principal monsoon rains (Ekanayake et al., 1989; Boonjung and Fukai, 1996). Contributing to drought vulnerability, 90% of the root mass in TPR systems is typically found in the surface 20 cm of the soil (Sharma et al., 1994). Deep rooting is considered an essential trait for drought resistance in rice (Yoshida and Hasegawa, 1982; Fukai and Cooper, 1995).

In Nepal, the extent of DSR systems is small (ca. 5%) and confined to well-drained soils with traditional cultivars (Upadhyaya, 1996). Several factors may make DSR advantageous for poorly drained areas. Typically, DSR can be established earlier than TPR and does not incur growth delays from transplant injury; hence, DSR may hasten physiological maturity, reducing vulnerability to late-season drought (Tuong et al., 2000). On adjacent plots, Naklang et al. (1996) note that DSR had more root biomass than transplanted rice and other studies show increases in assimilate allocation to deep roots (Azhiri-Sigari et al., 2000). Some findings suggest that DSR achieves higher tiller density, leaf area, and vegetative biomass (Dingkuhn et al., 1990; Schnier et al., 1990), and that yields match or exceed TPR (Naklang et al., 1996; Saleh and Bhuiyan, 1995).

When environmental conditions are sub-optimal, however, DSR systems may be comparatively more vulnerable to drought, nutrient deficiencies, poor establishment, and weed pressure (e.g. Morris, 1982). DSR is typically sown in advance of the principal monsoon rains, occasionally exposing fields to erratic precipitation patterns and early-season water deficit which can be damaging to stand uniformity (Tuong et al., 2000). On the other hand, early onset of heavy rains can cause seed-wash and inhibition of emergence if the soil becomes anoxic (Kordan and Ashraf, 1990; Naklang et al., 1996; Yamauchi et al., 1996). In some settings, soil physical conditions associated with DSR cultivation considerably increases seepage and percolation losses with respect to puddled systems (e.g. Singh et al., 2001), thereby increasing the probability of yield losses to drought (Sharma et al., 1987; Saleh and Bhuiyan, 1995) while reducing water use efficiency (Tuong, 1999). If DSR-induced changes to the plot water balance result in shallow or intermittent standing water, the competitive ability of many weeds increases (Garrity et al., 1992). Perhaps most damaging to yield, alternating cycles of soil wetting and drying are associated with low rates of nitrogen recovery (Kogano et al., 1991; Belder et al., in press).

Cultural practices like deep tillage in advance of soil puddling attempt to preserve the advantages of TPR while expanding the rooting zone above the plough sole. Evidence from China indicates that this practice shifts the top of the plough sole region to 30 cm, rather than the 10–15 cm in conventionally puddled soils (Hobbs et al., 1994). In an N-limited system, Dingkuhn et al. (1989) document a 2.4% yield increase for every centimeter of downward shift in plough sole location. Akhtar and Quereshi (1999) found a depth-wise increase in root distribution from 12 to 20 cm and a yield benefit of 30% with adoption of deep tillage prior to TPR. By contrast, deep tillage preceding DSR may breech pre-existing plough soles, potentially exacerbating hazards posed by drought, weeds, and nutrient deficiencies from changes to the field water balance.

The importance of landscape position and subsurface hydrology cannot be neglected when considering the impact of soil management on rice performance. Shallow groundwater contributes more than one-third of the water transpired by a rice crop in some areas (Bolton and Zandstra, 1981) and, independent of soil conductance, groundwater table position and flow velocity substantially affect floodwater export rates (ten Berge et al., 1995). Landscape hydrologic attributes may considerably influence the productivity, stability, and resource use efficiency of novel rice management practices.

In this 2-year full factorial experiment, water balance and rice growth responses to conventional and alternative cultural practices were compared in two adjacent landscape settings (terrace edge, central terrace) with contrasting groundwater characteristics. Three different tillage regimes (conventional shallow, deep chisel, or moldboard inversion + deep chisel) were paired with two forms of rice establishment: transplanting into puddled soil (TPR) and direct seeding into un-puddled soil (DSR). We anticipated that the most intensive form of deep tillage (moldboard + chisel) in tandem with direct seeding would result in the highest soil conductances for water transport, whereas shallow tillage in combination with TPR establishment would produce the lowest. We also anticipated that field water balance differences among the treatments would be more pronounced in the terrace edge environment where groundwater flux velocities are higher and watertable recession occurs more rapidly during low rainfall periods. For crop performance, we hypothesized that plots with higher SP rates, a lower proportion of the growing season under flooded conditions, and drier soils during period of low rainfall would be less productive for rice than the most water-conserving comparison treatments. On the other hand, we also expected that changes in rice morphology, specifically shifts in root distribution, would counterbalance changes in the field water regime.

2. Materials and methods

This experiment was conducted over 2 years (Y_1: 1999; Y_2: 2000) at the Nepal Agricultural Research Council (NARC) experimental farm in Khumultar, Nepal (27°N, 85°E). Situated in the Kathmandu Valley (1350 m a.s.l.), the experimental area has a geomorphology typical of mountain valleys found in the mid-hills physiographic region. Soils are silty loam textured with near neutral pH and exhibit significant vertic characteristics derived from the dominance of 2:1 clays in the fine fraction. Kathmandu receives an average of 1197 mm of annual precipitation, with 80% of this total concentrated in the summer monsoon (May–September). This experiment straddled the spatially adjacent central and near edge positions of a broad agricultural terrace, which are common landscape features in the valley bottomlands of the mid-hills.

