AN EVALUATION OF WIND EROSION HAZARD IN FALLOW LANDS OF SEMIARID ARAGON (NE SPAIN)

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Abstract

Long fallowing (16-17 months), in the cereal-fallow rotation, may favour soil losses by wind erosion in agricultural soils of semiarid Aragon (NE Spain). With the objective of evaluating the risk of wind erosion in this area, soil losses for the most critical period of fallow (February-April) were estimated from a total of 67 fallow fields by using the Wind Erosion Equation (WEQ). All soils were medium-textured soils being the loam the most frequent textural class (45%). The $CaCO_3$ content in the soil was higher than 200 g kg^{-1} in 90% of the fields. Mouldboard plough, chisel plough, and disk harrow were the main primary tillage tools used by farmers during fallow. Soil cover by crop residues was negligible (<1%) in 76% of the fields and only in 20% tilling was done perpendicularly to dominant wind direction. The highest erodibility values corresponded to soils with a sandy loam texture and traditionally tilled with mouldboard plough. Predicted wind erosion was high to very high in 30% of the fields (>20 Mg ha^{-1}). The WEQ estimated erosion reductions to tolerable levels if reduced tillage, with chiseling as primary tillage, is adequately adopted in the dryland cereal production areas of semiarid Aragon.

Key words: Wind erosion, fallowing, dryland farming, reduced tillage, crop residues, surface roughness, wind-erodible fraction.

Introduction

From a spatial point of view, it is generally thought that soil erosion by wind, as compared to water erosion, is not a major land degradation issue in the European Mediterranean environments (Poesen and Hooke, 1999). Accordingly, research and knowledge currently available on wind erosion processes in these environments are rather limited.

One of the potential wind erosion areas identified in southern Europe is located in Central Aragon, in the middle part of the Ebro river valley, north-east Spain (De Ploey et al., 1989). Many factors and conditions influencing wind erosion affect agricultural land across this region. The climate is semiarid, with a rainfall regime characterized by low and erratic precipitation imposing significant constraints on agricultural production (Austin et al., 1998). In semiarid Aragon, one of the driest areas in the Iberian peninsula and probably the most arid inland region in Europe, high evaporative demands are accentuated by dry and strong winds blowing throughout most of the year (Herrero and Snyder, 1997). These winds, locally known as Cierzo, have a dominant WNW direction and are frequent events with wind speeds and gusts higher than 10 m s^{-1} (Biel and García de Pedraza, 1962). The soil moisture regime is markedly aridic and soils are mostly alkaline, with low organic matter contents and a dominant loam to loamy sand texture.

In addition to these unique climatic and lithological features, current land use and management practices in semiarid Aragon contribute to making this area prone to land degradation by wind erosion. According to most recent statistics (Gobierno de Aragón, 2000), agricultural land accounts for 38% of the total surface (47,700 km^2) of Aragon. Within rainfed arable land (1.38 million ha), about 760,000 ha are cultivated with herbaceous crops (80% grown to wheat, *Triticum aestivum* L., and barley, *Hordeum vulgare* L.) and 460,000 ha more are fallowed every year. It is estimated that more than half of rainfed cropland is located in areas with an average annual precipitation less than 400 mm where the risk of wind erosion might be more accentuated. In these areas, the most common cropping system is the traditional cereal-fallow rotation (one crop in 2 years), which extends over about 430,000 ha and involves a long-fallow period of about 16-17 months. Ploughing of fallow fields in late winter and early spring dries out the surface soil and leaves bare fields prone to wind erosion especially at the end of the fallow period, from late spring to seeding of the next crop. In addition, overgrazing may also enhance the risk of wind erosion in fallow lands, especially in dry years when low crop yields result in insufficient residue cover.

Previous studies carried out at a plot scale in semiarid Aragon have shown that the risk of severe wind erosion could be high in agricultural soils. These studies also indicate that wind erosion processes (i.e. dust emission and saltation transport) are largely dependant on the type and timing of tillage operations and the frequency of strong *Cierzo* events (López et., 1998; Sterk et al., 1999). In this region wind erosion processes may occur slowly and their harmful effects on soil quality and productivity go unnoticed for many years, especially if they are masked by mixing by intensive soil tillage. Consequently, adoption of suitable land management and soil conservation practices, such as conservation tillage and crop residue management systems, in erodible dryland agroecosystems of semiarid Aragon are needed. However, before specific farmer-friendly measures to prevent wind erosion can be devised and transferred within dryland cropping systems, wind erosion research in the region should be conducted to assess at a large scale the magnitude of wind erosion hazards, identifying those areas where wind erosion could be most threatening to sustainable agricultural productivity.

The purpose of this study was twofold: (i) characterize fallow lands of semiarid Aragon with regard to current soil and crop residue management practices and their effects on soil surface properties affecting wind erosion and (ii) evaluate the risk of wind erosion during the most critical period of fallow using estimated values of soil losses from the Wind Erosion Equation (WEQ; Woodruff and Siddoway, 1965).

Materials and methods

Field characterization. A total of 67 fallow fields were randomly selected within the main dryland cereal production areas of semiarid Aragon with mean annual rainfall <400 mm (Fig. 1).

Field site selection was made according to the soil type, topography, and tillage practices characterizing each zone. The fields were located between latitudes 40º59'N and 41º50'N and longitudes 1º24'W and 0º15'E, covering an area of about 13,000 km^2. Within these dryland areas, fallow lands extend over about 200,000 ha. Elevation ranged from 250 to 760 m and most of the fields were nearly level. Only 10 fields had a knolly topography with slopes between 2 and 10%.

