Residual Impact of Topsoil Removal and Soil Amendments on Crop Productivity Over Sixteen Years

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Abstract

Soil erosion remains a threat to our global soil resource. This study was conducted to ascertain the effects of simulated erosion on soil productivity and methods for its amendment. Incremental depths (0, 5, 10, 15 and 20 cm) of surface soil or cuts were mechanically removed to simulate erosion at two sites (one dryland, one irrigated) in southern Alberta in 1990. Three amendment treatments (nitrogen + phosphorus fertilizer, 5 cm of topsoil, or 75 Mg ha^{-1} of feedlot manure) and a check were superimposed on each of the cuts. The sites were cropped annually until 2006. On average, sixteen year yield reductions were 10.0% for 5 cm, 19.5% for 10 cm, 29.0% for 15 cm and 38.5% for 20 cm of topsoil removal. Average grain yield loss was 50 kg ha^{-1} cm^{-1} yr^{-1} at the Dryland site and 59 kg ha^{-1} cm^{-1} yr^{-1} at the Irrigated site. Amendments ranked manure> topsoil > fertilizer in terms of restoring productivity to the desurfaced soils. The study reinforces the need to prevent erosion and indicates that application of livestock manure is an option for restoring soil productivity in the short term.

Introduction

Recent studies agree that erosion continues to have detrimental effects on global soil resources (Montgomery, 2007; Van Oost et al., 2007). In adequately assessing the vulnerability of agricultural production to soil erosion, an understanding of the response of crop productivity to soil erosion is of vital importance (Bakker et al., 2004). One of the problems in assessing erosion-productivity relationships is the difficulty in detecting a decline in productivity that results from erosion. Imperceptible yield change caused by imperceptible soil loss due to erosion may not be recognized.

Bakker (2004) concluded that it was impossible to monitor the effects of erosion on productivity directly, by measuring the evolution of yields on eroding sites through time. Consequently various indirect methods have been utilized which include (1) simulated erosion by mechanical topsoil removal or desurfacing, (2) adding topsoil to eroded soils, (3) eroded phases of landscape transects, (4) comparative plots with different levels of historical erosion but similar characteristics (landscape position, management practices, slope etc.) or (5) simulation modelling of crop growth response to erosion. Bakker et al. (2004) discuss the pros and cons of each of these five approaches.

As well as being one of most widely use approaches aimed at understanding erosion-productivity relationships (Eck, 1987; Gollany et al. 1992; Ives and Shaykewich, 1987; Oyedele and Aina, 2006; Tanaka and Aase, 1989), topsoil removal (simulated erosion) is one of the simplest. Bakker et al. (2004) suggested that the longer the time span following desurfacing, the more realistic the results.

As well as being a means of quantifying erosion-productivity relationships, addition of amendments to restore productivity to the desurfaced soils may also be studied with the simulated erosion approach (Dormaar et al., 1997). Various studies have looked at amending desurfaced soils with fertilizer (Larney et al., 1995b; Tanaka and Aase, 1989) or manure (Dormaar et al., 1988; Larney and Janzen, 1996, 1997; Punshon et al., 2002).

The study described here was initiated in 1990 and used a simulated erosion approach whereby incremental depths of topsoil (cuts) were mechanically removed and subsequent effects on crop productivity (continuous spring wheat) were monitored. Following topsoil removal, the resulting surfaces were amended with fertilizer, manure, or topsoil addition as a one-time application aimed at restoring soil productivity. Early results from these experiments have been previously reported by Larney et al. (1995a, 2000a, 2000b). This paper updates the findings on two southern Alberta sites which have been maintained since 1990.