Cropping system elements evaluated in this balanced factorial trial were *tillage* (shallow—T_1, deep chisel–T_2, deep chisel + moldboard plough—T_3), *establishment method* (transplanting with soil puddling (TPR) and direct seeding without soil puddling (DSR)), and *landscape position* (terrace edge "upland" and central terrace "lowland"). Landscape position was defined by proximity to the eastern terrace edge, which corresponds to the direction of the principal groundwater gradient (East–West) at the site (Fig. 1); preliminary char-

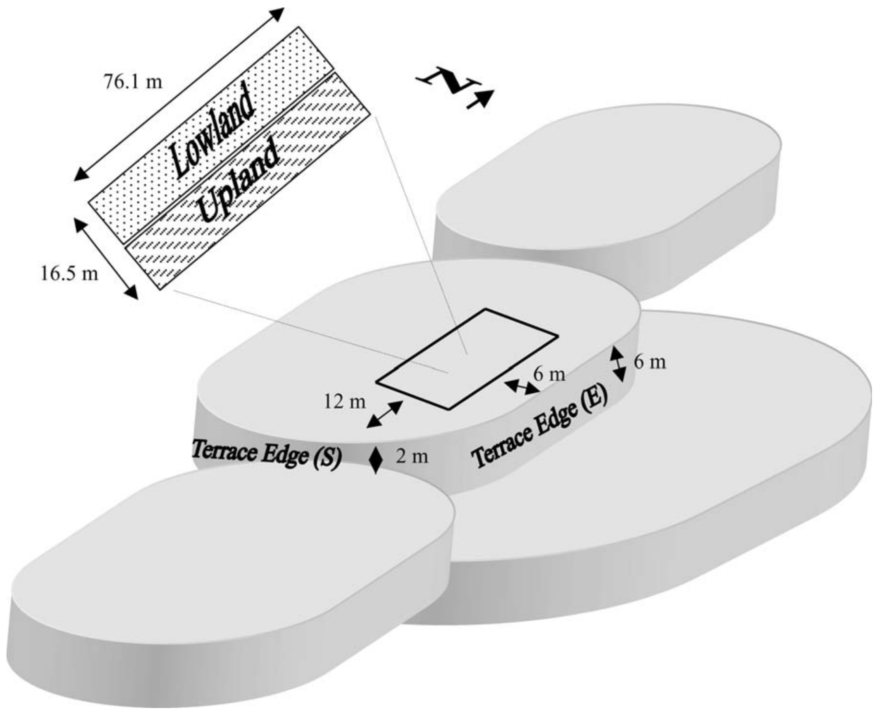

Fig. 1. Idealized schematic of terrace morphology and treatment layout at the experimental site. During the summer monsoon season, previous monitoring documented a substantial hydrology gradient along the east–west axis with groundwater flux and recession rates higher near the terrace edge. For this study, the site was divided into two generalized landscape positions with reference to the east–west gradient: central terrace "lowland" and terrace edge "upland."

acterization showed that areas closer to the terrace edge have higher groundwater flux rates and experience more rapid groundwater recession in low rainfall periods. Within each landscape position, there were six tillage and establishment combinations for a total of 12 treatments (landscape–tillage–establishment) repeated in three adjacent blocks for a total of 36 plots. Plot dimensions were 3.7 m × 7.5 m (27.75 m^2), with 0.5 m bunds separating all plots. This experiment followed a strip (tillage)–split (landscape)–split (establishment) design, with the tillage practices randomized within each block.

2.1. Instrumentation

Piezometers and time domain reflectometry (TDR) were utilized to document subsurface water dynamics. Piezometer tubes (5 cm diameter, PVC) were installed to monitor pressure head development at three depths (20, 50, and 100 cm) on a daily basis (see Wopereis et al., 1994), while a tube-access TDR system (TRIME-FM, IMKO Corp.) tracked volumetric moisture contents twice weekly to a depth of 63 cm. A sloping gauge was employed to measure floodwater depth. All of these instruments were clustered along the central meridian of each plot approximately 2 m from the bund, thereby minimize extensive soil compaction from foot traffic. When the plots were not flooded, a portable tensiometer (Quickdraw, Soil Moisture Inc.) was used to measure soil matric potential at 10 cm depth. Potential evapotranspiration (PET) rates were estimated with an atmometer (MEASURET, Aquaterr Instruments Corp.), and daily precipitation recorded with a manual raingauge accurate to 0.2 mm (Tenite Corp.).

2.2. Tillage and plot preparation

Tillage operations for rice were initiated in mid-May, prior to the arrival of intense monsoon rains. First, 24 plots were tilled to 50 cm with a single-shank chisel implement at 40 cm intervals. Then, soil in twelve of the chiseled plots was inverted to a depth of 30 cm with a moldboard plough (i.e. subsoiler + moldboard tillage). Lastly, all 36 plots were shallow tilled with a rotary plough to a depth of 10 cm. To mitigate the lack of hydrological independence between neighboring areas in this experiment, each plot perimeter was surrounded by 50 cm (height and width) bunds constructed with tightly compacted, low-permeability soil. Plastic barriers were installed on the boundaries of each plot to a depth of 30 cm to further minimize edge interactions.

2.3. Crop management and assessment

A short-duration, improved rice variety (Khumal 3) was utilized for both transplanted and direct seeded systems. TPR plots were transplanted into puddled and flooded soil with three seedlings per hill on 20 cm centers. DSR was line-sown into moist but unsaturated soil in rows at 20 cm intervals with seeding rates that approximated the densities achieved in the TPR plots. Identical NPK fertility rates (Y_1: 120:40:20 kg ha^{-1} NPK; Y_2: 150:40:20 kg ha^{-1} NPK) were used for all experimental treatments. All the P (diammonium phosphate) and K (muriate of potash) plus 1/2 the N (urea and diammonium phosphate) were applied at the time of main field establishment, either at seeding (DSR) or shortly after transplant (TPR). The remainder of the N was basally applied in the early tillering growth phase. After establishment, rice plots were irrigated on mornings when standing water did not exceed the bund height and water supplies were available. Irrigation was accomplished by breeching the bunds and allowing entry of floodwater from a channel adjacent to the experimental area. Bunds were re-sealed when there was approximately 10 cm of standing water in every plot.

