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4 **TILLAGE EFFECTS ON BARLEY RESIDUE COVER**
5 **DURING FALLOW IN SEMIARID ARAGON**
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Abstract

Maintenance of crop residues on the soil surface is considered the most effective method to control wind erosion. In semiarid Aragon (NE Spain), where the risk of wind erosion can be high, the adoption of conservation tillage systems has been encouraged as a fallow management alternative. However, little information concerning the dynamics of residue cover during fallow is available for this area. We report here results on the evolution of barley residues during two fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The three tillage treatments were compared under both continuous cropping (CC) and cereal-fallow rotation (CF). The CC system involves a summer fallow period of 5-6 months and the CF rotation a long-fallow of 17-18 months. Effects of specific tillage operations on soil cover are also presented and discussed in relation to wind erosion control during the long-fallow period. Average dry mass of barley residues at harvest was 1395 kg ha⁻¹ and 729 kg ha⁻¹ in the first and second year of the study. In general, crop residues at harvest were not significantly affected by tillage or cropping system. Primary tillage operations had the major influence on residue incorporation with reduction percentages of residue cover of 90-100% in CT (mouldboard ploughing) and 50-70% in RT (chiseling). During the two long-fallow periods, large clods (4-10 cm diameter) produced by mouldboard ploughing did not fully compensate for the complete burial of residues and the soil surface was insufficiently protected against wind erosion (soil covers <3% and random roughness ≈4%). The most critical period corresponded to that elapsed between primary and secondary tillage operations. The lack of residue-disturbing operations in NT makes this practice the best strategy for fallow management. After 17-18 months of fallow, the NT plots still conserved a surface residue cover of 10-15%. Similarly, standing residues, representing between 20% and 50% of the total residue mass, were also present on the no-tilled surface during the first 11-12 months of fallow. In general, RT plots maintained a soil erodibility condition similar to that of NT due to the combined effect of soil cover by clods and residues retained after tillage (5-15%) and the roughness created by clods (6-13%).

1 *Keywords:* Residue cover; Conservation tillage; Fallowing; Soil erodibility by wind; Standing
2 residues; Dryland farming.

1. Introduction

Maintenance of crop residues on the soil surface is widely recognised for its positive effects on soil and water conservation. Benefits of residue cover include improved soil water storage, enhanced soil organic matter content, nutrient recycling and protection against water and wind erosion (Unger, 1994; Smil, 1999; Kumar and Goh, 2000). Unfortunately, in many semiarid regions such conservation benefits are difficult to achieve due to low crop residue production and, in general, inadequate agricultural practices.

In semiarid Aragon (NE Spain), crop yield and residue production is limited by low and extremely variable precipitation. In contrast to many other semiarid regions, the rainfall regime is characterized by the absence of any well defined rainy season and in any month there is a high probability of having either an extremely low amount (<10 mm) or no rain at all (López et al., 1998). In addition, strong and dry winds (*Cierzo*), with a dominant WNW direction, are frequent all year round. The soils have a dominant loam to sandy loam texture and are mostly calcareous and alkaline with a low organic matter content. The most common cropping system is the traditional cereal-fallow rotation (one crop in 2 years), which involves a long-fallow period (about 16-18 months) in which the bare soils are pulverised by multiple tillage operations. This rotation extends across about 430,000 ha, in an area with an annual precipitation of less than 400 mm. These agroclimatic characteristics make semiarid, central Aragon an area prone to land degradation by wind erosion (López et al., 2001).