Following primary tillage operations applied in February-March, a general description of each field was made (field dimensions and orientation, tillage implement used, ridge characteristics). At the same time, soil samples from the upper 2.5 cm were collected to determine the following soil surface properties.

Particle size distribution was determined by the pipet method (Gee and Bauder, 1986) and organic matter content, $CaCO_3$ content, gypsum content, electrical conductivity, EC (H_2O, 1:5), and pH (H_2O, 1:2.5) by standard methods (Page et al., 1982). Percent soil cover with crop residues and stones and dry matter of residues (after oven-drying at 65-70 ºC for 48 h) were also determined.

Wind-erodible fraction (EF) was calculated as the percentage of dry aggregates <0.84 mm in diameter separated from the soil surface sample by using an electromagnetic sieve shaker (CISA, Barcelona). An electromagnet transmits vertical vibrations to the sieves along with a simultaneous rotating movement to the soil material, which prevents the classical clogging of sieves. Although we did not use the standard rotary sieve as required by the WEQ, we followed the general recommendations of Skidmore (1988) to achieve an adequate separation of dry soil aggregates when using a more readily available flat sieve. Thus, in order to determine the optimum combination of sieving time and sieving intensity (vertical vibration height), a series of experiments testing different sieving times and intensities were carried out using soils with contrasting EF values. After observing a good separation of soil aggregates, without clogging and breakdown, a sieving time of 6 minutes and a sieving intensity of 1 mm were finally fixed. The EF values obtained by this sieving procedure were compared to those estimated from soil physical and chemical properties, using the equation of Fryrear et al. (1994). The correlation found was highly significant (r=0.939; $P<0.01$). This finding and the fact that the equation of Fryrear et al. (1994) is used in the Revised Wind Erosion Equation (RWEQ; Fryrear et al., 2000) as an alternative to the standard rotary sieve, indicate that the EF values obtained in the present study are comparable with those that could have been obtained using the standard rotary sieve.

For a more complete characterization of soil surface conditions, in 16 representative fields all the above determinations were made at 6 points along a WNW-ESE transect, whereas in the rest of the fields only one sampling point was considered. Soil types were identified according to the FAO classification (FAO-UNESCO, 1990).

Application of the Wind Erosion Equation. The WEQ (Woodruff and Siddoway, 1965) is described in the following form

$$E = f(I, K, C, L, V)$$

where E is the annual soil loss (Mg ha^{-1}), I the soil erodibility factor (Mg ha^{-1} yr^{-1}), K the soil ridge roughness factor, C the climatic factor, L the unsheltered mean travel distance of wind across a field (m) and V the equivalent vegetative cover (Mg ha^{-1}).

The soil erodibility factor, I, is the potential annual soil loss from a wide, unsheltered, isolated field with a bare, smooth, noncrusted surface. It was obtained from the table for soil erodibility generated by Woodruff and Siddoway (1965) on the basis of the percentage of dry aggregates >0.84 mm in diameter. For fields with a knolly topography (windward slopes >1.5% and lengths <150 m) the I value was adjusted following Woodruff and Siddoway (1965).

The soil ridge roughness factor, K, takes into account the resistance to wind erosion caused by ridges. It is a function of the relation between ridge height and ridge spacing and it was obtained from the equations defined by Williams et al. (1984). Ridge orientation was determined with respect to the dominant WNW direction of the *Cierzo* wind.

The climatic factor, *C*, was derived from the wind erosion climatic erosivity (*CE*) as it was proposed by Skidmore (1986). *CE* is based on the mechanics of wind erosion and accounts for the influence of surface soil moisture, wind speed and wind speed probability distribution. Weather variables required for its calculation are precipitation, net radiation, wind speed and wind speed probability density function. Mean monthly values of these parameters were obtained for a 20-year period (1965-1984) using daily records of precipitation, wind and solar radiation collected at the Zaragoza Airport weather station (41º39’N, 1º00’W, 247 m asl). The wind data set for this reference period was the most reliable and suitably available for the study area.

Daily values of average wind speed were calculated from wind run readings. Mean monthly net radiation was calculated from solar radiation through the relationship given by Rosenberg et al. (1983). Since it was not possible to obtain the wind speed probability density function (only mean values of wind speed were available), *CE* was calculated from the simplified procedure developed by Skidmore (1986). Although *CE* was obtained for each month, only *CE* values corresponding to the period of interest (February-April) were used to calculate *C*.

The field length factor, *WF*, accounts for the influence of field dimensions on reducing wind erosion. On an unprotected eroding field the rate of soil flow is zero on the windward edge and increases with distance until reaching a maximum value. This maximum distance (*Lo*) and the mean travel distance of wind across the field (*L*) were incorporated into the equation developed by Williams et al. (1984) to determine *WF*. *L* was calculated by considering the width and length of the field and its orientation with respect to the prevailing wind direction (Williams et al., 1984).

The vegetative cover factor, *V*, expressed as small grain equivalent, takes into account the effect of amount, kind and orientation of vegetative cover on controlling wind erosion. The mass of crop residues was introduced into the equations developed by Williams et al. (1984) using crop specific coefficients for flat random winter wheat residues (Lyles and Allison, 1981).