Canopy height – from the ground to the apex leaf terminus – was recorded twice weekly for two plants in each plot. Once a week, light interception and leaf area estimates were obtained with an 80 cm probe-length ceptometer (AccuPAR-80, Decagon Devices). For each plot, photosynthetically active radiation (PAR) was measured once above the crop canopy to characterize incident solar radiation and at seven randomly selected locations beneath the canopy to ascertain mean light transmission through the canopy in the PAR range. Together with a measurement of fractional beam radiation, the zenith angle of the sun, and a parameter describing leaf angle distribution (x), one-sided leaf area index (LAI) of the crop was estimated (Accupar-80, 2001). Post-anthesis estimates of active leaf area are unreliable with this method and were avoided. Plant development was normalized to accumulated thermal time ($\sum T_{\text{maximum}} - T_{\text{minimum}}/2$, °C) for cross-treatment comparisons.

In Y_1, destructive core sampling was utilized to assess root biomass in 15 cm increments to a depth of 45 cm. Each core had a total volume of 295 cm^3 (5 cm diameter × 15 cm length) and the sampling point was centered directly over the base of the rice plant (two plants per plot). Roots were separated from the soil with a washing procedure over a small-diameter (1.68 mm) sieve. Roots samples were dried at 60 °C for 3-days to a constant weight to obtain dry-matter values. In Y_2, we interpreted moisture depletion patterns in the soil profile from periodic TDR measurements to make inferences about root function and, by extension, root distribution. When the supply of soil moisture is non-limiting (i.e. uptake is not reduced) over the entire length of the root zone and all other aspects of the water budget accounted for, a strong correlation exists between rates of water depletion at different soil depths and proportional root distribution (Mambani and Lal, 1983; Kamoshita et al., 2000).

Experimental evidence suggests that weeding operations in saturated soils can generate significant soil compaction (Wickham and Singh, 1978). To remove weeding as a potential source of physical change in the DSR treatments, these plots were drained to field capacity prior to weed removal and subsequently reflooded. Weed populations were assessed through biomass sampling and visual composition estimates (i.e. component species percentage of total infestation) at the time of weeding and also at harvest. Immediately preceding the weeding or harvest operations, a 0.5 m × 0.5 m quadrat was randomly placed at two locations in each plot (total sample area = 0.5 m^2 $plot^{-1}$). All aboveground weed biomass was collected and dried at 60 °C for 3-days to a constant weight to obtain dry-matter values.

Crop harvest took place after the rice plants had reached physiological maturity and attained grain moisture levels in the range of 10–15%. To minimize edge effects, the outer four rows on the periphery of all plots were excluded along with 70 cm buffers on the plot ends (harvest area = 2 m × 6.1 m = 12.2 m^2). Total above ground biomass was harvested, manually threshed to separate the grain and straw, and the independent fractions weighed. Moisture content of the grain was measured with a portable moisture meter, whereas straw sub-samples were dried at 60 °C for 3 days to derive correction factor for calculating shoot dry-material. Yield components (i.e. tiller density, bearing tiller density, mean panicle weight, and 1000-grain weight) were also evaluated at harvest by sub-sampling (0.5 m × 0.5 m quadrat) two randomly selected locations in each plot. All plant measurements were normalized to a dry weight basis, with reported yields corrected to 12% moisture content.

2.4. Rice seepage and percolation rates

Percolation refers to vertical water loss in a system, whereas seepage quantifies lateral movement. In practice, it is extremely difficult to separate these terms and they are usually combined in a single composite parameter (i.e. SP) (Bouman et al., 1994; Wickham and Singh, 1978). Determination of SP rates can be achieved by accounting for the easily measured or estimated components of the soil water balance and solving for the residual. For flooded rice systems with no current irrigation, SP (positive values indicate loss) can be calculated with

$$\mathrm{SP} = \Delta W + R - \mathrm{ET} \tag{1}$$

where ΔW is the change in ponded water depth, R the rainfall, and ET is the water lost to the atmosphere as evaporation or transpiration. The water flux estimate is adjusted to express SP losses on a 24 h basis (i.e. cm day^{-1}).

For all 24 h periods when standing water persisted in individual plots, changes in water depth (ΔW) were monitored with rainfall and PET recorded for the same period; together these measurements were utilized to calculate SP. Since there was a free water surface in the paddy for the duration of these measurements, we estimated that actual evapotranspiration approached the potential rate and therefore did not employ a crop coefficient to modify actual ET with crop growth stage.

2.5. Statistical analysis

Rice growth and water balance data was analyzed with a mixed-effects analysis of variance (ANOVA) model (SAS Institute, 2002). SP data was log transformed prior to analysis to ensure normal distribution. Main effects (i.e. tillage, establishment, landscape, and replicate) were tested for significance at the 95% confidence level ($P < 0.05$) along with the two and three-way interaction terms. Separation of treatment means was accomplished with a least squares procedure using the Tukey–Kramer adjustment, also at $P < 0.05$. Single and multi-variate linear regression was used for trend investigation with best-fit equations derived from least squares criteria (Minitab Inc., 2003). Independent variable selection for the regression models was limited to associations that could be biophysically justified.

2.5.1. Y_1 (1999) details

The nursery for the transplanted plots (TPR) was seeded on 4 June. One week later, the direct-seeded (DSR) treatments were line-sown. Assuming an effective germination percentage of 93% (based on a pre-plant tests), the DSR plots were seeded at a rate of 18.8 kg ha^{-1}. On July 1st, seedlings were transplanted in the TPR plots. An amount of 60 kg ha^{-1} N was sidedressed during the early tillering growth phase. All plots were weeded once by hand approximately one month after establishment in the experimental area. Rice plants reached physiological maturity around 30 September and 6 October for DSR and TPR, respectively.