Materials and Methods

The study methods have been described in detail by Larney et al. (2000a, 2000b). In summary, two sites (one dryland and one irrigated) on Dark Brown Chernozemic sandy clay loam soils (Typic Haploborolls) were desurfaced in spring 1990 at the Agriculture and Agri-Food Canada Research Centre at Lethbridge, Alberta (49^{o} 43' N, 112^{o} 48' W). Five main simulated erosion treatments (12 m x 10 m plots) were established at each site by mechanically removing 0, 5, 10, 15 or 20 cm of topsoil (hereby referred to as 'cuts') using an excavator with a grading bucket. In the initial year only (1990), four sub-treatments (3 m x 10 m sub-plots) were super-imposed (split-plot) on each of the main treatments: check, an optimum rate of N and P fertilizer (75 kg ha^{-1} N, 22 kg ha^{-1} P), or 75 Mg ha^{-1} (wet weight) of feedlot manure (0.35 kg kg^{-1} water content, 190 g kg^{-1} total C, 22 g kg^{-1} total N), or re-application of 5 cm of topsoil. Fertilizer N and P rates were doubled at the irrigated site. Plots were replicated four times in a randomized complete block design (5 cuts x 4 amendments x 4 replicates = 80 plots).

In 1990, seedbed preparation consisted of one pass of a powered rotary cultivator to 10 cm depth as the desurfaced plots were dry and compact. Subsequently the sites were managed with no-till practices and no further amendments were applied in order to monitor the residual effects of simulated erosion and the one-time addition of amendments. After 1990, all plots received broadcast applications of 40 kg ha^{-1} N and 9 kg ha^{-1} P (rates were doubled at the irrigated site). Spring wheat (*Triticum aestivum* L.) was seeded at a 17.5 cm row spacing in May/early June of each year from 1990-2006, except in 2004 when both sites were chemical fallowed (herbicides used for weed control) in an effort to control the buildup of wild oats (*Avena fatua* L.) and green foxtail (*Setaria italica* (L.) P. Beauv. subsp. *viridis* (L.) Thell.). Also, yield data were not collected at the Irrigated site in 2003 because of a severe infestation of wild oats was considered to have comprised treatment effects on wheat yield. Hence the experiment ran for 16 yr (1990-

2006) or 17 growing seasons with yield data from 16 growing seasons at the Dryland site and 15 growing seasons at the Irrigated site. Depending on precipitation amounts, the irrigated site received from 100 to 200 mm of irrigation water during the growing season to ensure that root-zone soil moisture was non-limiting.

For grain and straw yield, six 5-m long rows were hand-harvested from each sub-plot in 1990-91, while 13-15 m^2 of the 30 m^2 sub-plot area was harvested with a plot combine from 1992-2006. Straw was collected in removable bins attached to the rear of the plot combine. Straw from the unsampled portion of the plots was removed by baling in 1990-91 but returned to the plots via a straw-shredder on a large combine in subsequent years.

Statistical analysis was performed on all data using the General Linear Models Procedure (SAS Inst. Inc., 2007) with cut as the main treatment and amendment as sub-treatment in a split-plot design. Least significant differences (LSD) were used to compare treatment means. For yield parameters with significant (P <0.05) cut and/or cut x amendment effects, polynomial orthogonal contrasts were used to determine if increased depth of cut exerted a linear or quadratic effect. When the contrasts were significant, regression models were developed and evaluated on the corresponding treatment means.

Results

The 30 yr (1971-2000) normal growing season precipitation (GSP, May 1-August 31) at Lethbridge is 205 mm. The mean GSP for the study period (1990-2006, excluding 2004 fallow year) was 224 mm (109% of normal) with a range from 64 mm (31% of normal) in 2001 to 375 mm (183% of normal) in 2005.

In 2006, some 16 years after plot establishment, significant yield effects due to cut and amendment were found for grain and straw at each site (Table 1). Averaged over all amendments, there were significant linear declines in grain and straw yield at both sites with depth of cut. Averaged over all cuts, the manure amendment yielded significantly higher than the other three amendments at both sites, averaging 13-18% higher than the check treatment. At the Dryland site, the topsoil addition treatment had significantly higher (7%) grain yield than the fertilizer treatment and significantly higher (6-9%) straw yield than the check and fertilizer treatments. At the Irrigated site, the topsoil, check and fertilizer treatments were not significantly different from each other.

For simplicity, the study period was assessed as sixteen years even though it was technically 16 years 4 months (i.e. from seeding in May 1990 to harvest in September 2006, or 17 growing seasons, although crops were not harvested in all seasons).

