

Influence of nitrogen fertilizer sources and lime applications on water use efficiency of oats (*Avena sativa* L.) under no-tillage management in andisols of Southern Chile

Abstract

Food production under rainfed agriculture, is limited due to soil water storage, mainly from low and variable rainfall. The aim of this study was to evaluate the effects of nitrogen fertilization sources and lime applications on WUE of oats (*Avena sativa* L.), under no-tillage management in a Typic Haploxerand soil, during the growing season 2008-09. The experimental design was a randomized complete block with three replicates and four treatment. The treatments were: (T₁): triple superphosphate+sodium nitrate; (T₂), urea+mono-ammonium phosphate, MAP; (T₃): urea +MAP + 750 kg ha⁻¹ lime and (T₄) urea + MAP + 1500 kg ha⁻¹ lime. Evapotranspiration was measured by the water balance method and volumetric soil water content was monitored with a neutron probe. Dry matter was measured in the phenological stages of tillering (T), panicle emergence (PE), milky grain (MG) and dough grain (DG). Total dry matter and grain yield were measured at maturity. Water use efficiency was determined in the phenological stages of: tillering (T)-panicle emergence (PE), PE-milky grain (MG) and MG-dough grain (DG). The results showed that treatments with ammonium fertilizers and lime application enhanced WUE. The higher WUE was observed between PE-MG. The ammonium fertilization (T₂) showed lower values for WUE, rate growth and harvest index. The source of nitrogen did not affect crop evapotranspiration and the NP fertilization with lime improves the WUE of oats with no-tillage management in Andisols of Southern Chile.

Keywords: water use efficiency, nitrogen fertilizer, lime, water balance, oats

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Introduction

Irrigated agriculture is the primary user of diversified water globally, reaching a proportion that exceeds 70-80% of the total in the arid and semi-arid zones.¹ Scarcity of water resources and growing competition for water in many sectors reduce its availability for irrigation.² Most agricultural production in the world is not irrigated and depends of rainfall and therefore, capture of rainfall for crop use is critical in determining crop productivity.³

In facts, rainfed agriculture is practiced on 80% of the world's agricultural land area, and generates about 70% of the world's staple foods, including most of the food in poor communities.⁴ In developing countries the large gaps between actual and attainable in rainfed yields, in many regions of the world suggest a large untapped potential for yield increases.⁵

Water scarcity and increasing demands for agricultural products create much debate about improvement of water use efficiency in the agricultural sector.⁶ There are two broad strategies for increasing yields in rainfed agriculture: (1) capturing more water and allowing it to infiltrate into the root zone; and (2) using the available water more efficiently by increasing the plant water uptake capacity and/or reducing non-productive soil evaporation.⁵ In addition, a possible way to increase dry land crop yield is to manage the transpiration so that more water is used during the vegetative phase when vapor pressure deficit is lower.⁷

Water use efficiency (WUE) represents a given level of biomass or grain yield per unit of water used by the crop.⁸⁻¹⁰ In rainfed agriculture, the WUE is linked to the effectiveness of the use of precipitation because there is not other source of water available.⁸ However, up to 50% of the rainfall in semi-arid areas is lost from the fields as non-productive soil evaporation. Options to reduce soil evaporation include dry planting, conservation agriculture and mulching.⁵ According to Howell¹¹ the main pathways for enhancing WUE in irrigated agriculture are to increase the output per unit of water, reduce losses of water to unusable sinks, reduce water degradation and relocate water to higher priority uses.

In order to increase water storage within the soil profile is necessary to increase plant available soil water.² Soil management practices affect the processes of evapotranspiration by modifying the available energy, the available water in the soil profile, or the exchange rate between the soil and the atmosphere.⁸ Many studies have shown the effectiveness of a no-tillage system in the soil water storage.¹²⁻¹⁴ It has been stated that no-tillage enhances the hydraulic properties of the soil,¹⁵ since the maintenance of crop residues on the soil surface result in an increased rainfall infiltration and a reduction in evaporation.¹⁶

Water is limiting factor for grain production in rainfed farming systems of many semiarid dryland regions, where cereal crops are frequently grown under a crop-fallow system, one crop every 2 years.¹⁷ Greater yield per unit rainfall is one of the most important challenges in dry land agriculture.⁹ Therefore, to increase the yield is essential to optimize water and nitrogen use.^{8,18-21}

The Chilean soils derived from volcanic ashes showed acidic pH, high extractable Al and high P fixation.²² Andisols located in the Andean foothills of Southern Chile are used under rainfed conditions with the traditional rotation oats - wheat. Nevertheless, increasing crop yield requires improved rainfall storage efficiency and proper rates the soil acidification by using residue management, tillage systems and nitrogen fertilization. No-tillage management favors water accumulation in the soil profile and greater root growth.^{19,23,24} In addition, it has been shown that mulching with crop residue can improve water use efficiency by 10 -20% through reduced soil evaporation and increased plant transpiration.^{18,25}

The agronomic advantages of conservation tillage have also been questioned in terms of soil water storage efficiency during and at the end of the fallow period.¹⁷ On the contrary, the use of crop residues to conserve soil and water in arid and semiarid areas is becoming increasingly important.²³ Therefore, the aim of this study was to evaluate the effectiveness of different sources of nitrogen fertilization and lime on water use efficiency in oat crops under with no-tillage management in Andisols of Southern Chile.

