

Effects of topsoil loss on wheat productivity in dryland zones of Chile

N. Brunel^{1*}, F. Meza², R. Ros³, F. Santibáñez⁴

¹Centro de Desarrollo para el Secano Interior, Universidad Católica del Maule, Talca, Chile. ²Universidad del Mar, Sede Centro-Sur, Chile. ³Facultad de Ciencias Agrarias y Forestales, Universidad Católica del Maule, Talca, Chile. ⁴Centro de Agricultura y Medio Ambiente, Universidad de Chile, Santiago, Chile. *Corresponding author: nbrunel@ucm.cl

Abstract

Considering that the most important processes of biogeochemical cycles occur in the upper first centimetres of the soil, minor degrees of erosion may affect crop productivity, especially in the case of low input dryfarming production systems, which dominate the central coastal areas of Chile. The purpose of this study was to evaluate the effect of topsoil loss on wheat productivity in dryfarming areas with Mediterranean climates in Central Chile. The experiment was conducted on a Chilean Alfisol (Pencahue; 35°18'53''S and 71°53'40''W), and the topsoil of this soil was progressively removed from a depth of 2 to 18 cm (2, 6, 10, 14 and 18 cm). Once the plots (25 m²) were prepared, winter wheat (*Triticum aestivum* L.; cultivar Pandora-INIA) was sown by applying the traditional techniques of the zone. A design was established on randomised blocks with six treatments and three replications. After one growing season, the results showed significant differences ($p < 0.05$) in grain yield (kg ha⁻¹) between the control treatment (T₀) and the treatment with 18 cm of soil removed (T₁₈) with productivity decreasing by 35%. Furthermore, most of the considered productivity parameters were negatively correlated with the depth of soil removed. The results highlighted the importance of topsoil fertility and depth in crop yield.

Keywords: soil erosion, topsoil depth, desurfacing, Mediterranean climate.

1. Introduction

Wheat (*Triticum* spp.) is one of the main crops in dry-land areas worldwide. In Chile, approximately 70% of wheat crops are established in areas with an arid to subhumid Mediterranean climate, which has an important role in the rural economies of broad areas (Mellado, 2007). Most wheat growing areas are established on granitic soils, mainly in the coastal mountain areas of Central Chile, and 63% of these soils are undergoing severe erosion processes (Pérez and González, 2001). Soil degradation is a consequence of decades of dryfarming slope cultivation of cereals and overgrazing. Thus, many areas of soil have lost their surface horizon and fertility, which has led to a dramatic drop in wheat productivity and has reduced the income of poor rural populations.

The intensive tillage of these fragile soils has triggered a process of degradation characterised by critical surface erosion, which degrades the upper horizons and affects the topsoil depth and properties, thereby, reducing their productive potential (Thompson *et al.*, 1991; Izaurrealde *et al.*, 2006). Nonetheless, intensive production practices conceal the immediate effects of soil degradation, which makes early symptoms imperceptible or undetectable by simple observation (Flörchinger *et al.*, 2000; Malhi *et al.*, 1994; Bakker *et al.*, 2004; Fenton *et al.*, 2005; Larney *et al.*, 2009). During the erosion process in cultivated soils, the depth of the Ap horizon decreases and clay content increases as a consequence of mixing with finer particles from lower horizons due to tillage. In addition to being rich in clays, this material has low levels of organic matter, and these characteristics are then transferred to the new upper horizon during erosion (Frye *et al.*, 1982; Christensen and McElyea, 1988). Furthermore, the loss of topsoil is followed by an increase in bulk density, structural deterioration and alteration of the total po-

rosity with various suppressing effects on crop yield (Gollany *et al.*, 1992; Malhi *et al.*, 1994).

The depth of topsoil has proven to be a significant parameter in determining soil quality and land productivity. However, changes in the properties of this horizon may produce unexpected crop responses because of a combination of indirect effects (Power *et al.*, 1981; Mielke and Schepers, 1986; Christensen and McElyea, 1988; Larney *et al.*, 1995). Properties of the soil profile and interaction of different processes generate a complex system influencing crop behaviour. Thus, it is not always possible to apply a simple and universal quantitative relationship to topsoil thickness and crop productivity (Gollany *et al.*, 1992). Some authors have established linear and nonlinear relationships between crop productivity and topsoil degradation, and they have suggested that not all soils behave similarly with respect to erosion processes (Hairston *et al.*, 1988; Larney *et al.*, 1995; Larney *et al.*, 2000). The effect of soil loss may be explained with changes in the chemical and/or physical characteristics of the soil and by its interactions that impact crop production (Christensen and McElyea, 1988; Izaurrealde *et al.*, 2006; Thompson *et al.*, 1991).