In all four cases (grain and straw yield at both Dryland and Irrigated sites), the cut x amendment interactions were significant for average yields in 1990-2006 (Tables 1-4) and the effects were significantly linear (Figs. 1a-d). At the Dryland site, manure was able to maintain average grain yields above the level of the 0 cm Cut-Check treatment from 1990-2006 until depth of cut reached 17.6 cm (Fig. 1a). The equivalent depth on the Irrigated site was 10.8 cm (Fig. 1b). The fertilizer treatment maintained yields above the 0 cm Cut-Check treatment when cut was <2.7 cm depth on the Dryland site (Fig. 1a) and <1.8 cm depth on the Irrigated site (Fig. 1b). The topsoil treatment lost the ability to maintain yields above 100% of the 0 cm Cut-Check treatment when cut was >4.8 cm depth (Fig. 1a) on the Dryland site or >5.3 cm depth on the Irrigated site (Fig. 1b). These depth values are very close to the actual depth of the topsoil amendment treatment (5 cm of topsoil deposited on each of the exposed cut surfaces). The equations predicted that removing 4.8 to 5.3 cm of topsoil on the topsoil amendment treatment (i.e. where 5 cm of topsoil was added at the outset) maintained yield at the level of the 0 cm cut-Check treatment over a 16 yr period. This follows since removing 4.8 to 5.3 cm of topsoil where 5 cm of topsoil was added, essentially re-created the 0 cm Cut-Check treatment.

The average grain yield over 16 yr on the check treatment fell 2.1% cm^{-1} cut on the Dryland site (Fig. 1a) and 1.7% cm^{-1} for the Irrigated site (Fig. 1b). In contrast, grain yield on the manure treatment fell by 0.8% cm^{-1} cut on the Dryland site (Fig. 1a) and 0.9% cm^{-1} cut on the Irrigated site (Fig. 1b). Declines in grain yield on the topsoil treatment were intermediate between the check and manure treatments: 1.2% cm^{-1} cut on the Dryland site and 1.3% cm^{-1} cut on the Irrigated site.

For straw yields, amendment with manure maintained 16-yr average yields at higher levels than the 0 cm cut-Check treatment at all depths of topsoil removal on the Dryland site (Fig. 1c), e.g. removing 20 cm of topsoil and following with a one-time amendment of manure, resulted in 6% higher 16-yr average straw yields at the Dryland site than the 0-cm Cut-Check treatment. At the Irrigated site, manure maintained yields greater than the 0 cm Cut-Check treatment until depth of cut exceeded 8.1 cm. which was much less effective than at the Dryland site (Fig. 1d). However, the efficacy of topsoil addition was similar at both sites, maintaining straw yields greater than the 0-cm Cut-Check treatment when depth of cut exceeded 5.4 cm at the Dryland site and 3.9 cm at the Irrigated site.

The slopes of the equations for straw yield were slightly lower than their grain yield counterparts, showing that over the 16-yr period, topsoil removal and subsequent amendment has less of an impact on straw yield compared to grain yield. For example, straw yield losses on the check treatments (averaged over both sites) were 1.4% cm^{-1} cut compared to 1.9% cm^{-1} cut for grain yield. Similarly, on the fertilizer treatment, the average yield loss was 1.3% cm^{-1} cut for straw yield versus 1.9% cm^{-1} cut for grain yield; while the topsoil treatment averaged 0.8% cm^{-1} cut for straw yield and 1.3% cm^{-1} cut for grain yield.

The equations in Fig. 1 were used to predict values for grain and straw yield losses due to topsoil removal and amendment treatments at both sites (Table 2). The values show the relative effectiveness of the amendments in inhibiting yield losses in the order: manure > topsoil > fertilizer. For grain yield at the Dryland site, yield response ranged from a gain of 14.1% on the 0 cm Cut-Manure treatment to a loss of 42.9% on the 20 cm Cut-Check treatment. At the Irrigated site, the same two treatments were the highest and lowest yielding with a gain of 9.7% on the 0-cm Cut-Manure treatment and a loss of 34.1% on the 20 cm Cut-Check treatment.