2.5.2. Y_2 (2000) details

The nursery for the transplanted plots (TPR) was seeded on 30 May. On 11 June, the DSR treatments were line-sown. To compensate for the comparatively lower tiller densities observed in the Y_1 DSR plots and also for low seed viability (germination test = 83%), the DSR seeding rate was increased to 23.7 kg ha^{-1}. On 19 June, seedlings were transplanted in the TPR plots. Harvest data from Y_1 revealed that high SP rates were associated with lower yields. This trend was evident among plots with the same establishment method, suggesting a nutrient deficiency produced by variations in the field water balance. Previous studies at this site have not documented rice yield responses to P or K applications in excess of the recommended rates (M. Devare, personal communication). Hence, we speculated that the yield patterns were induced by N dynamics and increased the total N application to 150 kg ha^{-1}. All plots were weeded once by hand approximately one month after establishment in the experimental area. Rice plants reached physiological maturity around 27 September and 1 October for TPR and DSR, respectively.

3. Results

3.1. Productivity—grain and yield components

Tillage practice was not a source of yield variation in the first year ($T_1 = 5.5, T_2 = 5.6, T_3 = 5.5$ mt ha^{-1}). The influence of establishment method on grain production, however, was significant ($P = 0.04$) with the transplanted plots (TPR) out-yielding their direct seeded (DSR) counterparts by more than a metric ton in both the central terrace lowland (6.4 mt ha^{-1} versus 5.2 mt ha^{-1}) and terrace edge upland (5.8 mt ha^{-1} versus 4.7 mt ha^{-1}) environments. Although statistically non-significant, productivity for plots with the same establishment practice was lowered by about 0.5 mt ha^{-1} in the upland setting. The most favorable combination – TPR in the lowland position – conferred a yield advantage of 1.7 mt ha^{-1} over DSR in the upland environment. Similar trends (to yield) were evident for total biomass productivity. In contrast, harvest index was not influenced by establishment method, but was significantly reduced in the upland setting (Table 1). Two- and three-way interaction terms for the main experimental effects were not significant for yield; the influence of landscape and establishment practice appeared to be additive rather than multiplicative. Panicle grain number and individual grain size (i.e. 1000 grain wt) did not vary as a function of experimental treatment (Table 1). Differences in productive (i.e. panicle bearing) tiller density reflected the higher yields attained in the lowland environment among TPR plots (Table 1).

Yield component and productivity penalties associated with DSR and the upland setting were absent or greatly reduced in Y_2. As in Y_1, tillage practice ($T_1 = 6.6, T_2 = 6.8, T_3 = 6.8$ mt ha^{-1}) and interactions between the main effects were not significant sources of variation (Table 1). Minor differences did persist between DSR (6.5 mt ha^{-1}) and TPR (6.9 mt ha^{-1}) grain yields, but productivity was equivalent across landscape setting for each establishment method. Effective tiller density trends mirrored those observed for productivity, with no apparent influence of

Table 1
Rice productivity and yield components for each establishment-landscape treatment combination

	Tillers (# m^{-2})	Productive tillers (# m^{-2})	Panicle wt (g)	1000 grain wt (g)	Total DM (mt ha^{-1})	HI	Yield (mt ha^{-1})
Y_1							
DSR-lowland	264 b	198 (75%) a	2.34 a	23.4 a	9.34 a	0.52 ab	5.21 ab
TPR-lowland	340 a	241 (71%) b	2.36 a	23.2 a	11.38 b	0.52 a	6.42 c
DSR-upland	263 b	194 (74%) a	2.13 a	23.0 a	8.82 a	0.47 b	4.68 a
TPR-upland	292 b	229 (78%) b	2.21 a	22.4 a	11.03 b	0.48 ab	5.75 bc
Y_2							
DSR-lowland	274 a	252 (94%) a	2.31 a	25.2 a	10.73 a	0.53 a	6.47 a
TPR-lowland	290 a	281 (98%) a	2.21 a	25.8 a	12.04 a	0.50 ab	6.87 a
DSR-upland	258 a	255 (99%) a	2.18 a	25.8 a	11.19 a	0.51 ab	6.48 a
TPR-upland	295 a	267 (93%) a	2.31 a	25.8 a	12.65 a	0.49 b	6.98 a

Tillage system had no effect on rice performance in either year. Different letters indicate statistical significance of the least squares means at $P < 0.05$ for column-wise comparisons. Numbers in parentheses under productive tillers refer to the percentage of total tillers that had viable spikes.

environmental setting or establishment technique (Table 1).

3.2. The soil water balance

3.2.1. Piezometric surfaces

Free water was always observed at the three piezometric sampling depths (20, 50, 100 cm) when there was standing water in the plots. For these periods, mean values for each landscape—establishment combination are shown for Y_1 (Fig. 2). The influence of landscape position was substantial with significantly lower pressure heads at all monitoring depths in the upland environment, presumably due to the influence of terrace edge proximity on groundwater fluxes (i.e. distance to surface discharge). Within each landscape position, pressure head at 20 cm was consistently lower in the TPR treatments, reflecting reductions in soil hydraulic conductivity in the top 20 cm of the soil from puddling; all other factors being equal, pressure head is inversely related to the conductivity of the overlying soil (e.g. Hillel, 1982). Patterns observed in Y_2 were similar to those in Y_1, and tillage method did not significantly influence the piezometric surfaces in either year.

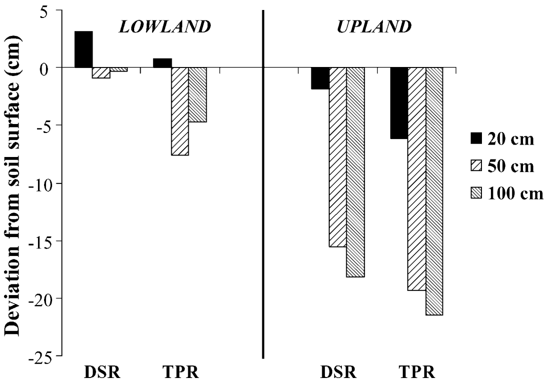

Fig. 2. Mean piezometric surfaces at 20, 50, and 100 cm soil depths for periods when floodwaters were present and the soil profile was fully saturated (Y_1). Piezometers measure positive water pressure (i.e. hydraulic head) at specific soil depths. Lower heads characterized all monitoring depths in the upland environment, reflecting higher groundwater flux rates near the terrace edge. Reduced hydraulic head in the TPR treatment is indicative of lower soil hydraulic conductivities relative to DSR.