Solution of WEQ gives the expected annual amount of wind erosion, *E*, from a particular agricultural field. The combination of factors to determine *E* was done stepwise as follows (Williams et al., 1984; Skidmore, 1988):

$$E1 = I \quad [1]$$

$$E2 = I\,K \quad [2]$$

$$E3 = I\,K\,C \quad [3]$$

$$E4 = (WF^{\,0.348} + E3^{\,0.348} - E2^{\,0.348})^{2.87} \quad [4]$$

$$E5 = \Psi 1\; E4^{\,\Psi 2} = E \quad [5]$$

The parameters Ψ1 and Ψ2 are functions of the factor *V* as described by Williams et al. (1984).

Statistical analysis. Correlation and regression analysis were performed to identify and evaluate the degree of association among the measured soil properties. Special attention was paid to the relationship between EF and the rest of physical and chemical properties as predictive variables. Analysis of variance (ANOVA) was applied to detect variations in the studied properties under different soil management practices and soil types. Duncan's multiple range test was used to compare among means. When data showed non-normality, transformations were made and ANOVA conducted with the transformed data. Computations were performed using Statgraphics Plus software.

Results and discussion

Susceptibility of soil to wind erosion. Soil erodibility (*I*) ranged from 0 to 244 Mg ha^{-1} yr^{-1}, corresponding to wind-erodible fractions (EF) of 8 and 83%, respectively. Following the erodibility classification of Shiyatyi (1965) (cited by Zachar, 1982), 21% of the studied soils were highly erodible with *I* values >100 Mg ha^{-1} yr^{-1} and EF >50%, 13% moderately erodible (*I* between 50 and 100 Mg ha^{-1} yr^{-1} and EF between 40 and 50%) and 66% slightly erodible (*I* <50

Mg ha^{-1} yr^{-1} and EF <40%). From this latter group, almost half of the soils, with *I* values <10 Mg ha^{-1} yr^{-1}, were totally resistant to wind erosion.

Basic soil properties, such as texture and organic matter content, and soil management have been frequently described as the main factors affecting soil aggregation in agricultural soils (Gillette, 1988; Black and Chanasyk, 1989; Zobeck and Popham, 1990; Fryrear et al., 1994). In our study, significant relationships were found between EF and some of the soil surface properties measured (Table 1). There was correlation of EF with texture (positive with sand content and negative with silt and clay contents), being EF adequately predicted from the sand/(silt+clay) ratio (Fig. 2). This significant relationship (r^2=0.426; P<0.001) was considered satisfactory due to the relatively narrow margin of textures found in the study area. All soils were medium-textured soils, varying from sandy loam to silty clay loam. Sand content ranged from 30 to 640 g kg^{-1}, silt from 210 to 800 g kg^{-1} and clay from 30 to 370 g kg^{-1}. As it can be seen in Fig. 2, the highest values of EF corresponded to sandy loam soils followed by loam soils, the most frequent textural class observed (45%). Whereas loam soils were present all over the study area, sandy loam soils were restricted to zone C (Fig. 1). The lower soil erodibility of the rest of soils is explained by the bonding effect of silt and clay fractions, providing a higher dry aggregate stability (Skidmore and Layton, 1992; Quiroga et al., 1998). However, the data scatter observed in Fig. 2, especially for the loam soils, indicates that other factors besides soil texture are affecting EF in the study area.

A significant but weak positive correlation was observed between EF and soil organic matter content (Table 1). However, this relationship was due to two outlying values of organic matter (33 and 36 g kg^{-1}) because their exclusion made this relation non significant (r=0.168; P=0.181). These two fields were in zone E, where soils are comparatively richer in organic matter, with mean contents of 35 g kg^{-1} (Machín and Navas, 1994). Despite the relatively high organic matter content of these soils, their EF values were also high (50-70%) which contrasts with the general association of good conditions in soil aggregation with high levels of soil organic matter (Fryrear et al., 1994). Different studies indicate, however, that organic matter can act as an aggregating or disaggregating agent or have no effect, depending of its amount, composition and the presence of other aggregating materials (Breuninger et al., 1989; Igwe et al., 1999). Furthermore, the effect of organic matter on soil aggregation depends on its decomposition process. Initially, an increase in soil aggregation occurs due to the numerous cementing substances produced by microorganisms attacking the vegetative matter. However, as the decomposition continues, the stability of aggregates decreases since the cementing products, in turn, are destroyed by other microorganisms. Therefore, a good soil aggregation condition depends on the frequent addition of vegetative matter to the soil, being a more persistent condition if this vegetative matter is retained on the surface (Chepil and Woodruff, 1963).

No significant correlation was found between EF and other soil chemical properties (Table 1). The $CaCO_3$ content varied between 16 and 772 g kg^{-1}, being higher than 200 g kg^{-1} in 90% of the soils. The gypsum content, ranging from 24 to 602 g kg^{-1}, was higher than 100 g kg^{-1} in only 13% of the soils. Although calcareous soils are dominant in Central Aragon (Montañés et al., 1991), gypsiferous soils area also present in 13% of the surface of the Zaragoza province, being the largest area of these soils in Spain (Machín and Navas, 1998). In our study, calcareous soils were unevenly distributed all over the study area, the most calcareous ones ($CaCO_3$ >600 g kg^{-1}) being located in some fields of zones K and L (Fig. 1). Gypsiferous soils were located in fields of zones D, F, G and K. The high content of $CaCO_3$ in our soils is probably an important factor of erodibility since, according to Breuninger et al. (1989), medium-textured soils have a more disaggregated surface layer when $CaCO_3$ is significant in their composition. In fact, this disaggregating effect of $CaCO_3$ has been observed for most of the soil textures except for sands and loamy sands (Chepil and Woodruff, 1963). In our study, no effect of $CaCO_3$ on EF was observed (Table 1). However, when only the data from soils classified as Calcisols were analyzed, a significant but relatively weak relationship was obtained (r=0.303; $P<0.05$), supporting the observations of Chepil and Woodruff (1963) and Breuninger et al. (1989). No correlation was found between gypsum content and EF.