The relationships in Fig. 1 and values in Table 2 showed that the magnitude of yield responses with addition of manure and topsoil (over the check treatments on equivalent cuts) increased with depth of cut. Using the values in Table 2, for example, Dryland grain yield increases with manure over the corresponding check plots at each cut were 14.1% on the 0 cm cut, 21.5% on the 5 cm cut, 28% on the 10 cm cut, 34.5% on the 15 cm cut, and 41% on the 20 cm cut. Values for topsoil addition and grain yield increases were 5.8% on the 0 cm cut, 11.2% on the 5 cm cut, 15.7% on the 10 cm cut, 20.2% on the 15 cm cut and 24.7% on the 20 cm cut. In contrast, fertilizer addition, resulted in yield increases which were in a relatively consistent range with cut: 5.2% on the 0 cm cut to 10.1% on the 20 cm cut for Dryland grain.

The ranges in grain yield increases due to manure and topsoil amendment on each cut on the Irrigated site were lower than on the Dryland site. For manure, the range was from 5.7% on the 0 cm cut to 25.8% on the 20 cm cut (compared with 14.1-41%). For topsoil the range was from 3.1% on the 0 cm cut to 14.1% on the 20 cm cut (compared with 5.8-24.7% on the Dryland site). The grain yield response to fertilizer was also quite consistent and lower than the Dryland site with a very narrow range from 1.1-2.9% across all cuts.

Manure proved to have a strong residual effect on crop productivity as indicated by grain yield at the Dryland site (Fig. 2). The residual effect (expressed as a percent yield increase over the equivalent cut-check treatment) was greater as depth of cut increased. Exponential equations revealed that within 3 yr of topsoil removal, the restorative power of manure had diminished substantially but then levelled off over time on the 10 cm cut to a value 30.2% higher than the 10 cm cut-check treatment. The 15-cm cut-manure treatment stabilized at 45.3% higher than the equivalent check treatment while the 20 cm cut-manure treatment maintained a 50.4% higher value (Fig. 2). The relationship with time on the 5 cm cut-manure treatment was non-significant. The relationships in Fig. 2 held true for manure at the Irrigated site and also for topsoil amendments at both sites.

By comparing grain yields on the 0 cm Cut-Check with those on the 0 cm Cut-Topsoil and the 5 cm Cut-Check, the effect of 5 cm of topsoil removal and 5 cm of deposition on crop productivity can be estimated. The 0 cm Cut-Check simulates a ‘non-eroded’ area, the 0 cm Cut-Topsoil a ‘depositional’ area receiving 5 cm of additional topsoil depth and the 5 cm Cut-Check an ‘eroded’ area losing 5 cm of topsoil. Based on 16-yr average yields at the Dryland site, there was a grain yield increase of 7.2% and a straw yield increase of 6.0% on the 'depositional' areas (with respect to the 'non-eroded' area) almost offsetting a grain yield decrease of 9.7% and a straw yield decrease of 8.4% on the 'eroded' areas (Table 2). The compensatory effect of deposition over erosion was similar for grain yield at the Irrigated site where a yield increase of 5.5% almost balanced a grain yield decrease of 8.0% on the 'eroded' areas. However, a straw yield increase of 2% on the ‘depositional’ area did not compensate for the 7.2% decline in straw yield on the ‘eroded’ area.

The robustness of our experimental technique can be assessed by comparing yields on the 0 cm Cut-Check treatment with those on the 5 cm cut-topsoil treatment. The only difference between these to treatments was that the 0 cm cut-check remained undisturbed while the 5 cm cut-topsoil treatment had 5 cm of topsoil removed and then re-applied to essentially re-create the 0 cm cut-check. The average 16 yr values for these two treatments were within 0.7% of each other for grain yield and 0.3% for straw yield at the Dryland site. On the Irrigated site, grain yields were within 3.4% of each other while straw yields were within 0.7% of each other for the two treatments.

Discussion

Some soils experience consistent productivity reductions with progressive soil degradation, while others suffer no loss until some critical point in one (or more) yield-determining factor is reached at which yield losses become apparent (Hoag, 1998). However, our results support den Biggelaar et al. (2001, 2004) who for ease of analysis and comparison of data, assumed that the relationship between soil degradation and soil productivity was linear in all cases, although they pointed out that in reality, linear relationships may not always best describe the relationships.