Materials & methods

Site description

A field experiment was carried out in El Carmen with geographic coordinates 36° 56' S , 71° 59' W at an altitude of about 290 m above the sea level. This area has a Mediterranean climate and it is located in the central southzone of Chile. The average annual rainfall is 1200mm with a 77% falling in May, June, July and August. Annual evapotranspiration is reported as 1100 mm, with a dry period of 3-4 months and with 5-6 frost-free months. Average annual mean temperature for this area is 13.6°C with an average temperature of 3.8 C° in the coldest month (June) and 19.7°C in the hottest month (January). Annual mean relative humidity is 71%.²⁶

The soil corresponds to a medial, amorphous, thermic Typic Haploxerands, derived from volcanic ashes. It is a deep and porous soil with good drainage. Soil texture is silt loam, with a clay proportion of 27.8%, silt 38.4% and sand 33.8%. Soil bulk density was 0.94Mgm⁻³ and soil water content at field capacity and wilting point were 63.72% and 33.55% by weight, respectively.

Experimental design

The field experiment was conducted in the 2008-09 growing season with oats (*Avena Sativa* L.) in a long-term crop rotation wheat (*Triticumaestivum* L.) and oats (*Avena sativa* L.) sowed during 1996-1997 growing season under no-tillage management. The sowing was carried out with 140 kg ha⁻¹ seed dose. The nitrogen fertilization was divided in 1/3 sowing and 2/3 tillering. In addition, 150 kg P₂O₅ ha⁻¹ and 120 kg K₂O ha⁻¹ were applied. The experiment was laid out in a randomized complete block design with three replicates (10 x 12 m) and four treatments. The treatments were: T1: triple superphosphate 325 kg ha⁻¹ + sodium nitrate, 750 kg ha⁻¹; T2: mono-ammonium phosphate MAP, 300 kg ha⁻¹ + urea, 260 kg ha⁻¹; T₃: lime, 750 kg ha⁻¹ + MAP, 300 kg ha⁻¹ + urea, 260 kg ha⁻¹; T₄: lime 1500 kg ha⁻¹ + MAP, 300 kg ha⁻¹ + urea, 326 kg ha⁻¹. Each experimental plot was 120m² with 2 m between plots.

Water balance

Evapotranspiration (ET) was calculated using the following equation:

$$ET = \Delta W + P - D$$

Where ΔW (mm) is the change in soil water storage between two soil moisture content measurements, P (mm) is growing seasonal rainfall and D (mm) is downward drainage out of the root zone. Soil water content was monitored using a neutron probe (CPN, 503-DR Hydroprobe, Campbell Pacific Nuclear International, California, USA) at 20, 40, 60 cm depth. This device was calibrated against volumetric soil water content (Θ_v) and neutron count rate (CR), using a calibration curve ($\Theta_v = 41,721CR - 53,015$). Soil water content was measured in the phenological stages of tillering (23 August), panicle emergency (11 October), milky grain (15 November) and dough grain (16 December). Rainfall was obtained from the automatic meteorological station located in the experimental area. Drainage rate was determined by measurements of volumetric water content between 40 and 60 cm-depth using the following relationship:

$$D = (\Delta\Theta/\Delta t) z = (\Theta_{v2} - \Theta_{v1}) / (t_1 - t_2) z$$

Where: D (mm) is the drainage out root zone; $\Delta\Theta$ (cm³cm⁻³) is the variation of soil volumetric water content as function of time; Δt (days) is the timing and z (cm) is soil depth.

Water use efficiency

Water use efficiency (WUE) was calculated for both dry matter and grain yield by dividing crop yield by evapotranspiration. Samples of fresh matter were obtained using the square method (0.25 x 0.25 m). Then, samples were oven dried at 65°C for 72 h (Memmert, UFP 800 RR, Schwabach, Germany) and the dry weight was determined. Dry matter yield was measured, in the phenological stages of tillering (T), panicle emergency (PE), milky grain (MG) and dough grain (DG).

At harvest, the grain yield was measured in the five central files of 3 m length for each plot, and the mean grain yield was expressed as kg ha⁻¹. The harvest index (HI) was calculated by expressing the grain yield over the final total dry matter yield. WUE was determined by dividing grain yield by evapotranspiration.