Although long-fallowing has been a traditional water conservation practice for dryland crop production in central Aragon and other semiarid areas of the Ebro River valley, its suitability has been questioned in relation to production costs, soil fertility, livestock use, soil erosion and, even soil water conservation (López and Arrúe, 1997; Austin et al., 1998; Lampurlanés et al., 2002). In spite of that, the area of fallow lands has increased by about 40% over the last decade as a consequence of several set-aside land directives of the Common Agricultural Policy of the European Union. However, among the compensatory agri-environmental measures recently issued

by the regional government (BOA, 2001), those oriented to improve the traditional fallow (“environmental fallow” regulations) could contribute to wind erosion prevention through a long-lasting soil cover with crop residues (stubble retention at least five months after harvest) and overgrazing control (grazing limited to appropriate stocking rates). In this context, crop residue management through conservation tillage systems should be encouraged as a promising alternative for fallow management to preserve soil fertility in semiarid Aragon. Previous experiments carried out at a plot scale under erosive *Cierzo* wind episodes, showed that reduced tillage decreased dust emission and saltation transport when compared with conventional tillage (López et al., 1998; Sterk et al., 1999). However, little information concerning production and dynamics of crop residues during fallow is available for semiarid Aragon.

In this paper we report results on the evolution of barley residue cover during two fallow periods in a dryland field under three tillage treatments for both continuous cropping and cereal-fallow rotation. Effects of specific tillage operations on soil cover provided by crop residues and clods are also presented and discussed in relation to wind erosion control.

2. Materials and methods

2.1. Site, tillage and crop management

The study was conducted at the dryland research farm of the Estación Experimental de Aula Dei (Consejo Superior de Investigaciones Científicas), located in the Zaragoza province (41°44’N, 0°46’W, 270 m alt.), where a long-term conservation tillage experiment was initiated in 1989. Site and soil characteristics, crop management practices and experimental design have been previously described in detail (López et al., 1996); therefore, only those aspects relevant to this paper are repeated here. The soil is a loam (fine-loamy, mixed, thermic Xerollic Calcicorthid) according to the USDA soil classification (Soil Survey Staff, 1975). The area is characterized by a semiarid climate with an average annual rainfall of 340 mm and an average annual air temperature of 14.7 °C.

The tillage treatments were: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The three treatments were compared under the traditional cereal-fallow rotation (CF) and under continuous cropping (CC) with barley (*Hordeum vulgare* L.). Dates of cultural practices were the same for all tillage treatments (Table 1) and, with the exception of the NT plots, which needed one or two more herbicide applications than the CT and RT plots, herbicide and fertilising treatments during each growing season were the same in all cases. The CT treatment in the CC system consisted of mouldboard ploughing of fallow plots to a depth of 30-40 cm in autumn, followed by secondary tillage to a depth of 10-15 cm with a sweep cultivator just prior to sowing in November-December. In the RT treatment, primary tillage was chisel ploughing to a depth of 25-30 cm (non-inverting action), followed, as in CT, by a pass with the sweep cultivator before sowing. Under the CF rotation, primary tillage by mouldboard (CT treatment) or chisel ploughing (RT treatment) was implemented in late winter or early spring during the fallow year. In CT and RT treatments a second tillage operation was carried out with a sweep cultivator in late spring. After this cultivation, the plots were not ploughed again until November-December when seedbed preparation with a point cultivator was carried out prior to sowing. Following mouldboard ploughing, and according to the traditional practice in the area to break down the large clods left by this tillage operation, a pass of a tractor mounted scrubber (metal beam) was implemented in the CT plots, under the CC and CF systems. In both cropping systems, weeds on NT plots were controlled with herbicides. A conventional planter was used in the CT and RT treatments. In NT, barley was sown directly into the crop residues from the previous harvest using a hoe drill.

Tillage treatments were arranged in an incomplete block design based on geostatistical concepts, with three replications for the RT and NT treatments and four for the CT treatment to ensure a balanced design. Details about this design and its efficiency are given elsewhere (López and Arrúe, 1995). Accordingly, three large blocks of plots with the three tillage treatments were available on the experimental field: one block for the CC system and the other two blocks for the CF rotation. In the CF blocks, the cropping and fallowing phases were alternated as to have an experimental long-

fallow period every year. The blocks were in turn arranged in a split block design with tillage as the main plot and cropping system as the subplot. The subplot size was 33.5 m x 10 m.

The present study was carried out over the fallow phases that followed the harvests of the 1998-1999 and 1999-2000 cereal growing seasons. Thus, during the experimental period, the CC and CF rotation involved two summer fallow periods (5-6 months) and two long-fallow periods (17-18 months), respectively (Table 1).

