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Effect of placement of straw mulch on soil conservation, nutrient accumulation, and wheat yield in a humid Kenyan highland

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Abstract

Mulching affects soil nutrient dynamics and crop yields. The effects of quantity and method of application of wheat straw mulch on soil loss, nutrient accumulation, nutrient loss, and wheat yield were evaluated in a field experiment in the acidic, dark red, Rhodic Ferralsols of Kenya. The experiment involved three levels of wheat straw mulch (0, 3, and 5 $Mg{\cdot}ha^{-1}$) either incorporated in the soil (0 to 0.2 m) or surface applied. Surface application at 5 $Mg{\cdot}ha^{-1}$ decreased annual soil loss to 1.82 $Mg{\cdot}ha^{-1}$ from 14 $Mg{\cdot}ha^{-1}$ in the control. Deep placement of 5 $Mg{\cdot}ha^{-1}$ of straw, however, increased soil organic matter content by 23%. Annual losses of NH_4–N, NO_3–N, PO_4–P, and available K in the sediments were 0.02, 0.04, 0.06, and 0.44 $kg{\cdot}ha^{-1}$, respectively in the 5 $Mg{\cdot}ha^{-1}$ surface treatment. Straw mulch treatments also enriched NO_3–N concentration in the 0 to 0.4 m soil layer. Surface application of 3 $Mg{\cdot}ha^{-1}$ straw gave the highest grain yield of wheat and the highest net returns (US$ 747), which was 30% more than that of the control.

Keywords: Soil erosion, Surface runoff, Soil organic matter, Sediment enrichment, Land degradation.

Introduction

Using straw mulch for soil and water conservation has been extensively studied in the arid and semi-arid conditions of tropical Africa (Tian et al., 1995; Danga et al., 2009). Few studies, however, have assessed its effects on soil conservation and wheat yield in the humid highlands. These regions are generally characterized by high annual rainfall and relatively low evaporation rates. Although the soils have high organic matter (OM) content and aggregate stability, which allow high infiltration rates (Wakindiki and Ben-Hur, 2002a), high soil loss rates even on gentle slopes have been reported. For example in West Africa, soil losses up to 20 $Mg{\cdot}ha^{-1}{\cdot}y^{-1}$ were reported on lands with 5% slope (Kaumbutho et al., 1999). Gachene et al. (1997) observed that surface placement of maize straw in Kabete, central Kenya increased infiltration rates and decreased soil erosivity. Crop residues also contain nutrients like N, which is mineralizable. Danga et al. (2009) attributed increased wheat yield following long-term straw application to improved N nutrition. However, high amounts of straw on the soil surface may increase disease infestation and lower soil temperatures early in the planting season, causing yield reductions in certain situations (Rasmussen et al., 1997). This necessitates optimizing the quantities of mulch applied as well as the method of straw application. Surface vs. deep placement of straw mulch can alter soil microbial activity too. For instance, incorporated straw decomposed faster than that placed on the surface (Christensen, 1986). We hypothesized that the amount and placement of straw mulch affect soil erosion, nutrient dynamics, and wheat yield in the humid tropical highlands. Our objective was to evaluate the effects of amount and placement of straw mulch on soil loss, nutrient accumulation and losses, and wheat (*Triticum aestivum* L.) yield in a humid highland of Kenya.

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Materials and Methods

A field experiment was conducted at the Moi University farm in Kenya (35°18'E and 0°35'N, at an elevation of 2154 m above sea level). The experimental site with 7% slope had been under wheat crop for 5 years. Long term precipitation ranges from 900 to 1300 mm, with an annual average of 1124 mm. Rainfall is evenly distributed from March to September, with three distinct peaks in April, June, and August (Fig. 1). Mean maximum and minimum temperatures were 23°C and 10°C, respectively, and temperature variability within a year was small. Soils of the experiment site are acidic, dark red, friable Rhodic Ferralsols underlain by tertiary phonolites and murram (FAO, 1990).

