Soil & Tillage Research 117 (2011) 76–84

Contents lists available at SciVerse ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization

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ARTICLE INFO

Article history:
Received 2 December 2010
Received in revised form 26 August 2011
Accepted 1 September 2011
Available online 19 October 2011

Keywords:
Dryland
Winter cereal
Soil mineral nitrogen
Water productivity
Direct seeding
Biomass

ABSTRACT

Conservation tillage systems (no-tillage, NT; and minimum tillage, MT) are being adopted in rainfed agroecosystems of the Mediterranean basin where water availability is the main limiting factor for crop productivity. We hypothesized that long-term adoption of conservation tillage systems would increase water use efficiency (WUE) and its response to N fertilizer additions due to improved soil water content.

A field experiment was established in 1996 on a loamy Xerofluvent Typic in the Ebro river valley (NE Spain). The experiment compared three nitrogen (N) fertilization levels (zero, 0 kg N ha^{-1}, medium, 60 kg N ha^{-1}, and high, 120 kg N ha^{-1}), under three tillage systems (CT, conventional tillage; MT and NT), annually cropped to barley (*Hordeum vulgare*, L.) as is usual in the region. Ten years after the experiment establishment, during four consecutive growing seasons, 2005–2006 to 2008–2009, we evaluated the response of soil water content, soil nitrate, above-ground dry matter, grain yield and yield components to long-term (>10 years) tillage and N fertilization treatments.

The long-term sustainability of NT and MT was confirmed. Mean yield and WUE under long-term conservation tillage systems were 66% and 57% higher than under CT, respectively. This improvement was mainly attributed to improved soil water usage under conservation tillage, mainly due to reduced water use during the pre-anthesis period. However, in a wet year yield did not significantly differ among tillage systems. The improvement of WUE with N fertilization was confirmed under NT, which medium and high N fertilizer level increased 98% mean grain yield and 77% mean WUE compared to CT. The increased response of crop and yield to N fertilization under NT was due to improved soil water content. Soil N accumulation together with the lower water accumulation explained the lack of response to N fertilization under CT, even on a wet growing season (i.e., 2008–2009).

Long-term NT adoption was a sustainable practice for barley monoculture in the region, allowing for reduced costs and yield increase with N fertilizer additions. N fertilizer rates on rainfed Mediterranean croplands should be adjusted depending on the reduction of tillage intensity and rainfall of the year. In our system and as an example for this agroecosystems, N fertilizer rates should be kept at or below 60 kg N ha^{-1}, and should be further reduced on intensively cultivated soils.

1. Introduction

Dryland agriculture in the Mediterranean region is mostly water limited, and yields vary markedly from year to year depending on the amount and distribution of precipitation, which are both highly variable (Austin et al., 1998). Water from precipitation must be captured and retained in soil and used efficiently for optimum yield production. Adequate management practices, such as conservation tillage and adequate N fertilization may increase water productivity, and limit environmental problems as soil erosion and N losses.

Conservation tillage practices include reduced soil tillage systems, such as minimum tillage (MT) and no-tillage (NT) systems, aimed at increasing the soil cover with the crop residues from the previous crop (CTIC, 2010). Improved soil surface cover usually improves water capture and retention (Unger et al., 1991). NT is a promising practice for croplands on the Mediterranean basin, where it can improve water use efficiency (WUE) (Cooper

Abbreviations: NT, no-tillage; MT, minimum tillage; CT, conventional tillage; ZN, zero nitrogen; MN, medium level of N fertilization (60 kg N ha^{-1}); HN, high level of N fertilization (120 kg N ha^{-1}); GWC, gravimetric water content; SWC, soil water content; SN, soil nitrate N content; WU, water use; WU_{pre}, WU during pre-anthesis period; WU_{post}, WU during post-anthesis period; WUE, water use efficiency; WUE_{pre}, water use during pre-anthesis period; WUE_{post}, water use during post-anthesis period; WUE_b, WUE of above-ground biomass production; WUE_y, WUE of grain production.

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doi:10.1016/j.still.2011.09.002

and Gregory, 1987; Mrabet, 2000). NT and MT are mainly used for winter cereals, and the adoption in European Mediterranean countries is greater than in North African countries (Arrúe, 2006). In Spain, conservation tillage is adopted on over 4% of the surface and in some areas of Spain, it has been adopted over 80% of the surface and for more than 25 years (Cantero-Martínez et al., 2008).

Under semiarid Mediterranean conditions, N fertilization may also increase WUE by stimulating dry matter production (Latiri-Souki et al., 1998), through a more rapid growth and improved transpiration efficiency. However, yields and WUE may be reduced when excessive N fertilizer is applied (Bladenopoulos and Koutroubas, 2003; Cantero-Martínez et al., 1995a). Moreover, N fertilization has to be adjusted because excessive N fertilization is an economical loss and leads to negative environmental consequences (Shepherd et al., 1993). In the Ebro river valley, as in other regions in the Mediterranean basin, N fertilizer rates for barley (*Hordeum vulgare*, L.) production has been usually applied between 100 and 200 kg of N ha^{-1} without agronomical control in many cases (Cantero-Martínez et al., 2003). These rates must be reduced to reach equilibrium among cost, environment and productivity.