2.2. Sampling and measurements

2.2.1. Crop residues

The amount and type of surface barley residues were determined just after harvest and before and after any soil disturbance (i.e. tillage) throughout each fallow period in the CC and CF rotations (Table 1). Although no tillage operation was implemented in the NT plots, crop residues were also collected in this treatment at the same dates as those for the CT and RT treatments. Residues were collected within a $0.5 \times 1 \text{ m}^2$ metal frame at four locations per plot. Standing residues ($>10^\circ$ from ground) were collected and bagged separately from residues lying flat on the soil surface. Residue samples were dried at 68°C for 48 hours and then weighed.

The percentage of soil surface covered with flat residues was estimated using the line-transect method (Shelton et al., 1993). This involved stretching a 5-m measuring tape diagonally at about a 45-degree angle across the crop rows and counting the number of the 10-cm marks along the tape that intercepted a piece of crop residue. The percent residue cover for the sampling area was then obtained by multiplying this count by two. Four measurements were made in each plot.

Additionally, in the sampling dates close to those for soil surface characterization (Table 1), frontal area of standing residues (silhouette area) was estimated from the measurements of stem diameter and height, and number of stems per m^2 .

2.2.2. Soil surface properties

Soil surface conditions in the three tillage treatments under the CF rotation were characterised immediately after harvest, primary and secondary tillage operations (Table 1). Soil samples to determine the wind-erodible fraction, EF (aggregates <0.84 mm in diameter), were taken from the upper 2.5 cm using a metal frame (15 x 15 cm) with a cutting edge. The samples were carefully transported to the laboratory where they were air-dried and sieved using an electromagnetic sieve shaker (CISA, Barcelona). When soil surface crusting occurred, the loose aggregates lying on the crust were collected using an ordinary vacuum-cleaner. Gravimetric soil moisture content was also measured in the 0-2.5 cm depth. Soil surface roughness was measured by using the chain method (Saleh, 1993). Frontal and basal surface areas occupied by clods (aggregates >38 mm in diameter) and pebbles were estimated with a 10 × 10 cm grid within a 1 × 1 m frame. With the exception of surface roughness, which was determined at eight points in each plot, all the above properties were measured at four points per plot.

To compare the effects of tillage treatments, analysis of variance (ANOVA) for the incomplete block design was used (López and Arrúe, 1995). To evaluate the cropping system and the tillage × cropping system interaction, ANOVA according to the split block design with three replicates was performed. Duncan's multiple range test was used to compare treatment means.

3. Results

3.1. Crop residues

Dry mass of barley residues at harvest ranged from 1126 to 1855 kg ha⁻¹ in 1999 and from 341 to 879 kg ha⁻¹ in 2000 (Table 2). Averaged over cropping systems and tillage treatments, residue production was 50% lower and grain yield was 40% lower in 2000 than in 1999. Although seasonal rainfall was about 200 mm in the two growing seasons (30% less than the long-term average for the November-June period), its distribution varied considerably. Whereas the rainfall received during the vegetative development of the crop (February-April) was near average in the 1999-2000 season (about 90 mm), in the 1998-1999 season it was 40% higher (128 mm). In

1 general, crop residues were not significantly affected by tillage or cropping system. The only
2 exception occurred in 2000 under CC, when there was a lower amount of residues in RT than in
3 NT (Table 2). This was probably due to a faulty sowing in one of the RT plots, which resulted in a
4 slightly higher residue production under CF compared with that under CC ($LSD=183 \text{ kg ha}^{-1}$;
5 $P<0.10$).

6 As the fallow period progressed, differences in the amount of surface residues among tillage
7 treatments increased (Table 2). After mouldboard ploughing, the residue mass retained in the CT
8 plots was only 0-13% of the initial mass after harvest. Although the amount of residues remaining
9 in the RT treatment was also very low after chiselling under CF (4-26% of the initial mass),
10 differences with respect to NT became more noticeable after secondary tillage. The higher residue
11 mass observed in the NT plots was maintained after sowing (on average, 206 kg ha^{-1} in NT, 53 kg
12 ha^{-1} in RT and 6 kg ha^{-1} in CT). The mass of residues remaining after any cultural operation was,
13 as expected, lower under CF than under CC, as a consequence of overwinter weathering losses
14 and a much longer time for residue decomposition in the CF system.