Average grain yield loss was 50 kg ha^{-1} cm^{-1} yr^{-1} at the Dryland site and 59 kg ha^{-1} cm^{-1} yr^{-1} at the Irrigated site. This compares very favourably to data presented by den Biggelaar et al. (2004) from 64 published erosion-productivity records for wheat in North America where the average erosion-induced yield loss was 51 kg ha^{-1} cm^{-1} yr^{-1}. However the mean duration of experiments they reported was five years, much shorter than our sixteen years.

The relative effectiveness of the amendments in mitigating yield losses ranked: manure > topsoil > fertilizer. A single application of manure at a modest rate at the outset of the study had lasting effect, contributing to significant yield responses at both sites in 2006, some sixteen years later. Increased NPP on the manure plots would have returned higher amounts of or root and straw residue mass to the soil, perhaps self-perpetuating the manure effect beyond a strict response to nutrient addition in the early years. This may have been coupled with an improvement in soil physical properties (Arriaga and Lowery, 2003) and microbial conditions (Mabuhay et al., 2006).

In a summary of a number of erosion-productivity studies, Bakker et al. (2004) reported that experiments based on comparative plots showed average yield reductions of 4.3% per 10 cm of soil loss, transect experiments averaged 10.9% per 10 cm and desurfacing experiments (similar to our approach) averaged 26.6% per 10 cm soil loss. Our average grain yield losses for 10 cm soil loss over sixteen years were 17.1% at the Irrigated site and 21.9% at the Dryland site. Straw yield losses were estimated at slightly lower values of 14% at the Irrigated site and 16.3% at the Dryland site. Bakker et al. (2004) concluded that desurfacing experiments overestimate the effects of soil erosion because they result in much stronger changes in soil properties than occur with normal soil erosion. Modelling results by Bremer et al. (2008) supported this conclusion but they suggested that due to the strong changes in soil properties and the utility of experimental designs using the desurfacing approach, these experiments are useful for evaluating models relating crop productivity to soil properties.

Conclusions

Our findings show that effort must be maintained to reduce water and wind erosion risk on agricultural soils. Widespread adoption of conservation tillage practices has reduced erosion risk on the Canadian prairies but other areas of the world still rely heavily on conventional tillage operations which leave the soil prone to erosion and jeopardize agricultural sustainability. In cases where soils have suffered from erosion in the past, even a one-time application of organic amendment like manure can have substantial residual effects in restoring crop productivity.

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Table 1. 2006 grain and straw yields at the Dryland and Irrigated sites showing responses to treatments applied 16 years earlier in 1990.

	Dryland		Irrigated	
Cut, cm	Grain	Straw	Grain	Straw
0	2.96a	3.52a	2.84a	3.49a
5	2.54b	3.28b	2.99a	3.74a
10	2.38b	3.16b	2.64b	3.49a
15	2.09c	2.89c	2.28b	2.89b
20	2.07c	2.89c	2.42b	3.13b
Cut_{lin}	***	***	**	***
Cut_{quad}	NS	NS	NS	NS
Amendment				
Check	2.28bc	3.02c	2.50b	3.17b
Fertilizer	2.25c	2.93c	2.59b	3.27b
Manure	2.69a	3.43a	2.83a	3.65a
Topsoil	2.40b	3.20b	2.61b	3.31b

Table 2. Average grain and straw yield losses (negative values represent yield gains) with incremental depths of topsoil removal and amendment treatments at Dryland and Irrigated sites, 1990-2006 (predicted from equations in Figs. 1a-d).

Cut	Amendment	Dryland		Irrigated	
		Grain	Straw	Grain	Straw
		% of 0 cm Cut-Check treatment			
0 cm	Check	0.9†	1.3†	0.1†	1.0†
	Fertilizer	-5.2	-1.7	-3.3	-1.1
	Manure	-14.1	-11.3‡	-9.7	-5.7
	Topsoil	-5.8	-4.3	-6.9	-3.1
5 cm	Check	11.4	8.8	8.6	7.5
	Fertilizer	4.3	4.8	5.7	5.4
	Manure	-10.1	-8.9‡	-5.2	-2.2
	Topsoil	0.2	-0.3	-0.4	0.9
10 cm	Check	21.9	16.3	17.1	14
	Fertilizer	13.8	11.3	14.7	11.9
	Manure	-6.1	-4.5‡	-0.7	1.3
	Topsoil	6.2	3.7	6.1	4.9
15 cm	Check	32.4	23.8	25.6	20.5
	Fertilizer	23.3	17.8	23.7	18.4
	Manure	-2.1	-4.6‡	3.8	4.8
	Topsoil	12.2	7.7	12.6	8.9
20 cm	Check	42.9	31.3	34.1	27.0
	Fertilizer	32.8	24.3	32.7	24.9
	Manure	1.9	-6.2‡	8.3	8.3
	Topsoil	18.2	11.7	19.1	12.9