Although high levels of gypsum or $CaCO_3$ in the soil surface allow to differentiate the four soil types identified for the sampled fields (Table 2), soil erodibility had no correspondence with soil type. Whereas soils are classified considering the different horizons of the soil profile, the measured properties characterize only the soil surface. In addition, the surface layer in the sampled soils has been continuously altered by annual tillage practices.

Three main tillage implements were identified in the study area as primary tillage tools used by farmers during the fallow period: mouldboard plough (MP), chisel plough (Ch) and disk harrow (DH). MP, the most traditional implement in the region, was used in 61 of the 67 fields and Ch and DH in 4 and 2 fields, respectively. In 7 cases, a roller (R) was attached at the rear of the main implement. DH replacing MP as primary tillage tool was observed in zone D (Fig. 1) whereas, as a complementary implement following MP (MP+DH), was noted in zone F. The use of Ch was restricted to zone I. Soil tillage had a significant effect on soil erodibility through EF (Fig. 3). Thus, Ch was distinguished from the rest of tillage practices by producing the lowest EF (P<0.001), between 15 and 36% less EF than that produced by Ch+R and MP+R, respectively. The lack of statistical significance among the other tillage operations was likely due to the large differences in the number of fields under each tillage practice (for example, 52 fields with MP and only 1 with DH). In addition, the influence of tillage on EF can be obscured by the effect of texture, as discussed above. A higher statistical precision in the comparisons can be obtained by both considering only EF data from the representative fields (with 6 values per field) and comparing soils with the same texture and similar chemical composition (organic matter, $CaCO_3$, and gypsum contents). Since not all tillage practices were done in soils with the same texture, a different ANOVA must be performed to compare among the maximum number of tillage practices. Only one field per textural class could be selected since Ch+R, DH+R and MP+DH were applied only in one of the representative fields. Results from Table 3 indicate that, whereas the EF produced by MP did not significantly increase by the following pass of DH (MP+DH), it did when R was attached to MP (MP+R). Likewise, Ch+R led to the most favourable soil aggregation with the lowest value of EF. A better soil aggregation status after Ch than after MP was also observed in previous wind erosion studies carried out in two different soils of semiarid Aragon (López et al., 1998; 2000). In contrast, this result does not agree with other observations in soils of Texas (Zobeck and Popham, 1990; Fryrear et al., 1994), reporting a reduction in soil erodibility with MP by bringing nonerodible aggregates to the soil surface. This disagreement may be due to the different nature of these soils. Thus, the Texas soils are much sandier than our soils and are not affected by high $CaCO_3$ contents. On the other hand, it is also probable that the soil moisture content at the time of tillage was lower in our fields. Tilling under low soil moisture content is not uncommon in the semiarid areas of Aragon, where the opportunity of tillage is limited because of the uncertain nature of rainfall distribution (López et al., 1996). Thus, whereas Ch operation may be done when soil is drier, MP requires a certain level of soil moisture to produce soil cloddiness. On the other hand, the increase in EF after R, regardless of the main tool to which it was attached, was in agreement with field observations of a high pulverization of soil aggregates during the pass of a crushing element.

In summary, soil texture and soil management were the main factors affecting soil erodibility, explaining together 50% of the total EF variability. Other factors not considered, such as soil water content at the time of tillage, could also have contributed to the remaining variability in EF. Among the I values >100 Mg ha^{-1} yr^{-1}, the highest (170-244 Mg ha^{-1} yr^{-1}) were found in zone C (Fig. 1) where soils had a sandy loam texture and tillage was done with MP or MP+R. Although soils in zone E were loam, the high I values (101-161 Mg ha^{-1} yr^{-1}) in all fields could be attributed to the relatively high sand content (average of 454 g kg^{-1}) and tilling with MP. The rest of the fields were dispersed among different zones (B, K and M) and their high erodibility could be explained by a high sand content, MP tillage and a high $CaCO_3$ content, as it was the case of fallow fields in zone K.