15 The dynamics of soil cover by flat residues during fallow in the CC system (summer fallow)
16 and in the CF rotation (long-fallow) are shown in Figures 1 and 2. At harvest, residue cover varied
17 from 50 to 80% in 1999 and from 15 to 40% in 2000. As in the case of the residue mass, the
18 lowest percent cover value was in the RT treatment under CC in 2000 (Fig. 1). In this case, the
19 three tillage treatments were statistically different, being NT the treatment with the highest
20 percentage of soil covered with residues (40% vs. 30% in CT and 15% in RT). In contrast, at the
21 1999 harvest, NT under CF had significantly lower residue cover than the other treatments (50%
22 vs. 80%; Fig. 2) and was responsible for the tillage $\times$ cropping system interaction found at this
23 date ($LSD=12\%$; $P<0.05$). With this exception, significant tillage $\times$ cropping system interactions
24 or cropping system effects were not found.

25 Three and five months elapsed from harvest to primary tillage in the summer fallows of 1999
26 and 2000, respectively (Table 1). In 2000, the date of primary tillage had to be delayed to late

November due to the high rainfall received during October and the first days of November (≈ 160 mm). After these periods without soil disturbance by tillage, the remaining cover was 30-40% in 1999 and 10-25% in 2000 (Fig. 1). These values indicate that during that fallow phase about 40-50% of residue cover was lost by decomposition and wind action. Obviously, these losses were higher during the two long-fallow periods of the study (reductions of 60 to 80%) due to a longer time until primary tillage (10 months). Thus, at this date, surface cover was 20-30% in the 1999-2000 long-fallow period and only 7-9% in the 2000-2001 long-fallow period (Fig. 2). In both summer fallow and long-fallow, primary tillage reduced pre-tillage cover by almost 100% in CT (mouldboard ploughing) and 50-70% in RT (chiselling) (Table 3). With the exception of the 2000-2001 long-fallow, where residue cover after primary tillage was very low in all treatments (0-9%) (Fig. 2), NT had cover values of 20-40% versus 4-13% and 0-2% in RT and CT, respectively (Figs. 1 and 2). After secondary tillage, the residue cover remaining in the RT plots was only 3-10% (reductions of 30-50%; Table 3). This cover disappeared after sowing in long-fallow but kept a value of 2-7% in summer fallow. Although the percentage of residue cover buried by no-till drilling was higher than that buried by conventional planting (Table 3), the NT plots after sowing still had a residue cover of 15-20% under CC but only 4-6% under CF.

Standing barley residues at harvest represented 30-50% of the total residue mass (data not shown). In all cases, 100% of these residues were flattened and buried by mouldboard ploughing in the CT treatment and between 70 and 95% by chiselling in RT (Fig. 3). Standing residues disappeared in RT during the secondary tillage operation. Although in the NT plots under CC the percentage of standing residues at sowing was 30-40% of the total mass (only 3-7% under CF), this percentage was markedly lower after sowing (3-10%). Thus, at the end of the fallow period, the amount of standing residues in NT was very low under CC (10 to 30 kg ha⁻¹) and negligible under CF (<1 kg ha⁻¹; Fig. 3).

3.1. Soil surface conditions

Table 4 shows the soil surface condition after harvest, primary and secondary tillage operations for the two long-fallow periods of the study. During the 10-month period from harvest to primary tillage, crop residues were the only roughness element present on the soil surface in the three tillage treatments (the presence of pebbles was negligible). Large clods (4-10 cm diameter) were then created by mouldboard ploughing and chiselling and 1-2 months later by the pass of a cultivator. Whereas in the 2000-2001 fallow the soil cover provided by clods was enough to compensate for the loss of flat residues due to tillage (in CT and RT vs. NT), in the 1999-2000 fallow the soil cover by clods was much lower (Fig. 4). In any case, surface cover by clods was never higher than 10%. In contrast, the frontal surface of clods in both CT and RT was, in general, similar to and even higher than that provided by the standing residues in NT (Fig. 4). Thus, in the 2000-2001 fallow, the clods created by tillage provided a frontal area 2-6 times higher than the standing residues remaining in NT plots. Soil surface roughness provided by clods and residues reflected the differences observed in the frontal area values among sampling dates and tillage treatments (Table 4).