3.2.2. Seepage and percolation and floodwater persistence

Seepage and percolation (SP) rates in Y_1 were significantly influenced ($P < 0.01$) by landscape position and rice establishment practice. In the upland setting, both establishment methods had substantially higher SP rates than the least water-conserving treatment (i.e. DSR) in the lowland environment (Table 2). The impact of direct seeding on SP was more pronounced in the upland landscape, with SP losses 1.7 cm day^{-1} higher than their TPR counterparts; although similar on a percentage basis, the absolute difference was reduced to 0.6 cm day^{-1} in the lowland position. Outcomes in Y_2 were very similar, but tillage was also a significant ($P = 0.017$) source of SP variation. Since saturated hydraulic conductivity (K_{sat}) of the top 50 cm of the soil profile was not

Table 2
Mean seepage and percolation rates (SP, cm day^{-1}) and number of days that continuous floodwater (DCF, day) was observed for each landscape–establishment treatment combination

	Seepage and percolation (SP, cm day^{-1})		Persistent floodwater[a] (DCF, day)	
	Y_1	Y_2	Y_1	Y_2
DSR-lowland	2.24 a	2.34 ab	21.0 ab	22.3 a
TPR-lowland	1.67 a	1.62 a	25.4 a	25.4 a
DSR-upland	4.70 b	6.12 c	8.8 c	13.0 b
TPR-upland	3.01 ab	4.11 bc	16.8 b	20.2 ab

As main effects, landscape placement and establishment method were significant ($P < 0.05$) sources of SP variation in both years of the experiment. Different letters indicate statistical significance of the least squares means at $P < 0.05$ for column-wise comparisons.
[a] Mean number of days (day) that standing water was continuously present at the soil surface over a 24 h period.

influenced by tillage method in Y_2 (see McDonald et al., in press), this outcome likely resulted from imperfect experimental blocking for intrinsic groundwater hydrology gradients and not as a result of fundamental changes to edaphic properties from tillage.

According to Darcy's Law, water flux density between two points is inversely proportional to the distance between them and directly proportional the conductivity of the soil. Hence, saturated soils in close proximity to surface discharge points like seeps and rivers will have higher water flux rates than areas situated further from these features, all other factors being equal. The sum of the inverse distances (i.e. $1/D_{east} + 1/D_{south}$) to the two principal terrace edges at our site (i.e. sites of surface discharge) explained 60% ($R^2 = 0.6$) of the variation in SP rates among the plots. Together with the saturated conductivity of the top 20 cm of the soil, log transformed SP rates were well predicted ($R^2 = 0.78$) in Y_2 with the linear regression:

$$\log(\mathrm{SP\,cm\,day^{-1}}) = -0.629 + (1.67\log(0-20\,\mathrm{cm\,K_{sat}\,cm\,day^{-1}})) + (7.83 \times \mathrm{sum\ inverse\ distance})$$

Proximity to the terrace edges and surface soil hydraulic conductivity were similarly responsible for determining floodwater export rates in Y_1.

Flooding persistence trends mirrored those in the SP data in both years, with differences between the establishment methods moderated in the lowland environment (Table 2). In the upland setting, TPR establishment resulted in 7–8 additional days with persistent floodwater. Since all plots were uniformly irrigated, the mean number of days in a fully flooded condition can be considered a proxy metric for the frequency of presumptive reduction–oxidation cycles.

3.2.3. Implications for stress

With cessation of the major monsoon rains and loss of consistent irrigation in the later stages of the growing season, the soils at our site were periodically unsaturated. For these comparatively dry periods, the strong cross-treatment correspondence of soil matric potentials (ψ_{matric} at 10 cm) within each landscape position suggests that rice cultural practices have little influence on soil moisture conditions as the profile dries (Fig. 3). Rates of groundwater recession were tightly coupled to landscape placement, with the watertable in the lowland position always within 50 cm of the soil surface (data not shown). Soils at 10 cm depth in the lowland position were consistently wetter than those in the upland setting, presumably due to higher rates of capillary rise from comparatively shallow groundwater. Rather than differences in hydraulic conductivity (e.g. from rice establishment method), these findings suggest that depth to groundwater – and by extension landscape position – is the principal factor controlling drought vulnerability at this site. However, in neither year of the experiment did the documented matric potentials exceed values suggested by other researchers as threshold points for the development of water stress (e.g. Hasegawa and Yoshida, 1982; Wopereis et al., 1996).

3.2.4. Associations with yield

In Y_1, the interrelated factors of SP rate and floodwater persistence were both correlated with grain yield. Lower floodwater export rates (SP) and more consistent flooding (i.e. fewer reduction–oxidation cycles) favored rice productivity. Considering all plots, the number of days with continuous floodwater (DCF) described over 50% of the total observed yield (mt ha^{-1}) variation (yield = 0.073 × DCF + 4.2, $R^2 = 0.54$) and this general trend held within each

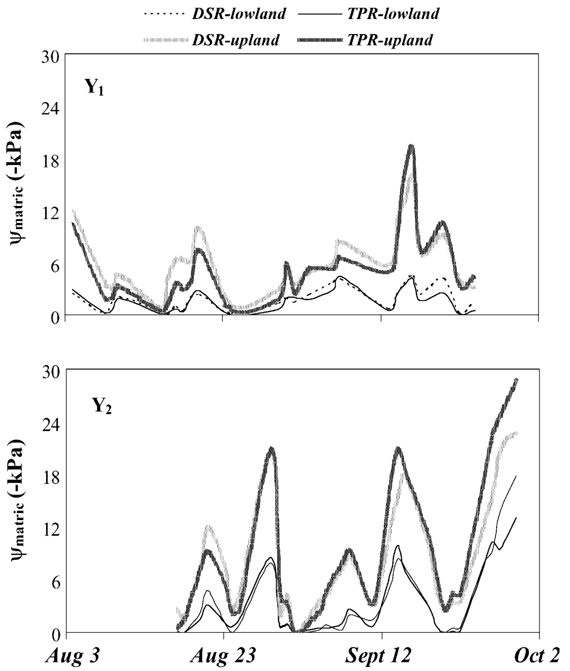

Fig. 3. Soil matric potential ($\psi_{matric,}$ kPa) at 10 cm depth during the late vegetative and reproductive phases of rice growth. Zero values indicate saturated conditions. Within each landscape position, the similarity of soil water status across all tillage and establishment practices suggests that landscape position rather than soil management factors determine drought vulnerability at this site.

establishment treatment. In contrast, differences in soil matric potential at 10 cm depth during the latter portion of the season were only weakly correlated with grain yield ($R^2 = 0.21$).