One method commonly used to evaluate the effects of erosion on productivity is the removal of topsoil or “desurfacing”. This technique simulates an erosive phenomenon, but the negative effects of this approach may be exaggerated because of the abruptness of the disturbance (Larney *et al.*, 2000; Bakker *et al.*, 2004). To overcome this limitation and to allow for more realistic results, these authors have proposed the removal of small amounts of soils in continuous intervals over a long period of time. In agricultural areas with degraded soils and limited access to technology, slight levels of soil loss can result in a negative tendency of crop productivity. The objective of

this experiment was to evaluate the decline of winter wheat (*Triticum aestivum* L.) productivity as a consequence of topsoil loss in a dryfarming system located in the subhumid Mediterranean climate area of the Maule Region in Chile.

2. Materials and methods

2.1. Characterisation of the study site

To determine the effect of topsoil removal on wheat productivity, a field trial was conducted during the

2008-2009 season in the locality of Pencahue, Maule Region, Chile (35°18'53''S and 71°53'40''W). The site is within an agroecological zone of interior dryland with a temperate subhumid Mediterranean climate, an annual average rainfall of 648 mm, a maximum average temperature of 32.6 °C and a minimum annual average temperature of 5.5 °C (CI-REN, 1997). The average ground elevation reaches up to 207 m a.s.l., and the average slope is less than 3%. Rainfall distribution during the crop season is shown in Table 1.

Table 1. Rainfall during growing season (2009).

Month	May	June	July	August	September	October	November	December	Total
Rainfall (mm)	77	126	53	107	31	41	22	0	457

The soil at the site is an Alfisol, which is classified as a fine, mixed, and thermic Mollic Palexeralfs (Pocillas Asociacion) (CI-REN, 1997), and it has a sandy clay loam texture and subangular blocky structure in the upper horizon. The site is located in a valley bottom positioned on alluvial-colluvial deposits. The following four horizons are recognised in the profile: Ap (0-17 cm; 10 YR 4/2 in moist conditions); Bw₁ (18-35 cm; 7.5 YR 4/4 in moist conditions with the presence of mottles); Bw₂ (36-95 cm; 10 YR 3/2 in moist conditions with 30% mottles) and BC (96-120 cm; 7.5 YR 4/4 in moist conditions to 7.5 YR 4/2 in moist conditions with a reduced presence of mottles). Topsoil characteristics prior to desurfacing based on six subsamples randomly selected within each plot (Table 2) were determined by soil analysis using the methodologies described by Sadzawka *et al.* (2006).

Table 2. Chemical properties of untreated topsoil (0-20 cm).

Properties	Value
Total N (mg kg ⁻¹)	4
P (mg kg ⁻¹)	5
K (mg kg ⁻¹)	81
Organic matter (%)	1.28
pH	5.51
Mn (mg kg ⁻¹)	6.10
Zn (mg kg ⁻¹)	0.56
Cu (mg kg ⁻¹)	2.93
Fe (mg kg ⁻¹)	44.02
B (mg kg ⁻¹)	0.24
Ca (cmol kg ⁻¹)	7.21
Mg (cmol kg ⁻¹)	2.04

2.2. Field methods and yield parameter determination

In November 2008, 18 plots (5 m x 5 m) were created by removing increasingly thicker topsoil layers as follows: 2, 6, 10, 14 and 18 cm (T_2 to T_{18} treatments). Furthermore, a control treatment (T_0) with unaltered soil was established. The removal of the first 2 cm of soil was done manually, and the remaining treatments were set mechanically using a skid steer loader (Bobcat brand, model S130, USA). The soil was kept under traditional fallow until May 2009, and it was then prepared with a Honda rototiller (model F600). An equivalent seed dose of 220 kg ha⁻¹ per plot of *Triticum aestivum* (Variety Pandora-INIA) was scattered without fertiliser application. In late July, soil macro- and micronutrients were analysed from samples taken at a 0-20 cm depth after the soil was removed for all six treatments using methodologies previously described by Sadzawka *et al.* (2006). At the time of physiological maturity, the wheat was harvested at ground level, and samples were collected from an area of one m² at the centre of each plot. A sample of 50 spikes was oven-dried at 70 °C for 48 h and then weighed. Dry weight was used to determine grain yield (kg ha⁻¹), biomass yield (kg ha⁻¹), 1000 grain weight (g), spikes (m⁻²) and grains per spike. Furthermore, a complete grain analysis was carried out using the methodologies described by Sadzawka *et al.* (2001).