In all cases, the wind-erodible fraction (EF) was significantly lower under NT than under CT and RT (Table 4). Since soil water content was similar in the three tillage treatments or even lower in NT (Table 4), the differences in EF among treatments can not be attributed to differences in soil moisture. The range of EF values found over the experimental period was 34-46% in CT, 31-41% in RT and 14-34% in NT. During the 1999-2000 fallow period, a surface crust about 5 mm thick was formed after the intermittent rainfalls received during April 2000. This crust was disrupted by primary tillage in the CT and RT plots. In NT, only 3.93 and 3.12 g m⁻² of loose, erodible aggregates lying on the crust were collected on the date of primary and secondary tillage operations, respectively.

4. Discussion

1 In the semiarid areas of Aragon, the amount and distribution of rainfall is highly variable
2 from year to year and during the growing season. Thus, the variability in the rainfall pattern
3 observed during the experimental period explains the differences in grain and residue yields of
4 barley found between the two years of the present study. While in 1999 the production of barley
5 residue reached and even exceeded 1000 kg ha⁻¹ (nearly 2000 kg ha⁻¹ in CT under CF), in 2000 it
6 was always below this value. In general, the information available on crop residue production in
7 rainfed cereal growing areas of Aragon is very limited. According to a recent report of the
8 Department of Agriculture of the Aragon Government (Vega, 2000), winter barley residue yields
9 in two semiarid areas of the Zaragoza province, with an average annual precipitation of 430 mm,
10 ranged from 2949 to 7693 kg ha⁻¹, depending on the year, locality and cultivar. On average, 71%
11 of the total residue mass is removed from the field mostly for animal feed, so that the amount of
12 residues finally left on the soil surface varies from 974 to 2440 kg ha⁻¹ (Vega, 2000). In another
13 semiarid area of the Teruel province (Southern Aragon), with an average annual precipitation of
14 406 mm, the residue production of a continuous barley crop measured at a collaborating
15 commercial farm in 1999 and 2000 was 2303 and 1918 kg ha⁻¹, respectively. From all the above
16 figures, it can be estimated that the amount of residues that, finally, are retained on the soil surface
17 in semiarid Aragon is about 1000-2000 kg ha⁻¹. However, residue production below 1000 kg ha⁻¹,
18 as occurred in one of the two years of the present study, is not exceptional in semiarid regions
19 where water supply is limited (Unger, 1994).

20 Concerning the role of crop residues in soil conservation, there is not a unique value for the
21 amount of residues required to prevent soil erosion, since it depends, among other factors, on the
22 type of crop, soil and management practices. However, it is widely accepted, as a general
23 guideline, that at least 1100 kg ha⁻¹ of small-grain residues are needed to protect soil from wind
24 erosion (CTIC, 1996). In our tillage study, this minimum quantity was only achieved in the
25 harvest of 1999, though in some cases this value was only slightly exceeded (i.e. 1126 kg ha⁻¹ in
26 NT under CF). In these low crop residue situations, maintenance of sufficient residue cover during

fallow becomes critical, particularly when a long-fallow period is involved (Lindwall et al., 1994; Schillinger et al., 1999).