Pre-treatment soil characterization was done by taking profile pits and collecting soil samples, horizon-wise. The samples were taken to the laboratory, air-dried, crushed, and sieved to pass a 2 mm mesh. Physical and chemical properties of the soil (Table 1) were determined following standard procedures (Rowell, 1994). The experimental field was cultivated to a depth of 0.2 m with hand tools, and raked to produce a uniform tilth on 28 March 2003. Fifteen erosion plots (2 m wide and 10 m long, separated by a 1 m wide buffer) were constructed across the slope, a month later. On 6 May 2003, 39.3 kg·ha^{-1} of P, as single-superphosphate, and 12.6 kg·ha^{-1} of N, as calcium ammonium nitrate, were incorporated into the soil (0.15 m) by raking. Mulching treatments, which included three levels of wheat straw application (control with no mulch and 3 and 5 Mg·ha^{-1} mulch) and two placement methods (deep placement into the top 0 to 0.2 m soil and surface placement) were administered simultaneously and wheat seeds (cv. 'Kenya Fahari C1') drilled across the slope at the rate of 125 kg·ha^{-1}. Deep placement, however, was done before seeding using hand tools but surface mulch was applied soon after seeding. The trial was laid out in a completely randomized factorial design with three replicates. Agronomic practices like tillage, planting, plant population, and fertilizer application were in accordance with the local farmers' practices. Selection of the straw mulch treatments also was consistent with the local practices of using wheat straw for erosion control. Small-scale wheat farmers in Kenya generally use an ox-drawn mould board plough, which can incorporate up to 5 Mg·ha^{-1} straw approximately 0 to 0.2 m deep.

Soil loss was measured after each erosive rainstorm event (Fig. 1). The contents of the tanks were thoroughly stirred after recording the total volume of the runoff (using a measuring cylinder) and 0.25 L and 0.75 L samples of the suspension were drawn. Soil loss was determined by oven drying the 0.75 L samples at 105°C and weighing the sediments. The 0.25 L samples were transported to the laboratory, centrifuged at 5500 rpm and the supernatant liquid and the sediment separated for measurement of NH_4–N, NO_3–N, PO_4–P, and K. NH_4 and NO_3 were extracted using 2 *M* KCl solution, PO_4 by the Bray I, and the K by the Mehlich-1. The nutrients in the extracts and runoff were determined by steam distillation for NH_4 and NO_3, by spectrophotometry at 660 nm for PO_4, and by ICP-AES for K (Rowell, 1994). The nutrient load of the sediment was expressed based on total soil loss per ha and clay percentage of the sediment.

Soil samples were also taken from three positions in all erosion plots for chemical analyses both before (prior to the fertilizer application and seeding) and after the

Table 1. Physical and chemical properties of the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland.

Depth	Sand	Silt	Clay	CEC	PH	OC	N	P	K	Ca	Mg	Na
(m)	(g·kg^{-1})			(cmol(+)·kg^{-1})	(g·kg^{-1})				(cmol(+)·kg^{-1})			
0-0.2	700	90	210	14.56	5.16	14.20	2.15	22.16	1.34	1.60	1.52	0.26
0.2-0.8	580	130	290	9.58	5.59	8.60	0.15	5.25	0.80	0.86	1.36	0.22
>0.8	760	80	160	8.56	5.63	7.40	0.05	5.60	0.75	0.80	1.20	0.20

CEC= cation exchange capacity; OC= organic carbon.