The impact of plot water balance variations on rice productivity was diminished in Y_2, presumably due to increased nitrogen fertilization to 150 kg N ha^{-1}. Neither SP rate nor flooding persistence (linear regression $R^2 = 0.14$) were strong predictors of yield in Y_2 and there was no correlation between productivity and soil matric potential at 10 cm despite the comparatively dry conditions observed during grain fill (see Fig. 3).

3.3. Weed dynamics

3.3.1. Composition and treatment effects

In both years of the experiment, the dominant weed complex for all treatments consisted of variable flatsedge (*Cyperus difformis* L.), ricefield flatsedge (*Cyperus iria* L.), junglerice (*Echinochloa colona* L.), and barnyardgrass (*Echinochloa crus-galli* L.). In Y_1, establishment method was a significant factor for weed biomass at rice harvest ($P < 0.05$), with DSR plots sustaining six-fold higher weed biomass (105.4 ± 37.1 g m^{-2}) than transplanted rice (18.1 ± 10.4 g m^{-2}). Landscape, tillage, and the interaction terms between the main effects were all non-significant. Similarly, higher DSR weed biomass was evident in Y_2 (87.4 g m^{-2} versus 35.4 g m^{-2}), although in this case differences were not statistically significant.

3.3.2. The water balance and weed growth

Landscape position did not influence weed biomass in Y_1 or Y_2; hence, we inferred that the substantial range of water regime variation documented in both years did not differentially suppress weed growth. Trend evaluation of weed responses to flooding persistence within each establishment treatment supports this conclusion (Fig. 4). Weed biomass under the most consistently inundating conditions was similar to that with the most ephemeral. These trends suggest that weediness differences between DSR and TPR establishment methods were principally determined by changes to the timing and efficacy of control measures and not by modifications to the soil water balance.

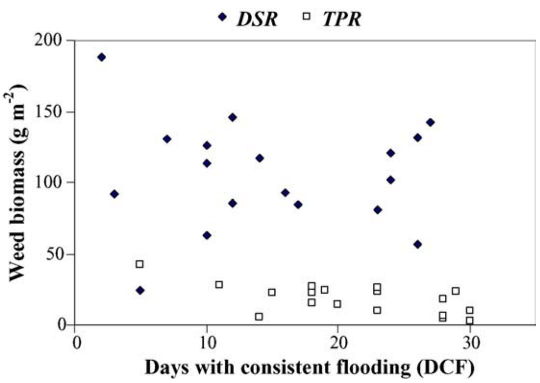

Fig. 4. Weed biomass at harvest (Y_1) for individual plots as a function of days with consistent floodwater inundation (DCF). Within each establishment method, there was no indication that differences in the plot water balance influenced the biomass or composition of the weed community.

3.3.3. Weed competition and rice productivity

Trend analysis of data segregated by establishment practice (Y_1) suggests that the inverse association between weed biomass and yield observed in the aggregated (i.e. experiment-wide) dataset was not causal. Within both the DSR and TPR treatments, there was no discernable yield loss relationship as a function of weed biomass. In Y_2, the range of weed pressure within each establishment practice was larger than in Y_1. Also, mean yields for TPR and DSR establishment practices were comparable in Y_2. Together, these factors diminished any association between weed biomass at rice harvest and the aggregated yield response. As in Y_1, there was no apparent yield loss relationship as a function of weed biomass within the establishment practices.

3.4. Rice growth and development

3.4.1. Leaf area

In Y_1, one-sided leaf area (LAI, m^2 leaf/m^2 ground surface) was influenced by rice establishment method, with direct seeding having significantly ($P = 0.018$) higher mean maximum values than the transplanted plots (DSR = 3.6, TPR = 2.7). This was reversed in Y_2 (DSR = 3.0, TPR = 4.0), but differences between the establishment methods were not statistically discernable. Tillage, landscape, and main effect interactions did not affect maximum LAI in either year.

Vigorous leaf area development in the first year was correlated with low rice yield. This observation is consistent with other research suggesting that supra-optimal LAI levels sequester nitrogen to the detriment of grain yield in N-limited systems (Dingkuhn et al., 1990; Schnier et al., 1990). Within each establishment treatment, however, associations between leaf area and yield were not apparent despite a substantial range (~1 unit LAI) of maximum values. With the yield gap between DSR and TPR narrowed in Y_2, there was no association between maximum LAI and grain yield.

3.4.2. Canopy height

Maximum canopy heights were similar for DSR and TPR plots in Y_1. Nevertheless, two instructive features segregated the establishment practices. First, early growth was delayed in the TPR plots by approximately 100 accumulated thermal units (Fig. 5). This difference held through maximum height attainment, suggesting an overall phenological delay from transplant injury of similar duration. In the early stages of Y_2, canopies of both establishment practices developed at the same rate and no growth penalty from transplanting was evident (Fig. 5). Yet the presumptive influence of transplanting on development was apparent later in the season, with DSR plots ceasing height expansion approximately 100 thermal units prior to TPR. With an extended period for vegetative growth and no penalty from transplanting, the TPR plants were an average of 14 cm taller than their DSR counterparts. At transplanting, rice seedlings were younger in Y_2 than in Y_1 (13 days versus 20 days from emergence) and apparently less vulnerable to the stresses of establishment while experiencing similar developmental delays to those observed in the first year.