†Values not zero as predicted from equations in Fig. 1.

‡Observed rather than predicted data as linear equation non-significant (see Fig. 1c).

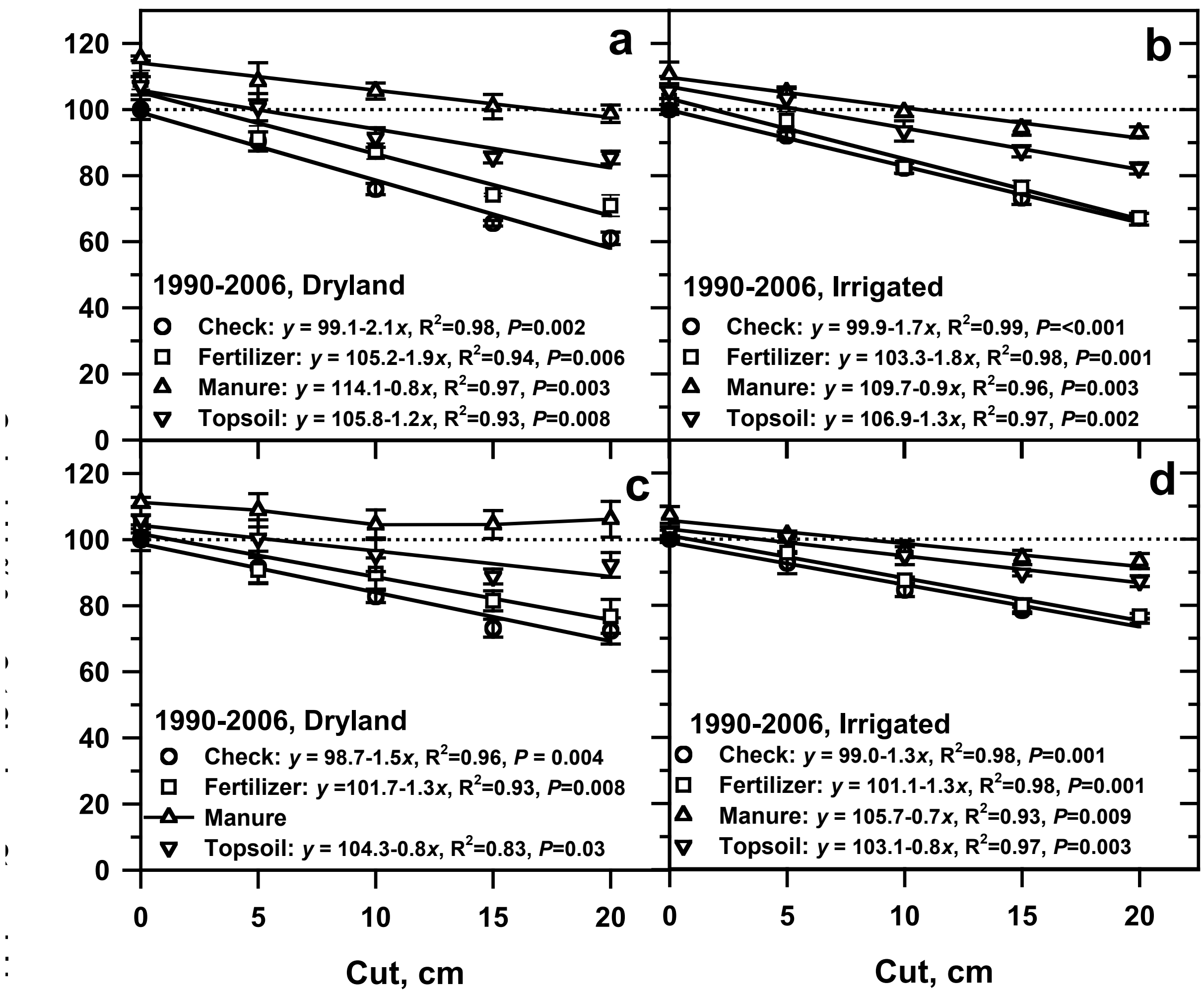

Figure 1. Effect of cut and amendment on average grain yield (a) 1990-2006 at the Dryland site; (b) 1990-2006 at the Irrigated site; and average straw yield (c) 1990-2006 at the