Statistical analysis

Data collected were subjected to analysis of variance (ANOVA). Differences between means of treatments were declared significantly different using Tukey test ($p < 0.05$).²⁷

Results and discussion

Volumetric soil water content and soil water storage

Figure 1 shows the changes of volumetric soil water content at 0 -20 cm and 20 -40cm soil layer. Soil water content showed a similar pattern for the two depths, but it changed in the different phenological stages due to the differences in seasonal rainfall and crop water requirements, reaching its highest value at milky grain where soil moisture was close to FC, due to 17 mm rainfall before measurement (Figure 2). Between the stages of T-PE, the Θ_v was under the threshold level (TL) as a result of the increase in crop water requirements. The Θ_v showed a decrease in the panicle emergency stage due to a low rainfall of 18 mm. However, the highest Θ_v was obtained at milky grain, with statistical differences ($p \leq 0,05$) as compared with panicle emergency and dough grain. This can be explained for the higher rainfall (37 mm) in October and the crop residues on the soil surface that decreased soil evaporation. On the other hand, Θ_v at dough grain (16 December) was lower than PWP as a result of higher evapotranspiration and rainfall scarcity in December.

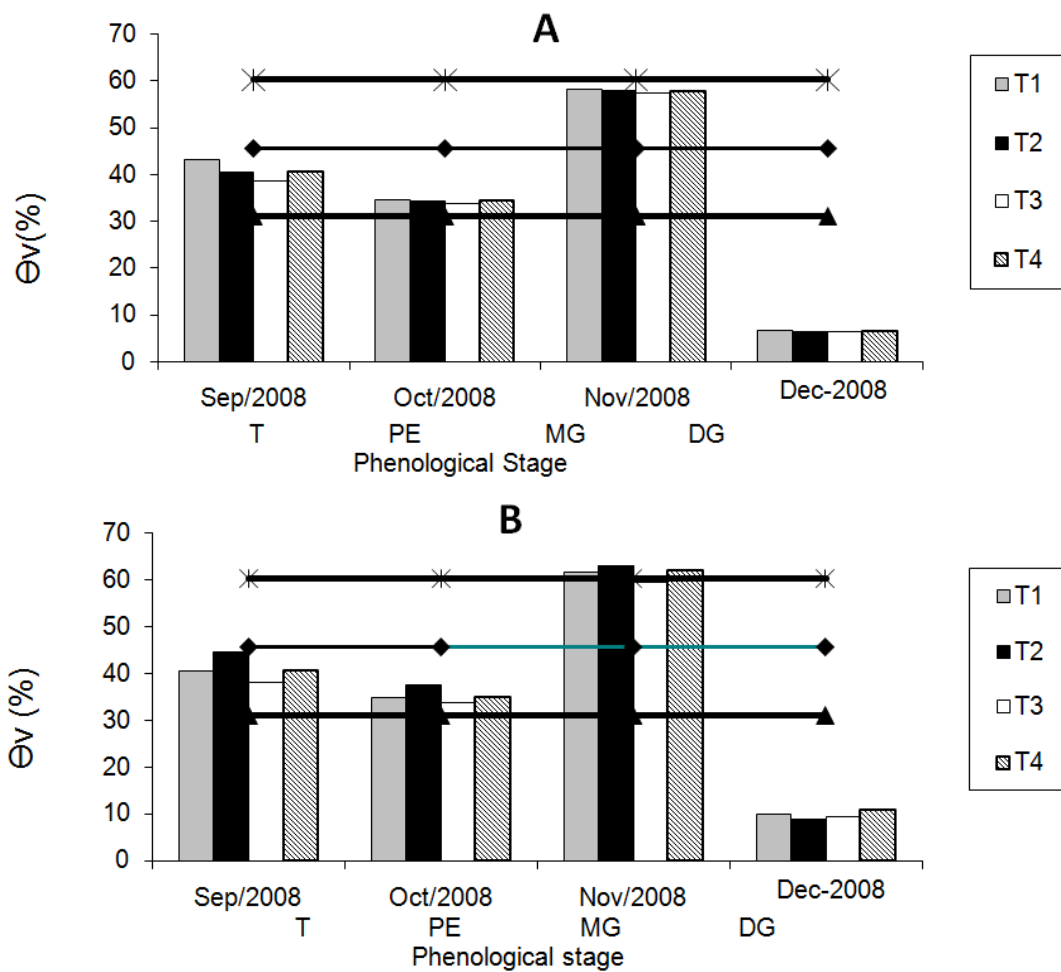


Figure 1 Volumetric soil water content, Θ_v (%) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilization sources and lime applications in aTypic Haploxer and soil at 20 cm(A) and 40 cm(B) depth.

FC, Field capacity; PWP, permanent wilting point; TL, threshold level (50%HA); HA, water availability (FC-PWP); Θ_v , volumetric soil water content; T, tillering; PE, panicle emergency; MG, milky grain; DG, dough grain.

