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Wheat responses to novel rice cultural practices and soil moisture conditions in the rice–wheat rotation of Nepal

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Abstract

Degraded soil physical conditions from puddled rice (*Oryza sativa* L.) have been associated with low wheat (*Triticum aestivum* L.) yields in the rice–wheat rotation. To assess wheat productivity responses to rice management alternatives at a site in Nepal, we compared the impact of six rice tillage (10 cm surface tillage – T_1, 50 cm deep chisel – T_2, deep chisel + moldboard plough – T_3) and establishment method (soil puddling + transplanting – TPR, direct seeding – DSR) combinations over two seasons (Y_1, Y_2). While significant soil physical differences were documented among the treatments during the rice season, we found little evidence that deep tillage or direct seeding for rice improves wheat performance. Rice cultural practices had no influence on the dynamics of soil water acquisition or inferred patterns of wheat root development. Although aboveground biomass production was similar, water acquisition, plant morphology, and yield were notably different between the first and second years. The Y_1 crop had superior grain size (500-grain weight: 19.2 g versus 17.8 g) and tiller densities (382 m^{-2} versus 320 m^{-2}), but grain productivity was 1.4 t ha^{-1} lower (3.0 t ha^{-1} versus 4.4 t ha^{-1}) than in Y_2. Comparatively poor performance in Y_1 was reflected in the harvest index (0.27 versus 0.41) and density of spike-bearing tillers (188 m^{-2} versus 247 m^{-2}). As an apparent consequence of pre-emergence irrigation, wheat in Y_2 had higher root activities at depth with 11% of total water uptake derived from soil regions below 54 cm under non-limiting moisture conditions. In contrast, the Y_1 crop was first irrigated at 42 DAE and uptake below 54 cm accounted for only 3% of the total under similar non-limiting conditions. Deeper rooting and a second irrigation at the end of tillering growth phase enabled the crop in Y_2 to sustain exponential development for 25 d during the floral initiation and spike growth stages, whereas the Y_1 crop sustained exponential growth for only 14 d. This difference was reflected in greater canopy height (94 cm versus 80 cm) and maximum leaf area (3.1 versus 2.7) in Y_2. For allocating limited water resources, these findings suggest irrigation at planting to facilitate deep rooting followed by a second application at the end of the tillering growth phase to minimize water stress during grain sink formation. Optimized water management rather than modified rice cultural practices appears to be the best route for maximizing resource capture and wheat productivity at this site.

Keywords: Rice–wheat system; Transplanted rice; Direct seeded rice; Deep tillage; Root distribution; Soil physical properties; Soil water dynamics; Drought stress; Morphology

1. Introduction

For dry-season crops like wheat in rice-based cropping rotations, soil physical conditions created by wet tillage for rice (i.e. puddling) are widely considered a key reason for the gap between potential and realized levels of productivity (Meelu et al., 1979; Hobbs et al., 1994; Timsina and Connor, 2001). Nevertheless, field evaluations of the link between puddled soils and low dry-season crop productivity have given inconsistent results, suggesting a strong site and year dependence. Accordingly, the benefits to dry-season crops from alternative management practices for rice (e.g. direct seeding into dry soils) are difficult to predict and influenced by interactions among factors such as soil texture and organic matter content, the legacy of previous land management practices, and weather.

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Silty soils tend to be structurally unstable and hard-setting when dry (Isbell, 1995). Hobbs et al. (2002) report a 10% yield advantage for wheat on a silty loam soil with adoption of no-puddle rice establishment practices, whereas no advantage was observed on a sandy loam. Likewise, productivity responses are inconsistent across crop types. Kirchhof et al. (2000) note that puddling for rice reduced soybean (Glycine max L.) yield but did not influence mungbean (*Vigna radiata* L.) or peanut (*Aracis hypogaea* L.) productivity at the same site. Other authors document substantial soil physical changes from puddling on finer textured soils that did not result in establishment or growth penalties for several cereal and legume crops (Humphreys et al., 1996; Singh et al., 1996; Tranggono and Djoyowasito, 1996). Some of this variability in response is undoubtedly due to the various ways which subsequent crops in the rotation can be affected by rice cultural practices.