2.3 Experimental design and statistical analysis

The experimental design was based on randomised blocks with six treatments (five levels of soil removal plus a control without soil removal) with three replications. Analysis of variance was performed to determine if there was an effect of soil removal on the considered target variables. Comparison of means was performed according to Tukey's test using IBM SPSS v.18 software.

3. Results and discussion

The results obtained for the first growing season showed a proportional decreasing trend in wheat yield according to the different levels of soil removed with major differences between T_0 and T_{18} as shown by the analysis of variance (Tables 3 and 4). Grain yield (kg ha⁻¹) was significantly reduced in proportion to the level of topsoil removal ($p < 0.05$). Similarly, the 1000 grain weight and grains per spike parameters decreased with increasing soil removal, and biomass yield showed no significant difference among treatments (Table 3). These results differed from those obtained by Izaurralde *et al.* (2006) who demonstrated marked effects on total dry matter yield according to simulated erosion levels. Nevertheless, in areas with arid to subhumid Mediterranean climate, such as in the coastal mountains of Central Chile, the rainfall distribution showed a marked peak between May and August (Table 1) followed by a sharp decrease in spring, thus, limiting soil water availability during the grain filling period, and this climatic condition affected grain yield more than total biomass production.

Table 3. ANOVA for target production parameters.

Parameters	Sum squares	Dof	Quadratic means	Sig.
Biomass (kg ha ⁻¹)	3402824	5	680564	.095
Grain yield (kg ha ⁻¹)	457260	5	91452	.000
Harvest index	0.007	5	.001	.494
1000 grain wg (g)	37.387	5	7.4	.000
Spikes m ⁻²	35428.484	5	7085	.208
Grain m ⁻²	1836273	5	367254	.001
Number of grains per spike	135.350	5	27	.005
Grain weight per spike (g)	.267	5	.053	.003

(Sig. < 0.05 means significant difference.)

Table 4. Effect of topsoil removal on productivity parameters of winter wheat (*Triticum aestivum*; cultivar Pandora-INIA).

Treatment (cm)	Grain yield (kg ha ⁻¹)	1000 grain wg (g)	Grain m ⁻²	Grain number per spike	Grain weight per Spike (g)
T0	1176 a	41.2 a	2853 a	15 a	0.62 a
T2	1046 ab	42.2 a	2478 ab	10 a	0.44 ab
T6	1095 ab	40.7 ab	2693 ab	10 a	0.40 b
T10	1080 ab	40.5 ab	2664 ab	9 a	0.37 b
T14	852 ab	39.0 bc	2181 ab	7 ab	0.28 b
T18	770 b	37.8 c	2032 b	8 b	0.30 b

Measured values accompanied by different letters in the same column indicate significant differences according to Tukey's test ($p < 0.05$).

Significant differences ($p < 0.05$) in grain yield (kg ha⁻¹) between T₀ and T₁₈ (Table 4) were observed. The removal of 18 cm of topsoil reduced grain yield by 35% as compared with T₀. This result was similar to the 39% reduction obtained by Larney *et al.* (2000) for 15 cm of topsoil removal and 44% reduction obtained by Tanaka and Aase (1989). These authors also observed a decrease in grain nitrogen content, which differed from the results obtained by Izaurralde *et al.* (2006) and those observed in this study where the amount of N increased by 18% in the wheat grain for T₁₈ as compared with T₀ (1.13 vs. 1.38%). This observation

may be a consequence of lower grain weight and production, which result in the concentration of nitrogen compounds. The other analysed nutrients in the wheat grain showed no significant differences among treatments. The decrease in grain yield was closely related to grain weight, and this last parameter was that most affected by soil removal with a high level of correlation ($R^2 = 0.71$). The results showed a reduction in grain weight by 6.5% on average between both T₁₄ and T₁₈ with respect to T₀, and these results were in agreement with those obtained by Izaurralde *et al.* (2006).