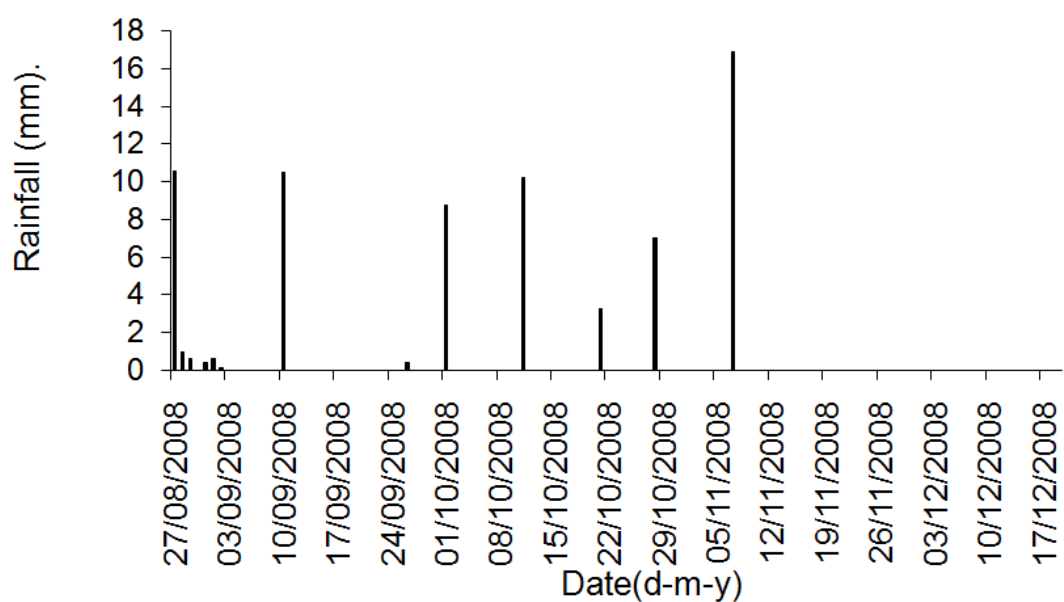


Figure 2 Rainfall during the experimental period in the site experimental, El Carmen, Chillán, Chile.

There was no significant difference ($P \leq 0,05$) between sources of fertilization and soil water storage at 0-20 y 20-40 cm-depth in the different phenological stages of the crop (Table 1). This is explained by the fact that energy state of soil water depends on capillarity, pore size distribution and particle size distribution. On the contrary, sources of fertilization have positive effects on the root development

and water uptake.²¹ However, T3 showed the lowest levels for soil water storage at 20-40 cm-depth that the T-PE-MG phenological stages, which can be explained for the higher water uptake due to greater root growth. According to Pala et al.²⁰ N application can increase the ability of crop to utilize soil available water.

Table 1 Soil water storage (mm) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilization sources and lime applications in a Typic Haploxer and soil at 0-20 and 20-40 cm depth

Depth (cm)	Treatments	Phenological stage			
		Tillering	Panicle emergency	Milky grain	Dough grain
0-20	T1	87aBC	69 aB	116 aC	132 aA
	T2	81 aB	68 aB	116 aC	127 aA
	T3	77 aB	68 aB	115 aC	130 aA
	T4	81 aBC	69 aB	116 aC	133 aA
20-40	T1	81aB	70aAB	123 aB	202 aA
	T2	89aB	75 aB	126 aC	176 aA
	T3	76B	68 aB	119 aC	189 aA
	T4	82aB	70 a	125 aC	219 aA

Columns with diferent lowercase letters and files with different capital letters differ significantly, Tukey's test ($P < 0.05$)

Evapotranspiration

The ET estimated by water balance is shown in Table 2. These results showed that root water-uptake is similar at 0-20 and 20-40 cm-depth, obtaining the highest water consumption between PE-MG, representing a 40% of total crop water extraction of soil profile.

No significant differences ($p \leq 0,05$) were observed between treatments, except during T- PE in T₁ (triple superphosphate+sodium nitrate) and T2 (MAF+ urea). This can be explained when considering that NH₄⁺ applications decrease the ability of crop to utilize soil water available.²⁰ Regarding phenological stages, significant differences ($p \leq 0,05$) were observed in T3 at 0-20 cm-depth and in T₃ and T₄ at 20-40 cm-depth.

Table 2 Evapotranspiration (mm) in the different phenological stages of an oat crop under no-till age management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and at 0-20 , 20-40 and 0-40 cm-depth

Depth (cm)	Treatments	Phenological stage			
		T-PE	PE-MG	MG-DG	Total
0-20	T1	41 bA	57 aA	51 aA	149 a
	T2	29 aA	51 aA	45 aA	125 a
	T3	34 abA	59 aB	51 aB	144 a
	T4	36 abA	53 aA	51 aA	140 a
20-40	T1	32aA	60aA	53 aA	145 a
	T2	26aA	54 aA	53 aA	133 a
	T3	31aA	59 aB	51 aB	141 a
	T4	31aA	61 aB	55 aAB	147 a
0-40	T1	73	117	104	294
	T2	55	105	98	258
T3	65	118	102	285	
T4	67	114	106	287	

Columns with diferent lowercase letters and files with different capital letters differ significantly, Tukey's test ($P < 0.05$). T, tillering; PE, panicle emergency; MG, milky grain; DG, dough grain

The highest ET and dry matter production was obtained between PE -MG, for all treatments, due to the increase in temperature during grain filling when the crop shows the highest hydric requirements. This is in agreement with Angus and van Herwaarden (2001) who reported that additional biomass from 1 mm of ET before anthesis was 30 kg ha⁻¹ and 35 kg ha⁻¹ after anthesis, with high N applied.