Prior to field preparation for wheat establishment, the surface soil must be sufficiently dry to permit access. Puddled soils may require several days of drainage and evaporation following rice harvest to reach an appropriate moisture content for tillage (Flinn and Khokhar, 1989). Several studies in South Asia have documented a linear decline in wheat productivity (ca. 0.7–1.5%) for every day planting is delayed beyond November (Randhawa et al., 1981; Hobbs et al., 1987; Ortiz-Monasterio et al., 1994; Ahmed and Meisner, 1996). Wheat productivity is sensitive to high temperatures (i.e. $T_{ave} > 20\ ^{\circ}C$) during anthesis and grain fill (Midmore et al., 1984), and daily average temperatures in this range are common in Nepal from April onwards, just as wheat reproductive growth begins. Conversely, slower drainage rates in puddled soils may promote favorable residual water conditions for wheat establishment.

High seed germination rates and stand uniformity require adequate seed–soil contact. When dry enough to initiate tillage, puddled soils typically have massive structure resulting from aggregate dispersion and compaction during wet tillage (Adachi, 1990). Working these soils into the smaller aggregates required for good seedbed tilth can prove difficult, with cloddy conditions commonly persisting even following intensive tillage (Hobbs et al., 1994; Timsina and Connor, 2001). Kirchhof and So (1996) found that mungbean emergence rates were negatively influenced by soil puddling on a silt loam soil. Farm surveys in the rice–wheat systems of South Asia associate poor wheat stands with low seed germination rates (Fujisaka et al., 1994).

Puddling reduces the hydraulic conductivity of the soil profile, and may lead to perched water tables and saturated conditions in the wheat root zone during heavy rainfall or flood irrigation. Under anoxic conditions, wheat has limited capacity to form aerenchyma as an adaptation to low soil oxygen concentrations. Persistent flooding can cause stomatal closure, limiting CO_2 acquisition and photosynthesis while promoting senesce as a result of reduced nutrient uptake (Drew, 1996). Likewise, root growth into deeper soils layers can be directly inhibited. Timsina et al. (1994) demonstrated the negative influence of persistent soil saturation on cowpea (*Vigna unguiculata* L.); crop growth rate, maximum leaf area, and final grain yield were significantly reduced relative to the well-drained control with root development in the saturated soil limited to the top 10 cm of the soil profile. Post-irrigation waterlogging has been identified as a principal constraint to wheat productivity on puddled soils in some regions of Nepal (Harrington et al., 1990).

The effect of soil compaction and increased mechanical resistance on root development is well established (Hasegawa et al., 1985; Oussible et al., 1992; Vleeshouwers, 1997). In the presence of a dense plough pan from soil puddling, wheat roots can be restricted to the surface soil layers (ca. top 15–30 cm), accessing insufficient water and nutrients to meet crop demand (Ishaq et al., 2001). Sur et al. (1981) showed a significant downward shift in root distribution and a 48% increase in total root mass for wheat established after maize rather than puddled rice. Sadras and Calvino (2001) suggest that every centimeter reduction in rooting depth can decrease wheat yield by 0.4%. Other research documents a 1.6 t ha^{-1} wheat yield increase for every 1 MPa reduction in soil strength in the plough pan (Busscher et al., 2000). Several studies have demonstrated the advantage of deep tillage for reducing penetration resistance within the plough pan (Busscher et al., 2000) and the positive influence that lowered soil resistance can have on root development (Khan et al., 1998), water acquisition (Holloway, 1991) and crop yield (Cassel et al., 1990). Deep root development reduces susceptibility to drought and helps retains yield potential during periods of low or no rainfall (Ahmed et al., 1996).

For most regions that utilize the rice–wheat cropping pattern, there is general consensus that wheat yields will be enhanced if soil puddling for rice is eliminated or its intensity reduced (Fujisaka et al., 1994; Hobbs et al., 1994; Timsina and Connor, 2001). Deep tillage before rice establishment can also improve soil physical conditions for dry-season crops by shattering existing plough pans or, alternatively, by promoting pan formation deeper in the soil when combined with puddling (Hobbs et al., 1994). We compared the influence of direct seeding (i.e. no-puddle rice establishment) and two forms of deep tillage for rice on wheat performance over two cycles of the rice–wheat sequence. Considering the characteristics of our experimental site (e.g. substantial soil cracking and elevated hydraulic conductivity following rice), we anticipated that the principal benefits of deep tillage and direct seeding would be deeper root development and an expanded zone for water and nutrient acquisition. We also anticipated that improved tilth from structural regeneration in the directly-seeded treatment would benefit wheat establishment.