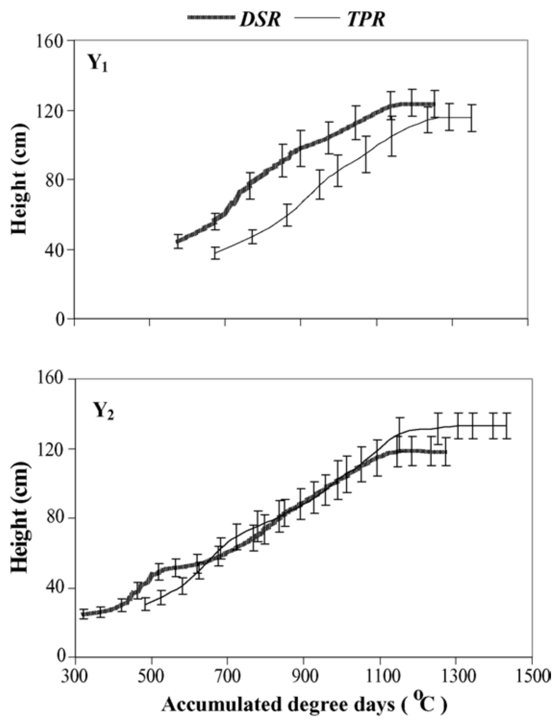

Fig. 5. Plant height (cm) as a function of cumulative thermal time and rice establishment method (±1S.D., $n = 18$). TPR seedling age in Y_2 was 13 days vs. 20 days in Y_1, and this difference likely explains the comparatively brief height development delay following transplanting in Y_2.

Landscape, tillage, and interactions among the main experimental effects had no influence on canopy height development.

3.4.3. Roots

Core sampling to 45 cm at anthesis (Y_1) revealed very similar root distributions with depth for every landscape–establishment combination. In all cases, over 85% of the root mass (ca. 4.45 mg cm^{-3} soil) was concentrated in the top 15 cm of the profile, with 3–5% (ca. 0.23 mg cm^{-3} soil) from 30 to 45 cm. In terms of total carbon allocation, rice in the upland setting partitioned marginally more assimilates to roots (ca. 0.15 mg cm^{-3} soil), though differences were not statistically significant.

In Y_2, functional rooting comparisons were made from analysis of soil moisture depletion patterns during low-precipitation periods when the rice crop had a closed canopy and was actively transpiring. Within each landscape position, total water depletion (to 54 cm) was equivalent across all treatments. For the upland setting, no differences in depth-wise acquisition patterns were observed (Fig. 6). During the most pronounced drying phase (early September), the bulk of the moisture loss in the upland setting occurred from 0 to 18 cm (54 mm), with smaller amounts removed from 18 to 36 cm (23 mm) and 36 to 54 cm (12 mm). In the lowland environment, establishment practice had a significant impact on the depth-wise distribution of soil water depletion (Fig. 6). In the September dry-down period, TPR plots lost 9 mm more water in the surface zone than the DSR plots, whereas the situation was reversed from 18 to 36 cm with DSR losing 9 mm more water. Neither establishment method demonstrated significant water content changes below 36 cm over the time-course of our measurements. Tillage had no impact on total water depletion or depth-wise acquisition patterns.

3.4.4. Crop duration

From planting to physiological maturity in Y_1, direct seeded rice accumulated 1521 thermal units (AccDD, °C). For transplanted rice, 1636 AccDD accrued from planting (in nursery) to maturity. These results suggest that transplanting stress delayed crop development on the order of 115 thermal units. The disparity between establishment methods was larger in Y_2, with DSR accumulating 1563 and TPR 1729 AccDD to reach physiological maturity.

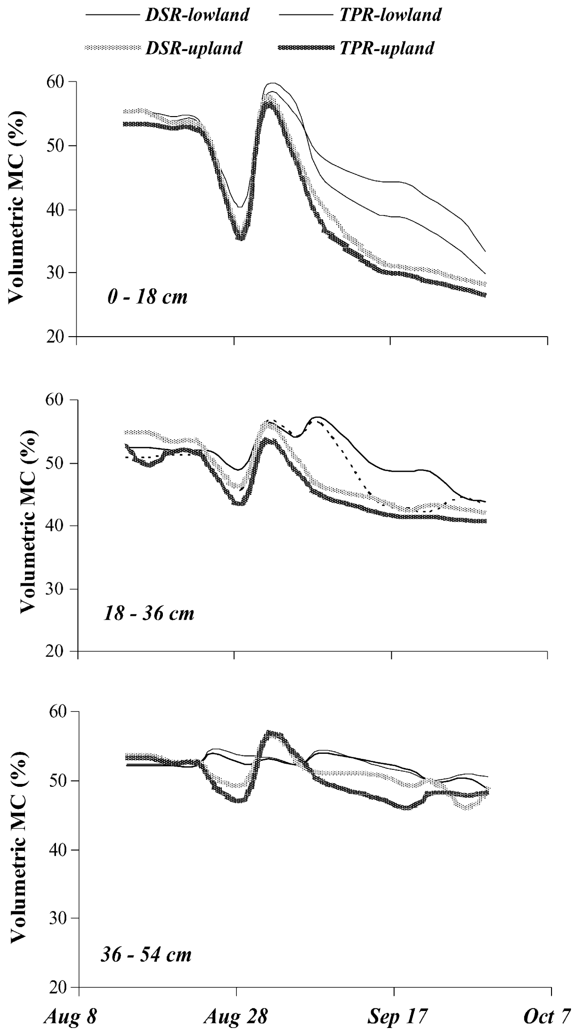

Fig. 6. Volumetric water contents in 18 cm increments (to 54 cm) for each landscape–establishment treatment combination. In the lowland setting for the mid-September measurement period, differences between DSR and TPR from 0 to 18 and 18 to 36 cm are statistically significant ($P < 0.05$).