Ridge roughness. Tillage affects soil losses by wind erosion through both soil aggregation, as discussed earlier, and surface roughness. The effectiveness of ridges in reducing wind erosion depends on their height, spacing and orientation with respect to wind direction. In the study area, MP produced ridges with a mean height of 6.7 cm and a mean spacing of 43 cm; ridges produced by Ch were 11 cm height and 51 cm apart; and those created by DH were 1.8 cm height at 13 cm intervals. Derived mean values of factor *K* were 0.46, 0.57 and 0.78 for Ch, MP and DH, respectively. These figures indicate a higher reduction in *I* (Eq. [2]) after Ch (54%) than after MP (43%) or DH (22%). In all cases, the roughness created by ridges was destroyed by R when it followed the main tool (*K*=1). On the other hand, the protection provided by ridges is really effective when ridges are oriented perpendicularly to wind direction. In our study, only 14 out of a total of 60 fields with a ridged surface, had tillage operations perpendicular to the WNW direction of the *Cierzo* wind. In these fields, the range in the ridge direction was between 0º (north) and 45º (north-east). On the contrary, in 20 fields ridges were running parallel to the *Cierzo*, exactly in the range of 90º-135º. In these cases, a value of 1 was assigned to *K* and, thereby, *I* was not reduced by tillage roughness. In the remaining 26 fields, ridge orientation was considered nearly perpendicular to the *Cierzo* and *K* was estimated as the mean value of those corresponding to the perpendicular and parallel directions. The absence of a predominant ridge direction indicates that, regardless of the type of tillage implement commonly used in a given zone, farmers in the region do not take into account the tillage orientation with respect to wind. In those fields where tillage was done perpendicularly or nearly perpendicularly to the *Cierzo* direction, *I* was reduced between 10% and 50% (average of 30%) (Eq. [2]).

The WEQ does not take into account the effect of stones as nonerodible material covering the soil surface. Since some fields showed a certain level of stoniness, soil cover by stones and pebbles was included in the WEQ by applying the mathematical relationship established by Fryrear (1985) between soil loss ratio and the percentage of soil cover by nonerodible material. Thus, some fields in zone I had the highest levels of stoniness with percentages of soil cover of

13% and 20%. Likewise, soils in zones E and C were covered by stones in about 10-15% of the surface. These values of soil cover implied reductions in *E2* ranging from 10% to 60%.

Climatic erosivity. Table 4 shows monthly values of climatic parameters used to calculate mean values of *CE* and *C* for a 20-year period. The scale (*c*) and shape (*k*) parameters of the Weibull distribution, determined from the wind speed, are also presented. Values of *k* close to 2 in all months allowed us to determine *CE* from the simplified method of Skidmore (1986). February, March and April, together with December, were the most erosive months with *C* values varying between 119% and 215%. According to the FAO classification (FAO, 1980), climatic erosivity in these months was high to very high. Wind speed seemed to be the determinant factor of the high climatic severity. A *C* factor of 166%, as mean value for the February-April period, was included in the step *E3* of the WEQ (Eq. [3]). From this point onward, it was assumed that the climatic conditions for this period prevailed for the entire year.

Field dimension and orientation. Field dimensions varied extensively with lengths ranging from 80 to 1650 m and widths from 40 to 1000 m (surfaces of 0.3-160 ha), without observing any tendency in their distribution by zones. Likewise, no predominant field orientation was detected. In any case, the field was not long enough to reach the *Lo* distance and, therefore, estimates of soil erosion were always lower than the maximum erosion at *Lo*. Reductions in *E3* (Eq. [4]) depended on the soil erodibility, being almost total in fields with I <10 Mg ha^{-1} yr^{-1} and only by 7% in fields with I ~200 Mg ha^{-1} yr^{-1}.

Soil cover by crop residues. Maintaining residue cover on the soil surface is considered the most effective method to control wind erosion (Skidmore, 1988; Watson, 1994). In many semiarid regions, however, low biomass production, as well as inadequate agricultural practices, lead to limited amounts of crop residues and, thereby, insufficient soil protection. This is the case of the study area, where soil cover by crop residues was negligible (<1%) in 76% of the fields. The highest percentages of residue cover (10-25%) corresponded to fields tilled with Ch in zone I. In all cases crop residues laid flat on the surface. Although residue covers of 2-5% provided reductions in *E4* of 10-20% (Eq. [5]), these were not sufficient to decrease soil erosion estimates from high to tolerable levels.

Expected soil losses by wind erosion. Estimates of average annual soil loss were multiplied by the fraction of *CE* corresponding to the February-April period (i.e. 42%; Table 4) to obtain values of expected wind erosion for this critical fallow period (Table 5). According to the FAO classification (FAO, 1980), the predicted wind erosion was high to very high in 30% of the fallow fields surveyed in the study area (from 22 to 141 Mg ha^{-1}) and moderate in 28% (5-19 Mg ha^{-1}) (Table 5). Fields with a high risk of wind erosion were located in zones C, E, B, D, K and M, and also, but with minor representation, in zones L and N (Fig. 4). This high expected wind erosion is explained by a high soil erodibility, mainly due to both a relatively high sand content and intensive tillage. In addition, the low amounts of crop residue coupled with the large unsheltered fields widths, and tillage more or less parallel to the *Cierzo* direction do little to reduce the risk of erosion.

It should be mentioned that values of soil erosion predicted from the WEQ are estimates of average soil loss and, therefore, they should be used with caution. The estimations may differ from the actual soil losses due to variations from the average of climatic parameters, such as precipitation and wind. Thus, the wind erosion hazard is accelerated during a drought year because the lack de precipitation leads to a lower residue production and a higher soil erodibility (Merrill et al., 1999). Likewise, the WEQ does not account for temporal variation of soil surface properties. Although in our study soil losses were only estimated for the February-April period and the soil was not disturbed by management practices during this period, some changes in soil erodibility could have occurred. For example, significant changes in EF in relatively short periods of time may be associated with climatic processes (Larney et al., 1994) and with the wind erosion process itself, such as a gradual depletion in erodible particles up to reach a situation of limited supply of particles available for erosion (López, 1998; López et al., 2000). In spite of these limitations, the WEQ has been useful in the present study to identify agricultural zones with a higher risk of wind erosion and to evaluate the effectiveness of alternative control practices.