In order to evaluate the influence of the soil surface conditions on wind erosion during the long-fallow period, the equation established by Horning et al. (1998) was applied. This relationship estimates the combined effect of residue cover and random roughness on soil losses by wind erosion. Figure 5 shows the results obtained from the data reported in Table 4. Soil loss ratio (SLR) refers to the soil loss from a protected soil divided by the maximum soil loss (bare, smooth surface). In spite of the relatively low amounts of crop residues after harvest, they would have been sufficient to reduce the potential soil loss in the three tillage treatments ($SLR < 0.01$). In addition to the flat residues, which provide soil cover higher than 30%, a similar amount of standing residues were present on the soil surface after harvest, creating a random roughness of about 20%. As is widely recognised, standing residues are more effective than flat residues in controlling wind erosion by reducing the wind speed near the soil surface and intercepting the saltating soil particles (Hagen, 1996; Nielsen and Aiken, 1998). During the subsequent 10 months without tillage, the amount of crop residues decreased considerably. However, the remaining residues would still be enough to reduce soil losses by at least 80%, as can be inferred from the SLR value in NT (Fig. 5). In contrast, once the primary tillage was done, the clods produced by mouldboard ploughing in CT did not compensate for the complete burial of residues, which could have led to a situation in which there was real risk of wind erosion ($SLR = 0.5-0.6$). This risk was reduced after the secondary tillage with a cultivator due to the increased amount of clods on the soil surface. In the RT treatment, the combined effect of the residue cover retained after chiselling and the roughness created by clods in the 1999-2000 fallow period, resulted in a soil erodibility condition comparable to that predicted for NT ($SLR = 0.25$). In the 2000-2001 fallow, soil erodibility was somewhat higher due to a very low residue cover ($SLR = 0.3$). In both long-fallow periods, clods produced by secondary tillage compensated for the lack of an adequate residue cover in the RT plots (Fig. 5). At that time, appreciable resistance of the soil surface against wind

erosion was achieved, even under CT ($SLR \approx 0.2-0.3$). However, it could be expected that the initial soil protection provided by cloddiness did not extend over the following 6-7 months until the end of the fallow period. Clods may be very short-lived compared with crop residues since the clods are broken down by rainfall, drying, and wind action or additional management practices. In this regard, the high content of $CaCO_3$ in the soils of the study area ($>300 \text{ g kg}^{-1}$ in many cases) is probably an important factor of erodibility, since the $CaCO_3$ present in medium-textured soils reduces the mechanical stability of clods and produces a more disaggregated surface (Gillette, 1988; Breuninger et al., 1989). All the above results indicate that in semiarid Aragon the most critical period of fallow in terms of wind erosion risk occurs under CT after primary tillage has been done. It should be noted that, during this study, primary tillage had to be delayed until April because soil moisture conditions were not suitable for tillage (very dry in the first fallow and excessively wet in the second fallow). However, weather permitting, farmers in the area usually plough their lands in February or March. This means that the risk of soil erosion would increase since the period of unprotected soil surface extends over the most erosive months of the fallow period (López et al., 2001).

Tillage has a considerable effect on the placement and distribution of crop residues. Consequently, the evaluation of individual tillage operations must be considered in planning effective fallow management systems for soil erosion control. In this sense, the values of residue cover reduction by tillage found in our study (Table 3) are, in general, in agreement with those published originally by the USDA Soil Conservation Service and the Equipment Manufacturers Institute (SCS-EMI, 1992) and later adapted by Shelton et al. (1995). Thus, a single pass of a mouldboard plough had the greatest influence on residue incorporation with reduction percentages of 90-100%, a range similar to that provided by SCS-EMI (1992). With chiselling, the burial percentage varied from 50 to 70%, also within the range of 40-70% given by Shelton et al. (1995) for chisel ploughs with similar characteristics (straight spike points). The reduction percentages for the cultivators used for secondary tillage (30-50%) and seedbed preparation (70%) were

1 slightly higher than those estimated by the SCS-EMI for similar implements (25-40% and 50-65%
2 for a field cultivator with sweeps and duckfoot points, respectively). Likewise, the conventional
3 planter used in our study buried a slightly greater proportion of residues (30%) than that estimated
4 by the SCS-EMI (10-20%). For the hoe opener drill, the residue cover losses were equal to those
5 previously published (40-60%). When comparing our measurements with the published values, we
6 have taken into account that tillage operations were performed over a month later and, therefore, a
7 higher reduction in the residue cover should be expected, with percentages closer to the upper
8 values of the SCS-EMI ranges. Similarly, the low pre-tillage residue cover and the fragile nature
9 of our barley residues have also been taken into account as comparison criteria.