The lowest ET values in the different phenological stages were found with the application of MAP and urea (T2) due to low plant density and the effects of soil acidification (pH=4,05). On the contrary, treatments T3 (pH=5,70) and T4 (pH=6,52) presented the higher ET, due to higher root development and water uptake as a result of lime application.

Evapotranspiration was very similar between treatments T₁, T₃ y T₄ with 294, 285 and 287 mm, respectively. On the other hand, in T₂ was 258 mm, decreasing in 12.5 % due to NH₄⁺ fertilization.

Drainage

Figure 3 shows that the highest drainage rate was recorded in T₂ with 55mm (0.65mmday⁻¹) due to lower root growth and leaf area. However, it can also be observed that drainage rate values were similar in the other treatments (Figure 3), reaching the highest value

between PE-MG phenological stages, for the effects of seasonal rainfall and soil acidity. In general, the drainage from the root zone was low with values of 30 mm in T₁, 22 mm in T₃, and 29 mm in T₄ during the growing season. These values result in low drainage rate of 0,36 in T₁; 0,25 in T3 and 0,35 mm day⁻¹ in T₄, which may be explained for a higher soil water retention and lower soil hydraulic conductivity of Andisols that ranged from 2 to 8x10⁻⁹ mseg⁻¹.²⁸ On the other hand, Lampurlanés and Cantero-Martínez²³ determined that the adoption of no-tillage decreased the hydraulic conductivity due to reduction in soil porosity in semiarid conditions. Furthermore, Angus and van Herwaarden⁷ estimated that the term of drainage is usually negligible on flat land in semiarid and subhumid conditions, while it is taken as zero in other studies.^{20,21,24} On the other hand, Tan et al.²⁹ reported that tillage had very little effect on tile drainage.

Yield parameters

Biomass was affected by the nitrogen source. The lowest yields were found with the T2 (MAP+urea), due to soil acid pH of 4.05 (Table 3). The highest dry matter yield and grain yield were obtained in T₃ and T₄ since lime application improved the soil structure and increased water storage. Therefore, management of nitrogen and phosphorus fertilization is crucial to obtain optimum pH for the crop in Andisols.

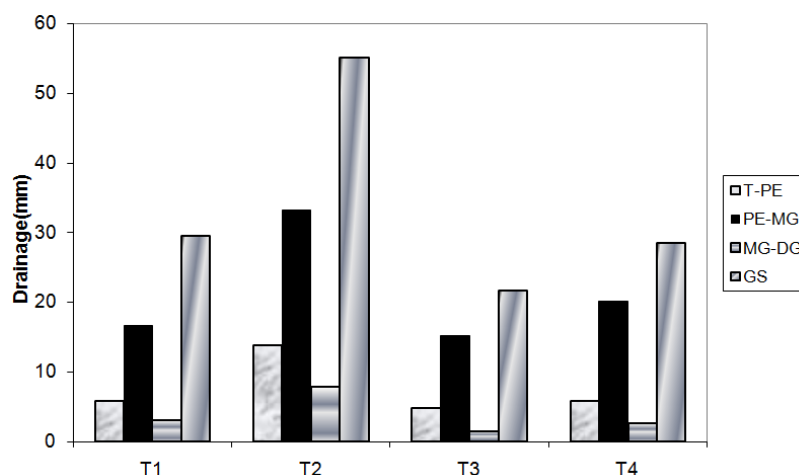


Figure 3 Drainage rate (mm) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilization sources and lime applications in a Typic Haploxer and soil.

T, tillering; PE, panicle emergency; MG, milky grain; DG, dough grain; GS, growing season.

Table 3 Soil acidity of an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil

Treatments	pH
T1	6,11b
T2	4,05d
T3	5,70c
T4	6,52a

Column with different lowercase letters differ significantly, Tukey's test (P ≤ 0.05)

The highest production of dry matter and growth rate was found between PE-MG (Table 4 & 5) showing statistical differences (P≤0,05)

as compared with the others phenological stages in all treatments, with the exception of T₄ that showed the highest growth rate. At the stages of MG -DG the growth rate showed the lowest value in T₂, probably because during the filling grain the crop did not have enough roots to extract soil water during the filling grain stage.²⁰ This suggests that the phenological stage corresponding to PE-MG is the period with the highest water requirements, period in which the crop needs greater soil water availability.

Respect to grain yield (Table 6) the results show that values were higher in the treatments with lime applications and showed statistical differences (P≤0,05) as compared with T₂ (ammonium fertilization without lime), T₄ was the treatment that presented the highest yield with a value of 4650 kg grain ha⁻¹.

The highest values for growth rate were obtained between PE-MG, with 203g DM day⁻¹ in T₃ (ammonium fertilization + 750 kg ha⁻¹lime).

Therefore, lime additions have positive effects to correct soil pH and increase the root growth in Chilean Andisols.³⁰ The growth rate in the vegetative phase and grain filling was lower, especially in treatment

T₂ (Figure 4) demonstrating that the use of ammonium-based N fertilizers is not recommended because the acidify soils and enhance P adsorption capacity.