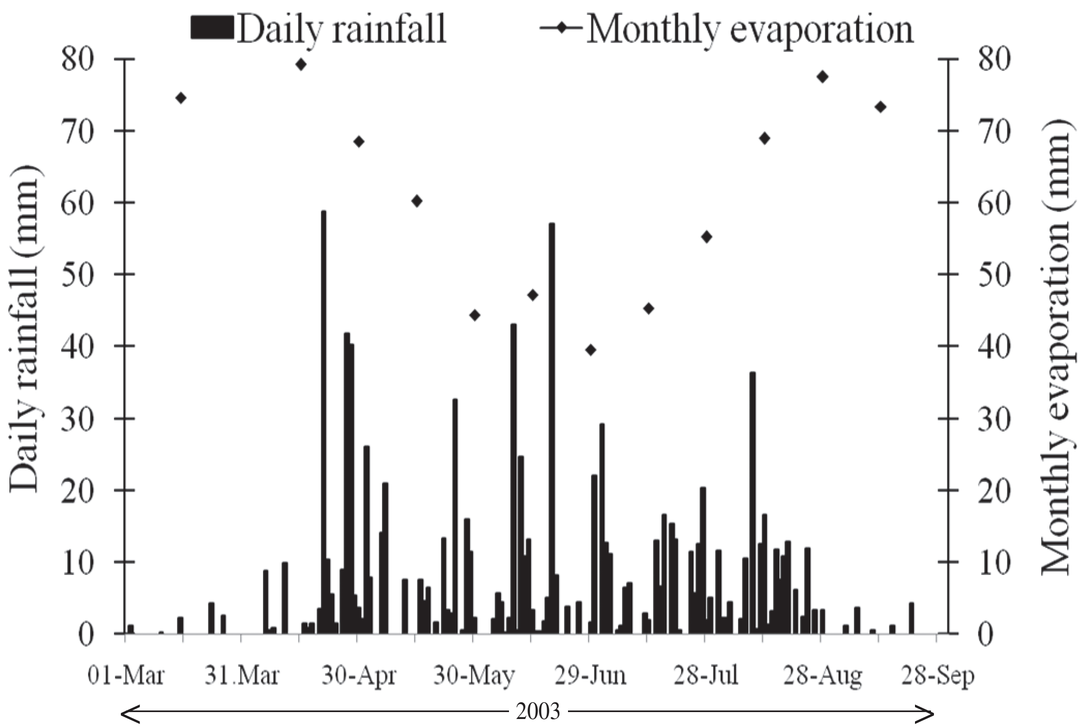

Figure 1. Daily rainfall and monthly pan evaporation distributions at Moi University farm, Kenya.

crop. At each position, 0 to 0.2, 0.2 to 0.4, and 0.4 to 0.6 m depths were sampled. Organic matter content (dichromate oxidation), available nutrient concentrations (NH_4–N, NO_3–N, PO_4–P, and K), and aggregate stability (wet sieving) were determined (Rowell, 1994) after the soil samples were air-dried, crushed, and passed through a 2 mm sieve.

During the growing season, plant height (height to the leaf tip of the tallest of 10 randomly tagged plants in a 1 m^2 patch in the middle of the erosion plot) and number of tillers per m^2 (at 2 weeks interval until 75 days after planting) were monitored. Weight of 100 kernels, grain and straw weights per square meter were recorded at harvest after oven drying the samples at 60°C for 48 h. The data were subjected to analysis of variance using the general linear model for completely randomized factorial design. Treatment differences were examined using Duncan's new multiple range tests ($p < 0.05$; Buysse et al., 2004). Cost-benefit analysis was done by accounting for total cost as cash expenses for land preparation, seed, fertilizers, pesticides and harvesting. Gross return was the product of grain yield and selling price. In calculating the income that could be derived from the various treatments, the amounts of straw mulch that were used in the various treatments were taken into account.

Table 2. Total runoff and soil loss, sediment load in runoff, mechanical composition of sediments, and mean weight diameter (MWD) of the soil samples (before and after the growing season) in the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland as influenced by mulching treatments.

Treatment	Runoff (mm)	Soil loss ($Mg{\cdot}ha^{-1}$)	Sediment concentration ($g{\cdot}L^{-1}$)	Mechanical composition (%)			MWD	
				Sand	Silt	Clay	Before	After
Control	48.5^{a}	14.0^{a}	28.9^{a}	30^{a}	20^{a}	50^{c}	0.75^{aA}	0.71^{cA}
DP (3)	32.4^{b}	6.7^{b}	20.7^{b}	29^{a}	14^{b}	57^{bc}	0.74^{aA}	0.75^{bcA}
DP (5)	23.6^{c}	4.6^{c}	20.4^{c}	20^{b}	9^{c}	71^{ab}	0.75^{aA}	0.77^{bcA}
SP (3)	22^{c}	3.96^{c}	18.4^{cd}	16^{b}	7^{cd}	78^{a}	0.74^{aA}	0.81^{abA}
SP (5)	10.3^{d}	1.82^{d}	17.7^{d}	15^{b}	5^{d}	79^{a}	0.74^{aA}	0.87^{aA}

Different lowercase superscripts following values within a column indicate significant differences between the treatments; different uppercase superscripts following values within a row indicate significant differences in the MWD between the two sampling dates. DP (3) = Deep placement 3 $Mg{\cdot}ha^{-1}$, DP (5) = Deep placement 5 $Mg{\cdot}ha^{-1}$, SP (3) = Surface placement 3 $Mg{\cdot}ha^{-1}$ and SP (5) = Surface placement 5 $Mg{\cdot}ha^{-1}$.