10 With regard to the cropping system, no large differences in barley residue production were
11 found between the CC and CF rotation. Obviously, the risk of wind erosion is higher in the CF
12 rotation since the soil surface during the fallow period is exposed to the wind action during a
13 much longer period of time. In this sense, the traditional management of fallowing in semiarid
14 Aragon seems to be ineffective for protecting the soil surface against wind erosion. Instead, the
15 adoption of conservation tillage practices must be encouraged, thus complying with the
16 environmental requirements demanded by the current Common Agricultural Policy of the
17 European Union. The lack of residue-disturbing operations makes NT the best strategy for fallow
18 management. However, NT does not always result in favourable soil conditions, as it has been
19 shown in previous studies performed in different dryland cereal-growing areas of Aragon (López
20 et al., 1996; López and Arrúe, 1997). The high soil strength under NT in many arid soils appears
21 to be a major limitation to its regular use in crop production. In such zones, where residue
22 production is low, RT through a combination of clods by tillage and residues could be
23 recommended as an alternative to CT for fallow management. In fact, the effectiveness of RT for
24 wind erosion control during fallow has been demonstrated in previous studies (López et al., 1998;
25 Sterk et al., 1999). Additional recommendations, based on a more effective use and management
26 of crop residues, can help to reduce the risk of wind erosion. Leaving as much residue standing

1 and as tall as possible would be highly beneficial because, in addition to a higher reduction of
2 wind erosivity, standing residues persist longer than a comparable amount of flat residues (Steiner
3 et al., 1999). Since primary tillage is the field operation that results in the highest residue
4 incorporation into the soil, it would be also advisable to delay its application, in the study area, at
5 least until early spring. In this way, the period of residue effectiveness is extended to the most
6 erosive months of fallowing (February-April). Finally, a higher percentage of residues remaining
7 on the soil surface would be achieved by decreasing the depth and speed of tillage operations
8 (CTIC, 1996; Hill and Stott, 2000).

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Figure legends

Figure 1. Barley residue cover in the continuous cropping system during the first (June 1999-November 1999) and second (June 2000-December 2000) fallow periods as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). Bars indicate LSD ($P<0.05$) for comparisons among tillage treatments at the same date, where significant differences were found.

Figure 2. Barley residue cover in the cereal-fallow rotation during the first (June 1999-December 2000) and second (June 2000-November 2001) fallow periods as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). Bars indicate LSD ($P<0.05$) for comparisons among tillage treatments at the same date, where significant differences were found.

Figure 3. Evolution of standing barley residue mass during the 1999-2000 long-fallow period under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). For the same date, different letters indicate significant differences at $P<0.05$.

Figure 4. Soil cover and frontal area provided by crop residues and clods as affected by field operations during two long-fallow periods of the barley-fallow rotation under different tillage treatments (CT, conventional tillage; RT; reduced tillage; NT, no-tillage). For the same field operation, different letters indicate significant differences at $P<0.05$.

Figure 5. Soil loss ratio as affected by field operations during two long-fallow periods of the barley-fallow rotation under different tillage treatments (CT, conventional tillage; RT; reduced tillage; NT, no-tillage). For the same field operation and fallow period, different letters indicate significant differences at $P<0.05$.

Table 1. Schedule of agronomic practices and crop residue and soil sampling during fallow in the continuous cropping system (CC) and the cereal-fallow rotation (CF).

Cropping system	Fallow period (Harvest-Sowing)	Primary tillage	Secondary tillage	Seedbed preparation	Sowing	Crop residue sampling	Soil sampling
			days after harvest			days after harvest	
CC	21 Jun 1999-4 Nov 1999	94	135	-	136	3, 92, 94, 129, 135, 141	-
	20 Jun 2000-13 Dec 2000	155	175		176	7, 153, 167, 175, 176	-
CF	21 Jun 1999-13 Dec 2000	309	343	540	541	3, 129, 161, 283, 316, 340, 344, 532, 540, 541	4, 309, 343
	20 Jun 2000-23 Nov 2001	294	351	519	521	7, 248, 293, 295, 350, 352, 518, 519, 521	6, 294, 351

Table 2. Dry mass of barley residues remaining after specific cultural practices applied during fallow under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation).