Dryland site; (d) 1990-2006 at the Irrigated site. Bars represent standard errors of the means.

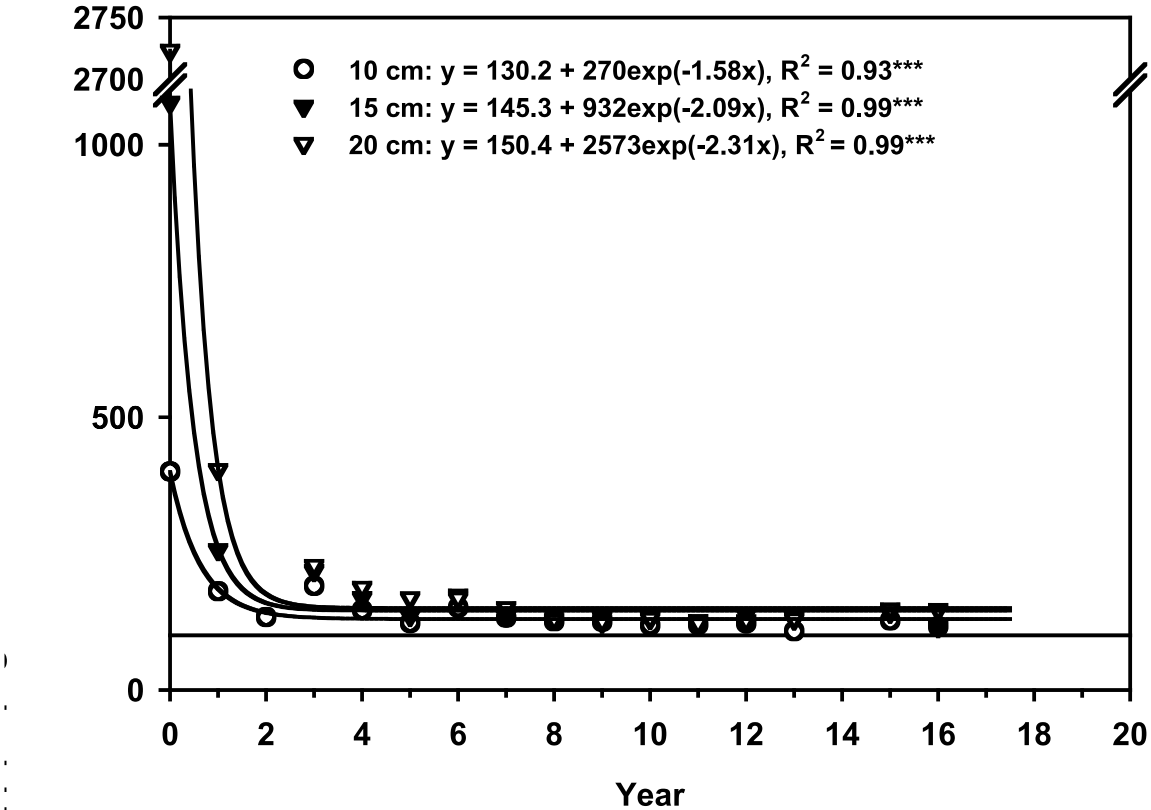

Figure 2. Effect of manure amendment on grain yield (expressed as a percent of equivalent cut-check yield) on the 10, 15 and 20 cm cut at the Dryland site (1992 data points for the 15 and 20 cm cuts were omitted as outliers).