The values for grain yield (kg ha^{-1}), 1000 grain weight and grains per m^2 were highly correlated with soil removal unlike biomass yield and spikes per m^2 , which showed no significant correlation. Figure 1 shows the regressions between the main yield components and the different levels of soil removal. The linear function of grain yield and topsoil removal showed a critical drop in wheat productiv-

ity. For every 1 cm of removed topsoil, there was a corresponding decrease of 24 kg ha^{-1} in grain yield ($R^2=0.75$). The use of fertilisers and manure in high levels masked the low soil productivity. Without fertiliser application, the obtained results indicated low crop yields in a zone resulting from centuries of soil loss events, which has been estimated to be $29.95 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Pérez and González, 2001).

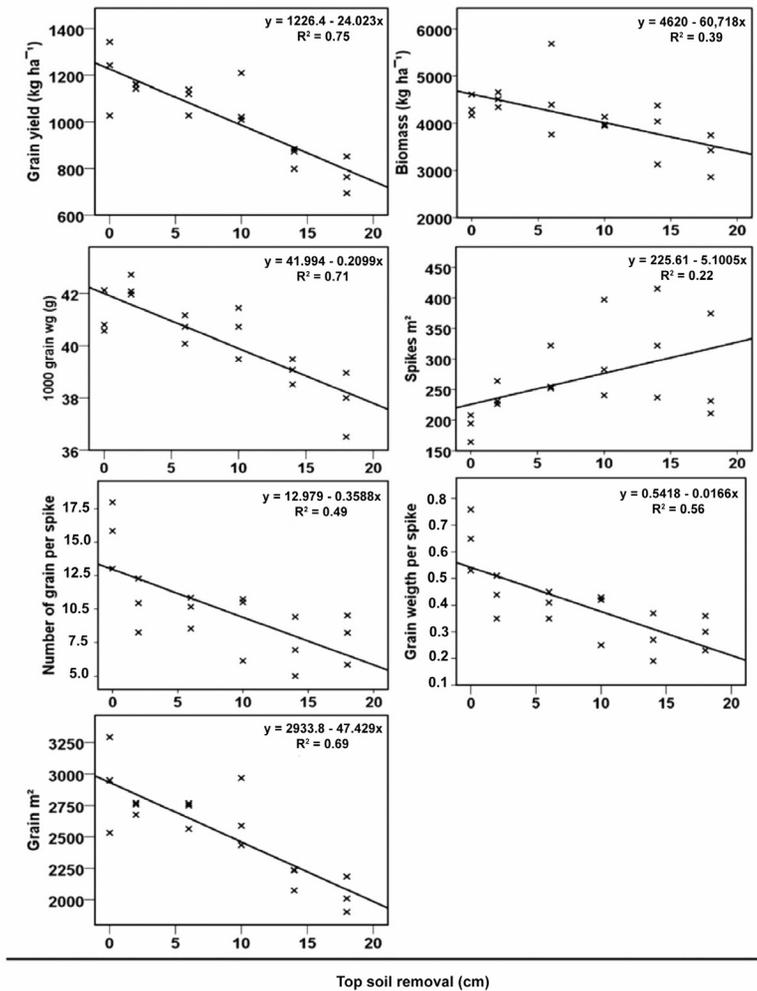


Figure 1. Correlation plot: productivity parameters vs. topsoil removal.

As a consequence of topsoil removal, the reduction in grain yield associated with the effect observed for grain weight may be related to a water deficit during the reproductive period, and this impact was higher with more soil removal. The low fertility status and low water retention were magnified by the low organic matter content (Table 5). This is especially

critical during the grain filling period, which occurs during a time of higher evapotranspiration demand and lower precipitation occurrence. On the basis of a series of studies, Den Biggelaar *et al.* (2001) determined that the yield decline in eroded plots in dry years is more significant than in years with abundant rainfall.

Table 5. Soil analysis for treatments after topsoil removal.