Table 4 Dry matter (kg DM ha⁻¹) in the different phenological stage of an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil

Treatments	Phenological Stages			
	Tillering	Panicle emergency	Milky grain	Dough grain
T1	883 aA	2755 aA	7811 aB	9789 aC
T2	752aA	2828 aAB	7629 aBC	8235aC
T3	1151aA	3830 aAB	9717 aBC	12.000aC
T4	1004 aA	3347 aAB	7768 aBC	11.156 aC

Columns with diferent lowercase letters and files with different capital letters differ significantly, Tukey's test (P < 0.05)

Table 5 Growth rate (g DM day⁻¹) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil

Treatments	Phenological stages		
	T-PE	PE-MG	MG-DG
T1	38 aA	174 aB	32 aA
T2	42 aA	166 aB	10 bA
T3	55 aA	203aB	37 aA
T4	48 aA	152 aB	55 aA

Columns with diferent lowercase letters and files with different capital letters differ significantly, Tukey's test (P < 0.05). T, tillering; PE, panicle emergency; MG, milky grain; DG, dough grain

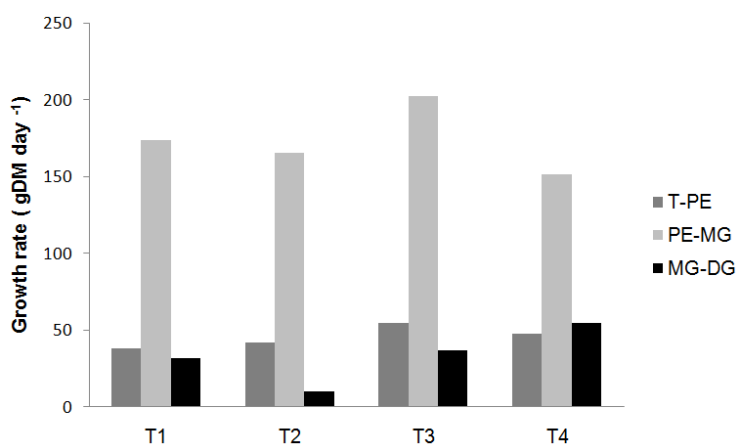


Figure 4 Growth rate (g DM day⁻¹) in the different phenological stages of an oat crop under no-tillage management to different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil.

T, tillering; PE, panicle emergency; MG, milky grain; DG, dough grain.

Harvest index (Table 6, Figure 5) did not present statistical differences (P≤0,05) between treatments. However, T₂ showed the lowest HI, due to a decrease in grain yield as a result of NH₄⁺ fertilization. This can be explained because the processes of grain filling were more affected that the growth period, reaching the lowest growth rate between MG-DG (Table 7). This results are in agreement with Caviglia y Sadras.³¹ who determined HI ranged from 0,28 to 0,47 with 80 and 160 kg Nha⁻¹ in a crop wheat, respectively.

Water use efficiency (WUE)

Table 8 shows WUE of dry matter perphenological stage with different source of fertilization. Results showed no significant

differences (P≤0,05) among treatments and sources of fertilization. Only T₂ showed significant differences between T-PE and PE-MG, obtaining the lowest WUE during the period MG-DG, with a value of 6,77 kg MS ha⁻¹ mm⁻¹. The crop phase between PE-MG showed the highest WUE for all treatments, obtaining a value of 50,42 kg MS ha⁻¹ mm⁻¹ in T₃. However, the phase between MG-DG showed the highest WUE in T₄ with a value of 25,26 kg MS ha⁻¹mm⁻¹.

In treatment T₃, WUE values before anthesis (tillering to panicle emergency) were higher than those determined by Cantero-Martínez et al.³² who obtained values that ranged from 11,3 a37,5 kg MS ha⁻¹ mm⁻¹ in barley and in a similar period. However, values WUE corresponding to post-anthesis (milky to dough grain) weresimilar to

the values reported by Cantero-Martínez et al.³² that ranged from 13,2 a49 kg MS ha⁻¹ mm⁻¹.

Although the T₂ showed a higher WUE value during T-PE and PE-MG in comparison with values obtained in treatments T₁ and T₄, the effect during the vegetative phase is less effective to increase yield since WUE decreased to 6,77 kg MS ha⁻¹ mm⁻¹ between MG-DG.

All the treatments showed a higher WUE between PE-MG (Figure 6). The lowest WUE value was observed between MG-DG for all treatments due to lower volumetric soil water content close to PWP in dough grain, limiting the water uptake due to lower potential gradient soil-roots. This results is in agreement with Ehlers³³ who reported a lower WUE value in the same phenological stage in oats.