Wind erosion control practices. The WEQ can be used to design optimal management strategies to control wind erosion by determining which combination of *I*, *K*, *L* and *V* is required to reduce soil losses to a tolerable level. With this purpose, the WEQ was applied in the fallow fields presenting a high to very high risk of wind erosion during the February-April period (>20 Mg ha^{-1}). Thus, for the fields with the highest risk of erosion (>80 Mg ha^{-1}; Fig. 4), where MP or MP+R was used, ploughing perpendicularly to the prevailing WNW direction, without the R pass, would reduce the expected wind erosion by about 40%. In addition, if *L* is shortened through a reduction in the field size, the expected soil loss would lower to moderate levels (i.e. 4-20 Mg ha^{-1}). Thus, the WEQ predicts a mean reduction of 80% in soil erosion if the field is shortened to about 20 m (an adequate distance to operate with the current farming machinery). Stripcropping, alternating narrow strips of cereal with fallow (the two stages of the traditional cereal-fallow rotation), could also be a viable strategy to reduce *L* and, hence, soil losses. Finally, a sufficient amount of crop residues could provide a good soil protection. However, between 600 and 1000 kg ha^{-1} of cereal residues would be needed to reduce erosion to a tolerable level (~4 Mg ha^{-1}) and maintaining this amount of residues after ploughing is not a possible option in the study area. A higher residue cover can be obtained through conservation tillage systems. In this sense, if MP is substituted by Ch, the amount of residues estimated by the WEQ to have a soil loss of 4 Mg ha^{-1} would be of 200-400 kg ha^{-1}. This level of crop residue could be retained most years in zones with an average cereal yield of 1300-1500 kg ha^{-1}. This takes into account that about 70% of cereal residues remains after chiseling (Carter et al., 1992) and about 80% after weathering from harvest to primary tillage (Dickey et al., 1986).

For the fallow fields with a high risk of wind erosion (i.e. 20-80 Mg ha^{-1}; Fig. 4), the WEQ indicates that tilling narrow strips of land (20-80 m wide) with MP or DH perpendicularly to the WNW direction would be sufficient to achieve low soil losses (<0.30 Mg ha^{-1}). However, better control of wind erosion would be achieved with conservation tillage, such as reduced tillage with chiseling as primary operation. Previous results on crop and soil response to conservation tillage (López et al., 1996, 1998; López and Arrúe, 1997) indicate that reduced tillage can be recommended as a fallow management alternative in semiarid Aragon. In fact, chiseling is being introduced by farmers in zone I.

It would be desirable that the above recommendations, which farmers could easily incorporate into their cropping systems with the farming equipment currently available, could be used for the development of specific guidelines on best agricultural management practices for wind erosion prevention in semiarid Aragon.

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Figure legends

Figure 1. Location of the study fields (λ) within main dryland farming areas (shaded areas) of semiarid Aragon with mean annual rainfall less than 400 mm.

Figure 2. Wind-erodible fraction (aggregates <0.84 mm in diameter) of soil surface (0-2.5 cm depth) as function of soil texture.

Figure 3. Wind-erodible fraction (aggregates <0.84 mm in diameter) of soil surface (0-2.5 cm depth) as affected by tillage (Ch, chisel plough; MP, mouldboard plough; DH, disk harrow; and, R, roller). Different letters indicate significant differences at $P<0.05$.

Figure 4. Predicted wind erosion in the study fields for the February-April period (, >80 Mg ha^{-1}; , 20-80 Mg ha^{-1}; , 4-20 Mg ha^{-1}; , <4 Mg ha^{-1}).

Table 1

Correlation coefficients of physical and chemical soil surface properties (0-2.5 cm depth)

	EF	Sand	Silt	Clay	Org. matter	$CaCO_3$	Gypsum	EC	pH	Stoniness
EF[a]	1									
Sand (2000-50 μm)	0.531***	1								
Silt (50-2 μm)	-0.413***	-0.873***	1							
Clay (<2 μm)	-0.324***	-0.427***	-0.068	1						
Organic matter	0.278**	-0.113	0.085	0.074	1					
$CaCO_3$	0.082	0.146	-0.151	-0.018	0.057	1				
Gypsum	-0.073	-0.197	0.433***	-0.400***	-0.179	-0.381***	1			
EC[b]	-0.030	-0.403***	0.541***	-0.180	-0.120	-0.153	0.612***	1		
pH	-0.180	0.243**	-0.281**	0.023	-0.325***	0.138	-0.213*	-0.639***	1	
Stoniness[c]	0.402***	0.502***	-0.423***	-0.243**	0.376***	-0.078	-0.085	-0.335***	0.029	1

[a] Wind-erodible fraction.
[b] Electrical conductivity.
[c] Percentage of soil cover by stones.
* Significant at *P*<0.10.
** Significant at *P*<0.05.
*** Significant at *P*<0.01.