The study of soil and crop responses to N fertilization under different soil tillage systems is useful to understand the interaction between these two factors, and to define best practices for improved N fertilization. Conservation tillage systems may improve water capture and retention, thus increasing crop growth and N uptake. This may reduce the availability of soil mineral N and may require increased N fertilization (Malhi et al., 2001; McConkey et al., 2002). In our Mediterranean dryland systems, a previous study in the area found that the interaction between these two practices in the short-term (1–3 years) was not significant and no additional fertilizer was needed when MT and NT were adopted. However long-term adoption (>10 years) may lead to a different response.

We hypothesized that long-term adoption of conservation tillage systems and reduced N fertilization would be a sustainable strategy in the region 10 years after their adoption, and that WUE and response to N fertilization would be increased under conservation tillage systems due to improved soil water conservation. Consequently, the objective of this study was to evaluate long-term effects of tillage and N fertilization on crop response and WUE in a rainfed Mediterranean agroecosystem.

2. Materials and methods

2.1. Site, tillage and N fertilization

A long-term experiment on tillage and N fertilization of winter-barley was initiated in 1996 in Agramunt (41°48′N, 1°07′E; Lleida, Spain) (Cantero-Martínez et al., 2003). The experiment consisted of a factorial combination of three levels of N fertilization (zero, ZN; medium, 60 kg N ha^{-1}, MN; and high, 120 kg N ha^{-1}; HN), and three tillage systems with two conservation tillage systems (NT and MT) and one intensive tillage system (conventional tillage, CT). The experimental design was a randomized complete block design with three repetitions and a plot size of 50 m × 6 m. The mean annual rainfall in the area is 435 mm, and the soil was classified as Xerofluvent Typic (Soil Survey Staff, 1994). Main soil characteristics in the plough layer were the following: soil pH was 8.5; sand, silt and clay content were 465, 417 and 118 g kg^{-1}, respectively; and soil organic carbon content (SOC) in the soil surface (0–5 cm) was around 16 g kg^{-1} under NT, around 13 g kg^{-1} under MT and around 8 g kg^{-1} under CT, while SOC at deeper layers (10–25 cm) was similar among tillage systems, around 7 g kg^{-1}. Such increase in SOC at surface level under conservation tillage systems led to increased stock of C within the SOC (Morell et al., 2011a). Water storage capacity of the soil at the beginning of the experiment was 215 mm within the top 1 m soil depth (Cantero-Martínez et al., 2003).

On average, rainfall has a bimodal distribution, with the major part occurring in autumn and late spring and little precipitation in winter and summer. However the pattern is highly variable and there is a high probability (25%) of low rainfall in the spring (<50 mm). Barley is the main crop in the region, and it is widely adopted as a monoculture crop, with the growing season between November and June. Barley monoculture is the most extended cropping system in most of the areas within the region, where rotations with leguminous or other crops have demonstrated not feasible because the lack of economical benefits (Álvaro-Fuentes et al., 2009).

The CT treatment consisted of intensive tillage with a mouldboard plough to a depth of 25–30 cm with almost 100% of the residue incorporated in the soil. The mouldboard plough consisted of three bottoms of 0.50 m width. The MT treatment consisted of a cultivator pass to a depth of 10–15 cm with an incorporation of approximately 50% of the crop residue. The cultivator plough consisted of 5 rigid shanks spaced 20 cm apart and with a shank width of 5 cm. In the NT treatment, no soil disturbances occurred, and sowing was done by direct drilling after spraying with herbicide. Tillage operations were annually conducted between the end of October and the beginning of November. Barley cv. Hispanic was annually sown at a rate of 450 seeds m^{-2}, in rows spaced 17 cm apart with a no-till disc drill.

N fertilizer was split into two applications, with one-third being broadcast before tillage as ammonium sulphate (21% N) and two-thirds at the beginning of tillering as ammonium nitrate (33.5% N). Split application between sowing and tillering, with a major portion at tillering, have shown to improve the recovery of the applied N under semiarid Mediterranean conditions (Ramos et al., 1995).

Harvesting was done by the end of June with a standard medium-sized combine. The straw was chopped and spread over the plots by the combine machine. The field was kept free of vegetation for three to four months each summer. Additional details of the experimental site and cropping practices are given in Angás et al. (2006) and Cantero-Martínez et al. (2003).

2.2. Measurements

This study was conducted over a 4-year period, during the cropping seasons 2005–2006, 2006–2007, 2007–2008 and 2008–2009, hereafter referred to as 2006, 2007, 2008 and 2009, respectively, and after 10 years of the initiation of the experiment. During the four cropping seasons under study, we evaluated the long-term effects of tillage and N fertilizer on above-ground growth and yield of barley and on water productivity. Additionally we determined the soil water content (SWC) at significant growth stages and residual soil nitrate content at sowing (SN).

2.2.1. Weather conditions and SWC

An automated weather station at the experimental site registered daily maximum and minimum temperatures, precipitation and air humidity.

In every cropping season, soil samples were collected at sowing, tillering, beginning of stem extension, anthesis and harvest for determinations of SWC. The soil samples were taken using a 4 cm diameter soil auger. At each sampling, two samples per plot were taken at 25 cm increments to a depth of 100 cm. To reduce the effects of spatial variability on successive samplings, soil samplings were conducted on two regions of 10 m^2, 15 m away from each end of the plot.

Gravimetric water content (GWC) was determined for every depth interval by drying a soil sub-sample in a forced-air oven at 105 °C for 48 h (Campbell and Mulla, 1990) in a % basis. SWC up to