4. Discussion

On the silty loam soils of the Kathmandu basin, rice establishment method (direct seeding or transplanting into puddled soil) had significant implications for water losses to seepage and percolation, whereas deep tillage had little impact. Nevertheless, spatial proximity to the terrace edge was the foremost controlling factor for SP at our experimental site. Establishment practice effects on SP (TPR: 25–36% decrease) were less significant than the influence of landscape position (lowland: 45–62% decrease). In contrast to our findings, other researchers document a three-fold SP increase with direct seeding (DeDatta et al., 1973) and a four-fold rise in water export when pre-existing plough soles are breeched with deep tillage (Chen and Liu, 2002). As the soils dried with the weakening of the monsoon rains, matric potential in the root zone was governed by landscape position and its impact on shallow groundwater dynamics. In contrast to Sharma and DeDatta (1985) and Saleh and Bhuiyan (1995), these findings imply that rice establishment practice does not alter drought probability at our site.

Weed pressure was higher in the DSR plots in both years of the experiment, but did not appear to be linked to changes to the field water balance. Rather, we speculate that the direct seeded plots had more intense weed pressure due to reduced control efficacy. In DSR systems, rice is typically sown prior to the principal flush of weed emergence; hence, primary tillage confers less effective early control. Moreover, DSR plots were drained to field capacity before post-emergence hand weeding to minimize soil compaction. Incomplete root stock removal and rapid population re-establishment in the DSR plots contrasted to whole-weed eradication in the flooded TPR system. Despite sustaining higher weed biomass, we found no compelling indication of competition-induced yield losses for DSR with one post-emergence hand weeding.

Consistent with other research on hydric soils, core sampling in Y_1 revealed that more than 85% of the total root biomass was concentrated in upper 18 cm of the soil (e.g. Sharma et al., 1994) and that root distribution was not appreciably influenced by rice establishment method (e.g. Sharma et al., 1987; Samson et al., 1995). A slight increase in total root dry matter was documented in the upland environment but was not statistically significant. Analysis of moisture depletion patterns in Y_2 suggested comparable root activities at depth for TPR and DSR plots in the upland environment, whereas DSR plots in the lowland position had marginally higher root activity from 18 to 36 cm than their TPR counterparts. Unlike Akhtar and Quereshi (1999), we found no evidence that deep tillage facilitated preferential root elaboration at depth.

In the first year of the experiment, lower SP rates – and more consistent inundation – were positively associated with grain production, implying that persistent flooding is advantageous to rice productivity. DSR yielded significantly less than TPR in both landscape positions (ca. 1 mt ha^{-1}), with the lowland environment outperforming the upland (ca. 0.5 mt ha^{-1}). Based on this evidence, we speculated that higher SP rates and more cycles of oxidation and reduction inhibited crop nitrogen recovery by way of nitrate leaching losses from the root zone and, to a lesser extent, denitrification (e.g. Sanchez et al., 1973; Reddy and Patrick, 1975; Lal, 1985). To determine if nitrogen was contributing to the observed yield dynamics, the rate of fertilizer N was increased from 120 to 150 kg N ha^{-1} in Y_2. With this change and a higher DSR seeding rate, the productivity gap between TPR and DSR was reduced to 0.5 mt ha^{-1} and there was no yield penalty associated with the upland environment despite root zone matric potentials that approached −30 kPa during the reproductive growth phase. As in Y_1, weed biomass was higher with DSR, but trend analysis did not suggest a causal relationship with yield. Unlike the first year, transplanting younger seedlings (13 days versus 20 days) extended crop duration for the TPR plots without compromising early season growth rates. We conclude that the 0.5 mt ha^{-1} productivity increase of TPR over DSR was generated by the extended growing period from establishment to physiological maturity in the transplanted plots. By contrast, in years with earlier cessation of the monsoon rains, longer crop duration may prove less favorable – or perhaps damaging – to rice productivity.

Notwithstanding comparable grain output in Y_2, direct seeding and the upland landscape position appear to be inefficient with respect to nitrogen utilization. As a rule, farmers in Nepal apply fertilizers at sub-optimal rates. For Nepal, the FAO (2002) estimates that average fertilizer use is 35 kg ha^{-1} year^{-1} and that the inherent nitrogen supplying capacity of most soils is low. The paucity of amendment use in Nepal suggests that extension personnel should advocate the most water-conserving management practices to maximize nitrogen recovery.

Evaluation of the agronomic water use efficiency (i.e. yield per unit water input) is somewhat more complicated. Direct seeded rice occupies the main fields earlier than TPR, but is characteristically a shorter duration crop and cannot be flooded until it attains sufficient stature to avoid complete inundation. Fundamentally, the water use efficiency metric is most relevant when water resources are being allocated between competing uses or from limited-source storage (e.g. ponds). On the hydric land units of the Kathmandu Valley, much of the overland flow into rice paddies is passive and does not represent an opportunity cost in any real sense if on-site storage is lacking and water stress is principally determined by landscape position. Furthermore, water export from a paddy as seepage and percolation often serves as irrigation for lower elevation fields.

5. Conclusions

Despite significant changes to the field water balance with direct seeded establishment (DSR), we found no evidence that selective drought or more substantial weed populations limited rice performance. In fact, drought vulnerability at this site appears to be solely determined by the relationship between landscape placement and shallow groundwater dynamics. Our results suggest that DSR productivity can approach transplanted systems when nitrogen fertilizer is supplied at high rates (ca. 150 kg N ha^{-1}). Nevertheless, establishment practice and landscape placement significantly affected seepage and percolation rates and the continuity of standing water in the rice field, thereby influencing the apparent nitrogen economy of the system. SP differences (i.e. mm day^{-1}) between DSR and transplanted plots increased threefold in the upland setting, suggesting that appropriate landscape selection can moderate the risk of low nitrogen recovery in DSR systems.

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