Table 2

Soil surface properties (0-2.5 cm depth) for different soil types (mean values and standard deviation)

	Calcisol	Gypsisol	Leptosol	Regosol	ANOVA *F* prob.
Frequency	46	7	7	7	
EF[a] (%)	35±21 a[c]	33±10 a	45±17 a	34±11 a	0.441[d]
$CaCO_3$ (g kg^{-1})	398±122 a	205±73 b	277±194 ab	347±110 a	0.001
Gypsum (g kg^{-1})	47±16 a	360±145 b	57±11 a	89±76 a	<0.001[d]
EC[b] (dS m^{-1})	0.60±0.81 a	2.46±0.17 b	0.53±0.89 a	1.61±1.10 b	<0.001[d]
pH	8.4±0.3 a	8.2±0.2 a	8.2±0.2 a	8.3±0.3 a	0.110
Organic matter (g kg^{-1})	12.0±4.5 a	9.7±4.3 a	20.2±10.3 b	11.4±4.5 a	0.024[d]

[a] Wind-erodible fraction.
[b] Electrical conductivity.
[c] Within rows, mean values followed by the same letter are not significantly different at $P<0.05$.
[d] Statistics calculated with transformed data.

Table 3

Wind-erodible fraction of soil surface (0-2.5 cm depth) as affected by tillage[a]

Textural class	Tillage practice[b]	EF[c] (%)	ANOVA *F* prob.
Silty clay loam	MP	25 a	0.114
	MP+DH	31 a	
Sandy loam	MP	71 a	0.015
	MP+R	80 b	
Silt loam	Ch+R	13 a	<0.001
	MP	32 b	
	DH+R	42 c	

[a] Data from 7 representative fields with six samples per field.
[b] MP, mouldboard plough; DH, disk harrow; R, roller; and Ch, chisel plough.
[c] Wind-erodible fraction.

Table 4

Basic climatic information to calculate monthly wind erosion climatic erosivity (*CE*) and climatic factor (*C*) for the period 1965-1984

Month	Precipitation (mm)	Net radiation (Mj m^{-2})	Wind speed[a] (m s^{-1})	*c*[b] (m s^{-1})	*k*[b]	*CE* (MJ m^{-2})	*C* (%)
Jan	21	166	4.8	5.3	1.7	150	93
Feb	21	209	5.0	5.6	1.8	193	**119**
Mar	28	313	5.2	5.8	1.9	265	**164**
Apr	32	369	5.5	6.1	1.9	346	**215**
May	41	474	4.7	5.2	1.7	151	93
Jun	31	528	4.5	5.0	1.7	125	77
Jul	15	598	4.8	5.3	1.7	187	116
Aug	21	526	4.5	5.1	1.7	137	85
Sep	22	393	3.9	4.4	1.5	53	33
Oct	27	307	4.0	4.5	1.6	60	37
Nov	37	185	4.5	5.0	1.7	67	41
Dec	21	137	5.1	5.7	1.8	204	126
Year	317	4205	4.7	5.3	1.7	1938	100

[a] At 10-m height.
[b] *c* and *k* are the estimated scale and shape parameters of Weibull distribution (Skidmore, 1986).