T	N	P	K	O.M.	pH	Mn	Zn	B	Ca	Mg	Sand	Silt	Clay
cm	---- mg kg ⁻¹ ----			%	----- mg kg ⁻¹ -----				--- cmol kg ⁻¹ ---		%	%	%
<i>T</i> ₀	12	7	96	1.60	6.22	4.03	0.50	0.34	6.32	1.81	52	26	23
<i>T</i> ₂	10	5	85	1.25	6.12	3.81	0.39	0.15	7.16	1.95	51	27	23
<i>T</i> ₆	8	5	93	1.05	6.22	3.89	0.71	0.15	6.92	1.97	50	26	25
<i>T</i> ₁₀	9	5	84	1.11	6.26	3.70	0.32	0.15	7.11	1.91	51	25	25
<i>T</i> ₁₄	13	4	74	1.05	6.31	2.21	0.25	0.16	8.13	2.33	51	23	27
<i>T</i> ₁₈	11	4	87	0.98	6.48	1.87	0.22	0.15	10.24	3.02	45	25	31

(The following abbreviation is used: OM, organic matter content)

Several factors can affect crop yield as result of the interaction of the effects of topsoil loss. Oyedele and Aina (2006) concluded that the primary impacts of soil removal more significantly affects soil physical properties and organic matter content than other chemical properties. In contrast, other studies conducted on soils to simulate erosion have found that nutrient deficiency is the main factor in yield reduction with drastic changes observed in the chemical properties of soil in relation to the depth of removed soil (Larney *et al.*, 2000; Izaurralde *et al.*, 2006).

As shown in Table 5, the soil analysis after topsoil removal showed that the remaining horizon had lower contents of organic matter and micronutrients, such as Mn, Zn and B, as compared with the original soil. These results revealed the preliminary effects of topsoil loss associated with the exposure of the lower horizons. Thus, the impacts of topsoil loss will be even

more severe in degraded dryland soils because the upper horizons have already been severely diminished and few fertile materials rise towards the surface. Both of these factors are directly related to the effects of soil erosion (Frye *et al.*, 1982; Larney *et al.*, 1995).

Organic matter content is one of the properties mainly affected by erosion because the concentration of organic carbon is consistently higher in the first 15 cm of the soil profile (Bauer and Black, 1994). The reduction in organic matter due to topsoil removal and its impact on crop productivity has been documented in other studies (Malhi *et al.*, 1994; Gollany *et al.*, 1992; Izaurralde *et al.*, 2006; Oyedele and Aina, 2006). In terms of soil productivity, Bauer and Black (1994) estimated that the contribution of 1 Mg ha⁻¹ of organic matter in the upper 30.5 cm is equivalent to 35.2 and 15.6 kg ha⁻¹ of biomass and grain yield, respectively. In this study, the decrease in organic mat-

ter content between T_0 to T_{18} (0.62%) corresponded to a loss of approximately 15.84 Mg ha⁻¹ between 0 and 18 cm given that the soil bulk density was equal to 1.42 Mg m⁻³, which would have a direct impact on crop productivity.

For organic matter and clay percentages, the differences observed were even greater at a depth below 14 cm. The topsoil removal in these treatments (T_{14} - T_{18}) resulted in an average decrease in organic matter (36%) and an increase in clay (19%). Consistent with data obtained by Gollany *et al.*, (1992), the increment in clay content in T_{18} can be explained by the exposure of the Bw_1 horizon of the original pedon. In turn, the increase in the clay fraction may be associated with the higher concentrations of Ca²⁺ and Mg²⁺ ions in the soil, which may explain the increase of these exchange bases deeper within the profile. Despite that topsoil loss due to water erosion is imperceptible each year and is not a uniform phenomenon, the result of this study demonstrated that the low crop productivity in the study area is due to hundreds of years of soil degradation.

4. Conclusions

In this study, the wheat grain yield had a proportional decreasing trend with respect to the levels of soil removed. However, the results obtained for one growing season only presented statistical differences for excessive soil loss (>2000 Mg ha⁻¹). Removal of 18 centimetres of soil resulted in the loss of a fertile layer within the soil profile (0-15 cm), which was reflected by a 36% reduction in organic matter content in this study. The effects on the physical properties of soil, mainly on available water storage, are factors that influence this relationship, and these effects must be evaluated. Similarly, agroclimatic conditions, especially rainfall patterns, may also have an impor-

tant role in establishing the shape of this function. In general, these results obtained from dryland areas in Central Chile highlighted the importance of topsoil where physical, chemical and microbiological factors may be critical in defining the decay function of crop productivity and soil loss.

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