Table 6 Harvest index (HI) of an oat crop with different nitrogen fertilizer sources and lime applications under no-tillage management in a Typic Haploxer and soil

Treatments	Grain(kg ha-1)	Dry Matter(kg ha-1)HI
T1	344098790,35a	82350,19a
T2	1570	12
T3	4599	0,38a
T4	465011.156	0,42a

Column with different lowercase letters differ significantly, Tukey's test (P ≤ 0.05)

Table 7 Water use efficiency (kg MS ha⁻¹ mm⁻¹) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilization sources and lime applications in a Typic Haploxer and soil

Treatments	Phenologicalstage		
	T- PE	PE - MG	MG- DG
T1	25,65aA	45,87aA	19,02aA
T2	37,02aAB	45,76aB	6,77bA
T3	42,34aA	50,42aA	23,58aA
T4	35,63aA	39,13aA	25,26aA
CV%	28,36	37,91	95,5
LSD	26,07	48,61	56,55

Columns with diferent lowercase letters and files with different capital letters differ significantly, Tukey's test (P<0.05). T: tillering; PE: panicle emergence; MG: milky grain; DG: dough grain; CV: coefficient of variation; LSD: least significant difference

Table 8 Use efficiency (kg ha⁻¹ mm⁻¹) in an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil

Treatments	WUE dry matter	WUE grain
T1	28,2a	9,50 ab
T2	27,4a	5,38 a
T3	34,1a	13,06 b
T4	30,6a	13,07 b
CV%	37,19	19,42
LSD	29,42	5,35

Columns with different lower case letters differ significantly, Tukey's test (P ≤ 0.05)

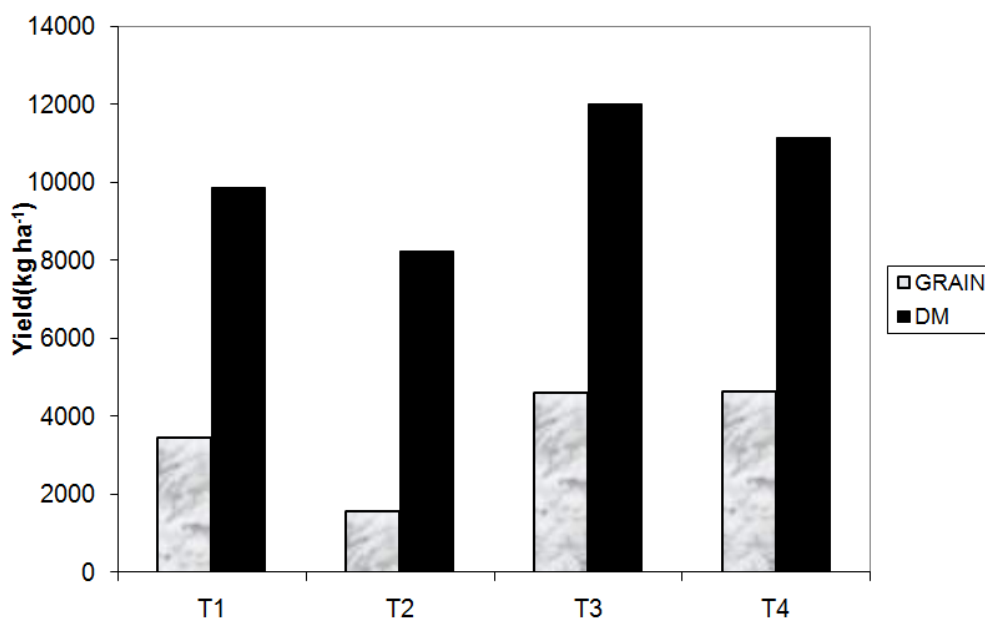


Figure 5 Grain and dry matter (DM) yield of an oat crop with different nitrogen fertilizer sources and lime applications under no-tillage management in a Typic Haploxer and soil.

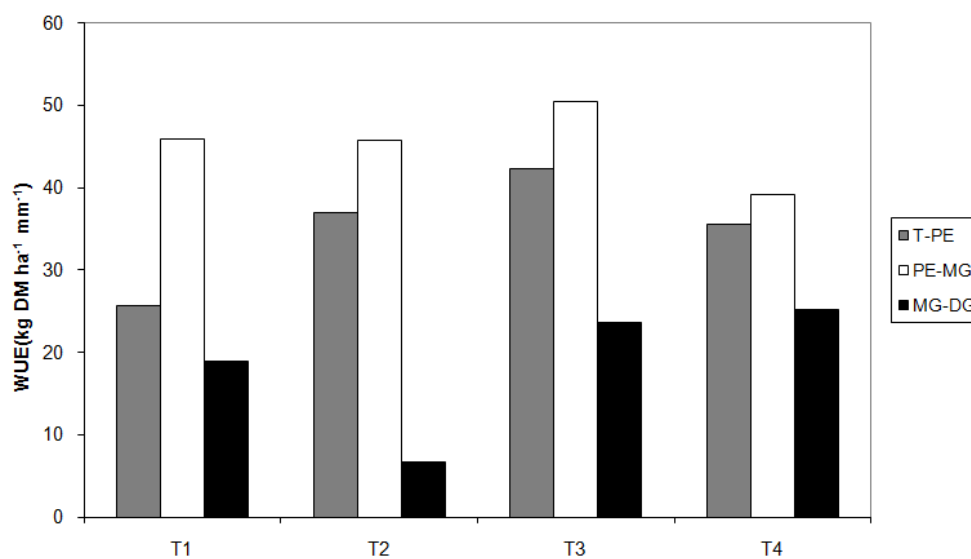


Figure 6 Water use efficiency ($\text{kg ha}^{-1}\text{mm}^{-1}$) in the different phenological stages of an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil.