Results and Discussion

Soil loss and runoff

The 5 Mg·ha^{-1} straw mulch treatment was significantly more effective in checking runoff and soil loss than the 3 Mg·ha^{-1} treatment, regardless of placement methods (Table 2). Annual soil loss was 2.2, 3.1, 3.8, and 8.1 times greater in the control than in 3 Mg·ha^{-1} deep placement, 5 Mg·ha^{-1} deep placement, 3 Mg·ha^{-1} surface placement, and 5 Mg·ha^{-1} surface placement treatments respectively. The corresponding annual runoff amounts were 1.5, 2, 2.1, and 4.6 times greater than the control. Soil loss due to particle detachment by raindrop impact, erosive power of runoff, sediment transportation by raindrop splash, and surface runoff flow are well known (Watson and Laflen, 1986). The present results indicate that straw mulch application not only reduced the surface runoff but also provided a cover to the soil surface decreasing soil detachment by raindrop impact. It also reduced the runoff velocity along the slope, thereby decreasing runoff erosivity, and trapped the sediments carried by surface runoff. These phenomena were more pronounced in the surface placement than in the deep placements as evident from the significantly lower sediment load in the runoff water in the former (Table 2).

Mechanical composition of the sediments in the runoff water indicates that the percentage of coarse fraction was significantly higher in the control than in all other treatments, except for the 3 Mg·ha^{-1} deep placement (Table 2); but the percentage of clay was lower. Such decreases in sand and silt percentage in the runoff in the mulched plots may be on account of trapping the relatively large sized particles by straw mulch. Furthermore, this effect was more pronounced in the surface placement than in deep placement.

Our results also suggest that runoff erosivity in the humid region is greater than that of the semiarid region. Average annual soil loss per millimeter of rainfall in this humid highland was 18.0 kg·ha^{-1}·mm^{-1} (Table 2), as against 1.14 kg·ha^{-1}·mm^{-1} in a semiarid region with similar slope gradient, erosion plot size, and soil mineralogy (Wakindiki and Ben-Hur, 2002b). Mulching, however, significantly reduced soil loss. Surface placement mulch is particularly more effective than deep placement. As can be seen from Table 3, surface placement of straw mulch either at 3 or 5 Mg·ha^{-1} significantly increased aggregate stability of soil. Increased OM content in soil, following addition of wheat straw, is a plausible explanation for this, which is consistent with the reports of Lado et al. (2004).

Soil organic matter content

Surface soil (0 to 0.2 m) consistently had the highest OM content and 0.4 to 0.6 m layer had the lowest (Table 3), except for the control treatment where the differences were not significant. In all straw mulch treatments, the OM content in the 0 to 0.2 m soil layer modestly increased

Table 3. Organic matter content at different soil depths before and after the wheat crop in the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland as influenced by mulching treatments.

Treatment	0–0.2 m		0.2–0.4 m		0.4–0.6 m	
	Before	After	Before	After	Before	After
Control	25.1aA^{a}	23.9aA^{a}	14.8aA^{b}	15.1aA^{b}	4.8aA^{c}	4.8aA^{c}
DP (3)	26.6aB^{a}	28.0bA^{a}	15.0aB^{b}	15.6aA^{b}	4.5aA^{c}	4.9aA^{c}
DP(5)	25.1aB^{a}	29.4bA^{a}	14.8aB^{b}	15.6aA^{b}	4.6aA^{c}	4.9aA^{c}
SP (3)	24.3aB^{a}	27.0bA^{a}	14.8aB^{b}	15.1aA^{b}	4.3aA^{c}	4.6aA^{c}
SP (5)	26.6aB^{a}	29.1bA^{a}	15.0aA^{b}	15.4aA^{b}	4.7aA^{c}	5.0aA^{c}

Different lowercase letters following values within a column indicate significant differences between the treatments; different uppercase letters indicate significant differences between the two sampling dates for each treatment and soil layer; different superscript letters indicate significant differences between the soil depth for each treatment and sampling date. DP (3) = Deep placement 3 Mg·ha^{-1}, DP (5) = Deep placement 5 Mg·ha^{-1}, SP (3) = Surface placement 3 Mg·ha^{-1} and SP (5) = Surface placement 5 Mg·ha^{-1}.

after the growing season. Deep placement of straw mulch either at 3 and 5 Mg·ha^{-1} also increased soil OM content in the 0.2 to 0.4 m layer. None of the straw mulch treatments affected the OM content in the 0.4 to 0.6 m layer. Although the differences between the OM contents of the 0 to 0.2 m soil layer in the deep placement and surface treatment were not significant, the effect of the surface placement on aggregate stability was significant (Table 2). It is probable that surface placement enhanced the soil microbial activity, which enhanced soil aggregate stability (Maqubela et al., 2009).