Year	Cropping system	Tillage treatment	Grain yield (kg ha ⁻¹)	Residue mass (kg ha ⁻¹) retained after				
				Harvest	Primary tillage	Secondary tillage	Seedbed preparation	Sowing
1999	CC	CT	1489	1276	162	16	-	24
		RT	1153	1424	974	193	-	154
		NT	1052	1302	1424	992	-	427
		LSD (0.05) ^a	NS	NS	531	282	-	105
	CF	CT	2754	1855	0	0	0	0
		RT	1806	1388	355	208	26	22
		NT	1396	1126	581	498	219	118
		LSD (0.05)	981	NS	177	69	47	42
2000	CC	CT	877	618	22	0	-	0
		RT	467	341	125	40	-	36
		NT	634	850	648	648	-	229
		LSD (0.05)	207	327	204	194	-	42
	CF	CT	1491	850	4	0	0	0
		RT	1727	879	36	26	4	0
		NT	923	837	269	178	85	49
		LSD (0.05)	672	NS	85	64	34	18

^aLeast significant difference, $P < 0.05$. NS, not significant.

Table 3. Influence of field operations during fallow on barley residue cover reduction under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation)

Cropping system	Tillage treatment	Percentage of cover reduction after			
		Primary tillage	Secondary tillage	Seedbed preparation	Sowing
CC	CT	89-94	100 ^a	-	-
	RT	63-67	27-32	-	26-33
	NT	-	-	-	37-44
CF	CT	96-100	100 ^a	-	-
	RT	52-72	38-50	67-73	90-100 ^a
	NT	-	-	-	56-60

^a Initial residue cover is null or negligible (<2%).

Table 4. Soil surface conditions after harvest and tillage operations during long-fallow as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage).

Fallow cycle	Date	Tillage treatment	Soil cover ^a (%)	Frontal area ^b (cm ² m ⁻²)	Random roughness (%)	Wind-erodible fraction (%) ^c	Water content (g kg ⁻¹)
1999-2000	25 Jun 1999 Harvest	CT	78.3	1131	21.7	46	20
		RT	76.7	992	23.4	41	22
		NT	48.7	1047	25.0	34	17
		LSD (0.05) ^d	10.9	NS	NS	12	NS
	25 Apr 2000 1st tillage	CT	3.1	201	3.6	38	124
		RT	14.5	149	5.7	31	96
		NT	24.2	307	5.0	— ^e	—
		LSD (0.05)	7.3	151	NS	NS	28
	29 May 2000 2nd tillage	CT	6.4	407	9.3	34	74
		RT	10.2	304	11.1	32	68
		NT	19.5	295	5.7	— ^e	—
		LSD (0.05)	4.0	NS	3.3	NS	NS
2000-2001	26 Jun 2000 Harvest	CT	39.5	966	17.8	46	20
		RT	36.3	883	19.4	39	19
		NT	33.7	1061	19.7	29	23
		LSD (0.05)	NS	NS	NS	8	NS
	10 Apr 2001 1st tillage	CT	3.1	196	4.7	42	99
		RT	5.4	276	7.5	39	49
		NT	8.5	134	9.0	15	26
		LSD (0.05)	NS	NS	NS	9	10
	6 Jun 2001 2nd tillage	CT	9.8	590	9.7	43	24
		RT	10.8	582	12.5	34	29
		NT	14.1	102	5.6	14	19
		LSD (0.05)	NS	359	3.0	14	NS

^a Flat residues + clods (aggregates >38 mm in diameter).

^b Standing residues + clods (aggregates >38 mm in diameter).

^c Aggregates <0.84 mm in diameter (0-2.5 cm depth).

^d Least significant difference, $P < 0.05$. NS, not significant.

^e Soil surface crusting. See text for details.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5