T, tillering; PE, panicle emergence; MG, milky grain; DG, dough grain.

WUE values for dry matter (Table 8 & Figure 7)) found in this study were lower than those reported by Ehlers³³ and Cantero-Martínez et al.³² Values ranged from 41 kg MS ha⁻¹mm⁻¹ in oats to 38,7 kg MS ha⁻¹mm⁻¹ in barley, but were higher than the results findings in wheat by Li et al.³⁴ values that ranged from 7.39 a 14,3 kg ha⁻¹ mm⁻¹. Reasons for these differences can be related with the photosynthetic efficiency reported by Fischer and Turner,³⁵ who indicated that more efficient plant as CAM and C4 produced 34 kg MS ha⁻¹mm⁻¹ as compared with plants C3 with 15 kg MS ha⁻¹mm⁻¹.

Grain WUE (Table 8 & Figure 7) showed significant differences

($p \leq 0,05$) among treatments, being the T2 the lowest WUE with 5.38 kg grain ha⁻¹ mm⁻¹. Treatments T₃ and T₄ showed the highest WUE as compared with other treatments. These results are in agreement with the results reported by Cantero-Martínez et al.³² in barley with 13,77 kg grain ha⁻¹ mm⁻¹. As compared with wheat, WUE was higher than the value reported by Li et al.³⁴ with a value of 4.99 kg grano ha⁻¹ mm⁻¹ but lower than the value reported by Ilbeyi et al.³⁶ with a value of 18,2 kg grain ha⁻¹ mm⁻¹. According to the results obtained in our study, it is possible to use of ammonium fertilizers with lime additions in order to increase WUE and improve particles aggregation and water storage in acid soils of rainfed areas.³⁷

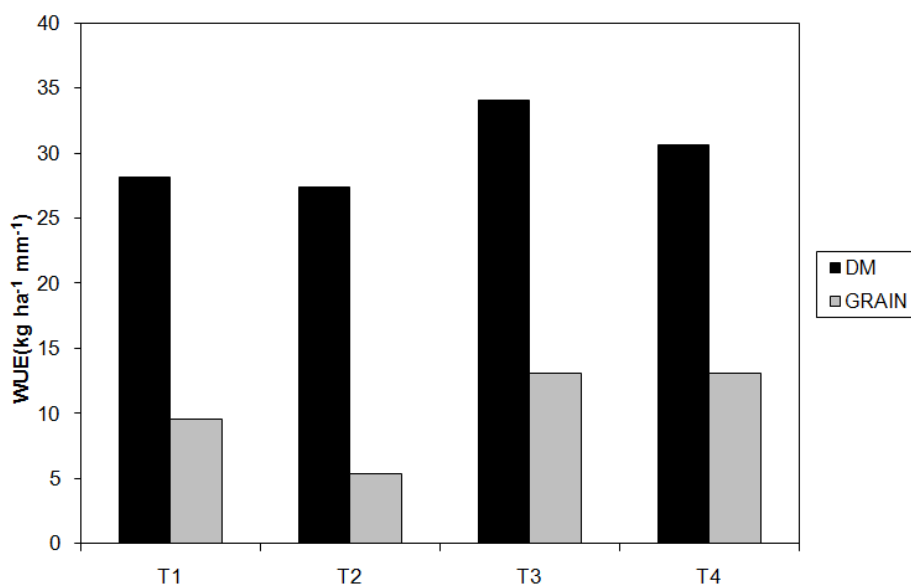


Figure 7 Water use efficiency ($\text{kg ha}^{-1}\text{mm}^{-1}$) per dry matter and grain yield in an oat crop under no-tillage management with different nitrogen fertilizer sources and lime applications in a Typic Haploxer and soil.

Conclusion

The deficit and high variability of rainfall in rainfed areas make necessary to study the effect of soil management practices and fertilization on water storage within soil profile and water use efficiency. In the present study, it was found that the use of ammonium nitrogen sources with lime additions increased WUE, dry matter production and grain yield in an oat crop with no-tillage management. Regarding the phenological stages, the highest WUE value was observed between panicle emergence and milky grain. On the contrary, ammonium fertilization (T2) showed the lowest WUE, growth rate in the grain filling period and a lower harvest index. Soil acidification decreased water and nutrients roots uptake. Treatment T3 with ammonium fertilizers and $750 \text{ kg lime ha}^{-1}$ showed the highest WUE. On the other hand, the nitrogen fertilizer sources had no effects on crop evapotranspiration or soil water storage. Based on these findings, the application of ammoniacal fertilizer sources with lime additions in Chilean Andisols are recommended to improve precipitation use efficiency in oat crop under no-tillage management.

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Conflicts of interest

Authors declare no conflict of interest exists.

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