Nutrients accumulation and loss

In all straw mulch treatments, total annual losses of NH_4–N, NO_3–N, PO_4–P and K in runoff and sediment were significantly lower than that of control, with the smallest nutrient losses in the 5 Mg·ha^{-1} surface applied straw mulch (Table 4). Annual N and P losses accounted 5 and 1% respectively of the total amounts that were applied as fertilizer in the control, as against 0.5 and 0.2% respectively in the 5 Mg·ha^{-1} straw mulch surface placement. Moreover, annual nutrient loss in runoff was about 10 times greater than that in the sediments.

Both surface placement and deep placement of straw mulch at 5 Mg·ha^{-1} enriched the soil NO_3 but deep placement at 3 Mg·ha^{-1} and surface placement at 3 and 5 Mg·ha^{-1} enriched soil NH_4. Probably the larger volume of water that infiltrated under surface placement compared to deep placement (Table 2) resulted in greater leaching losses of the mobile NO_3–N relative to NH_4–N (Ambus and Jensen, 1997). Sediment-associated N–NH_4, N–NO_3, P–PO_4, and K in the straw mulch treatments were modestly higher than those in the control, although these differences were not significant. This higher nutrient concentration in the sediments form the straw mulch treatments could have been caused by two main factors. First, the mineralization of wheat straw, which resulted in enhanced nutrient concentrations in the topsoil (Danga et al., 2009). Secondly, the higher clay percentage in the sediment in the straw mulch treated plots than the control (Table 2). Clay fraction was the component of the sediments that was strongly associated with or enriched with nutrients.

Wheat yield

Straw mulch treatments significantly altered crop emergence and grain, straw and total biomass yields (Table 5). Lowest emergence value was noted in the 5 Mg·ha^{-1} deep placement treatment. Surface placement of 3 Mg·ha^{-1}, however, did not significantly reduce wheat emergence. Deep placement of 3 Mg·ha^{-1} and surface placement of 3 and 5 Mg·ha^{-1} increased crop yields, whereas deep placement of 5 Mg·ha^{-1} decreased it. Soil water was probably not a limiting factor because precipitation was more than evaporation (Fig. 1). Higher yields in the mulched treatments, compared to that of control could have resulted from lower nutrient losses (Table 4) and the high aggregate stability in the

Table 4. Nutrient losses in runoff water and sediments in the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland as influenced by mulching treatments.

Treatments	Runoff water (kg·ha^{-1})				Sediments (kg·ha^{-1})				Sediments (mg·kg^{-1} clay)				Total nutrient loss (kg·ha^{-1})			
	NH_4	NO_3	PO_4	K	NH_4	NO_3	PO_4	K	NH_4	NO_3	PO_4	K	NH_4	NO_3	PO_4	K
Control	0.150^{a}	0.381^{a}	0.345^{a}	1.786^{a}	0.022^{a}	0.004^{a}	0.049^{a}	0.460^{a}	23.8	23.5	52.6	50.6^{ab}	0.17^{a}	0.38^{a}	0.39^{a}	2.25^{a}
DP (3)	0.067^{b}	0.224^{b}	0.242^{b}	1.189^{b}	0.011^{b}	0.002^{b}	0.024^{b}	0.238^{b}	24.8	22.7	54.0	53.8^{a}	0.08^{b}	0.23^{b}	0.27^{b}	1.43^{b}
DP (5)	0.054^{b}	0.167^{c}	0.175^{c}	0.986^{b}	0.009^{b}	0.001^{bc}	0.016^{bc}	0.165^{bc}	26.3	21.4	48.6	47.7^{abc}	0.06^{c}	0.17c	0.19^{c}	1.15^{bc}
SP (3)	0.064^{b}	0.178^{c}	0.156^{c}	0.887^{b}	0.008^{b}	0.001^{bc}	0.014^{cd}	0.144^{bc}	24.5	18.6	43.0	43.2^{bc}	0.07^{bc}	0.18^{c}	0.17^{c}	1.03^{c}
SP (5)	0.017^{c}	0.037^{d}	0.050^{d}	0.369^{c}	0.004^{b}	0.000^{c}	0.007^{d}	0.068^{c}	26.2	19.3	44.9	42.5^{c}	0.02^{d}	0.04^{d}	0.06^{d}	0.44^{d}

Different superscripts following values within a column indicate significant differences between the treatments. DP (3) = Deep placement 3 Mg·ha^{-1}, DP (5) = Deep placement 5 Mg·ha^{-1}, SP (3) = Surface placement 3 Mg·ha^{-1} and SP (5) = Surface placement 5 Mg·ha^{-1}. Nutrient losses in sediments are expressed in relation to total (sand, silt, and clay) sediment and clay fraction in the sediment.

Table 5. Seedling emergence, yield, and some yield parameters of wheat in the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland as influenced by mulching treatments.

Treatments	Emergence value (seedlings·m^{-2})	Dry weight (Mg·ha^{-1}) Grain	Straw	Total	Number of tillers (m^{-2})	Weight of 100 kernels (g)	Grain/Total dry weight ratio
Control	30^{a}	2.82^{bc}	4.78^{c}	7.65^{c}	473^{b}	3.23^{ab}	0.38^{a}
DP (3)	26^{bc}	3.60^{a}	5.34^{c}	8.94^{b}	434^{bc}	3.46^{ab}	0.4^{a}
DP (5)	23^{c}	2.69^{c}	3.64^{d}	6.33^{d}	356^{c}	3.45^{ab}	0.42^{a}
SP (3)	28^{ab}	3.74^{a}	6.23^{b}	9.97^{ab}	467^{b}	3.53^{a}	0.38^{a}
SP (5)	24^{bc}	3.36^{ab}	7.29^{a}	10.64^{a}	657^{a}	2.97^{b}	0.32^{b}

Means with the same superscripts within a column do not differ significantly. DP (3) = Deep placement 3 Mg·ha^{-1}, DP (5) = Deep placement 5 Mg·ha^{-1}, SP (3) = Surface placement 3 Mg·ha^{-1} and SP (5) = Surface placement 5 Mg·ha^{-1}.

surface placement treatments (Table 2), which in turn, increased drainage and improved soil aeration (Blanco-Canqui and Lal, 2007)

Dry weight of straw and number of tillers were significantly higher in the 5 Mg·ha^{-1} surface placement than in the 3 Mg·ha^{-1} surface treatment; but the weight of 100 kernels and the grain to biomass (total dry weight) ratio were significantly lower than other mulching treatments (Table 5). All the straw mulch placement methods, except deep placement at 5 Mg·ha^{-1}, increased net returns relative to the control (Table 6). The highest net revenue (US$ 747) was earned in the 3 Mg·ha^{-1} surface placement treatment owing to the relatively low land preparation costs and high gross revenue from grain yield.

In conclusion, cultivated humid highlands in Kenya are prone to significant soil loss and nutrient depletion. Surface placement of straw mulch was more effective in soil conservation than deep placement. Furthermore, 5 Mg·ha^{-1} straw mulch was significantly more effective in conserving soil than at 3 Mg·ha^{-1}. All the straw mulch treatments except deep placement of 5 Mg·ha^{-1} significantly increased the grain, straw, and total biomass yields of wheat. The highest financial benefit would be from surface placement at 3 Mg·ha^{-1} because of lower cost of land preparation and the relatively high gross returns from wheat grain.

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Table 6. Cost-benefit analysis of wheat straw mulch treatments in the acidic, dark red, Rhodic Ferralsols in a humid Kenyan highland.

Control	Seedbed preparation	Seed	Pesticides	Fertilizers	Harvesting (US $·ha^{-1})	Total expenses	Gross returns	Benefit
Control	8	50	79	28	50	215	811	596
DP (3)	38	50	70	28	46	232	868	636
DP (5)	57	50	61	28	42	238	512	274
SP (3)	19	50	55	28	40	192	939	747
SP (5)	38	50	45	28	35	196	815	619

DP (3) = Deep placement 3 Mg·ha^{-1}, DP (5) = Deep placement 5 Mg·ha^{-1}, SP (3) = Surface placement 3 Mg·ha^{-1} and SP (5) = Surface placement 5 Mg·ha^{-1}.

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