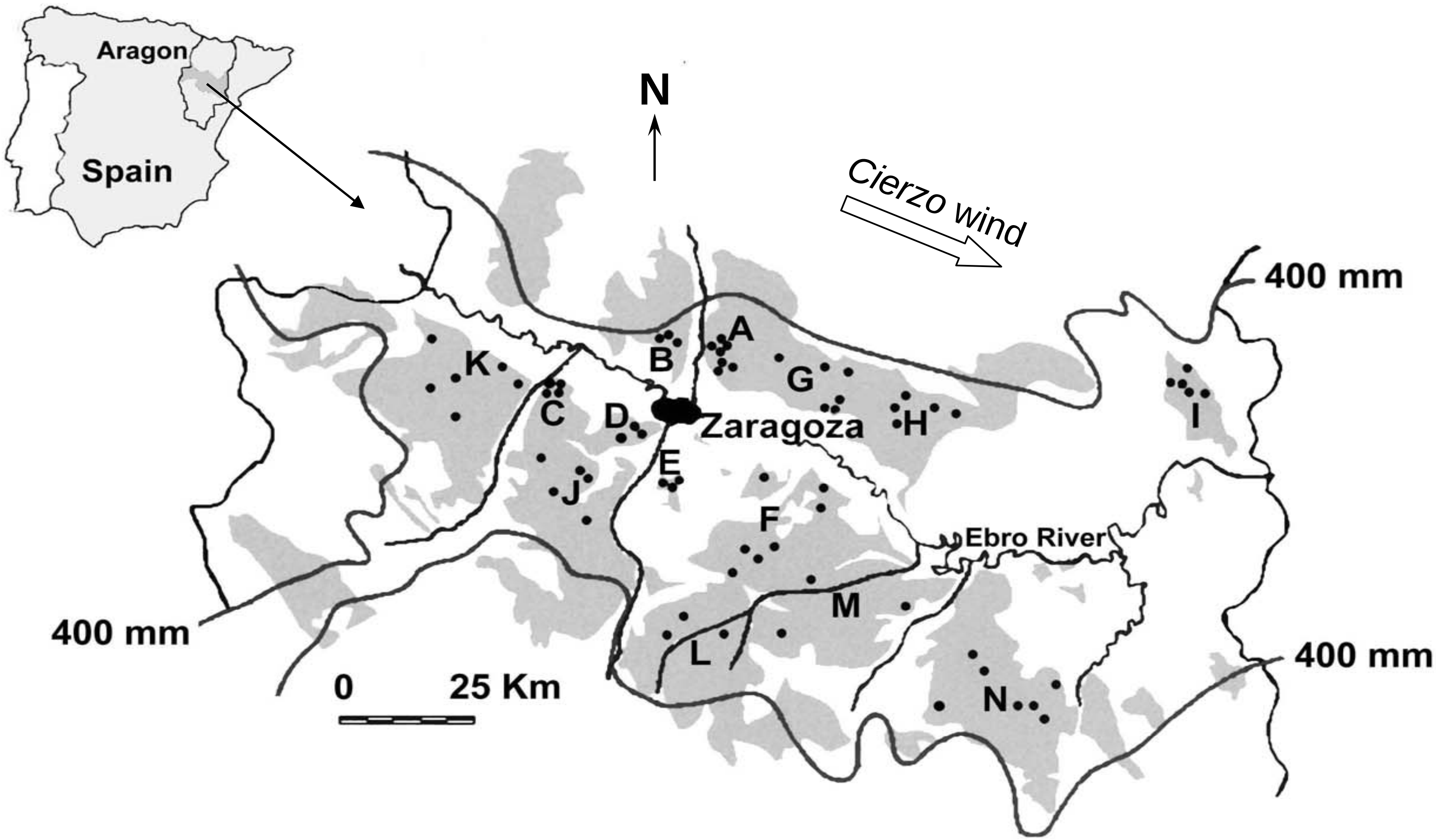
Table 5

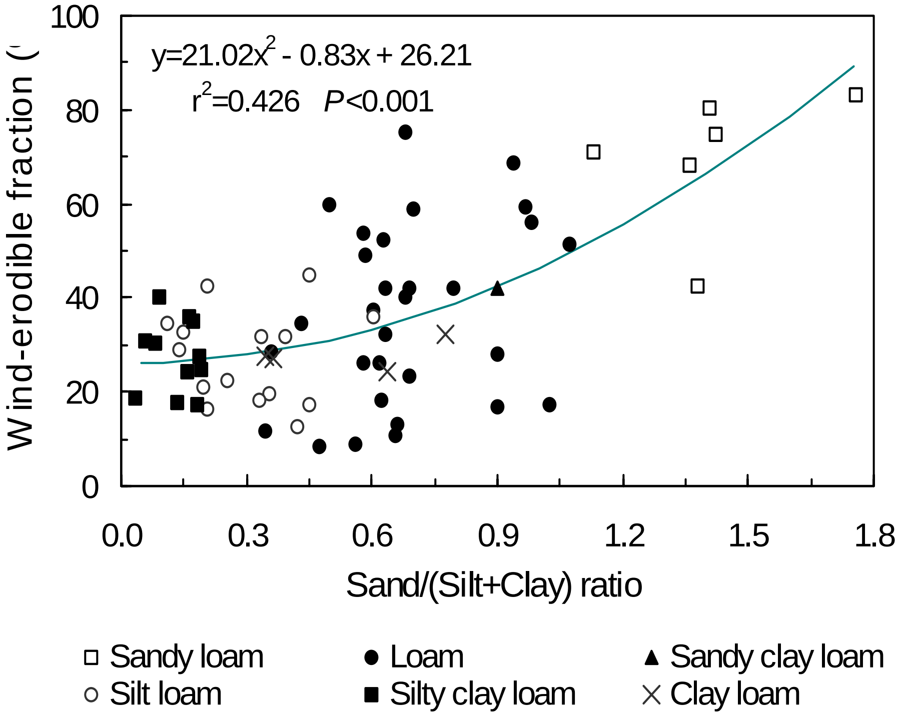
Values and classification of the expected soil losses by wind erosion in the study area

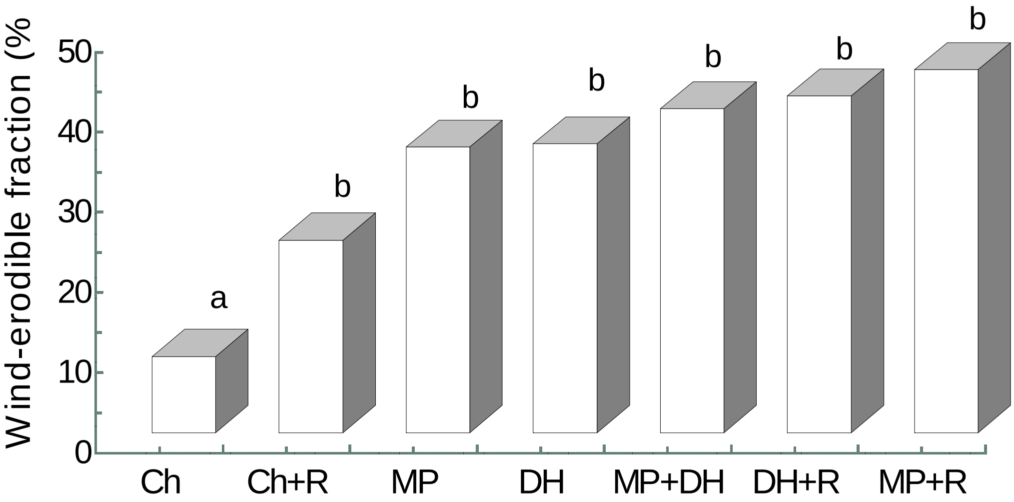
Wind erosion class[a]	Soil loss Annual[b] (Mg ha^{-1} yr^{-1})	Soil loss Feb-Apr (Mg ha^{-1})	Frequency (%)
Zero to slight	<10	<4	42
Moderate	10-50	4-20	28
High	50-200	20-80	21
Very high	>200	>80	9

[a] FAO (1980).

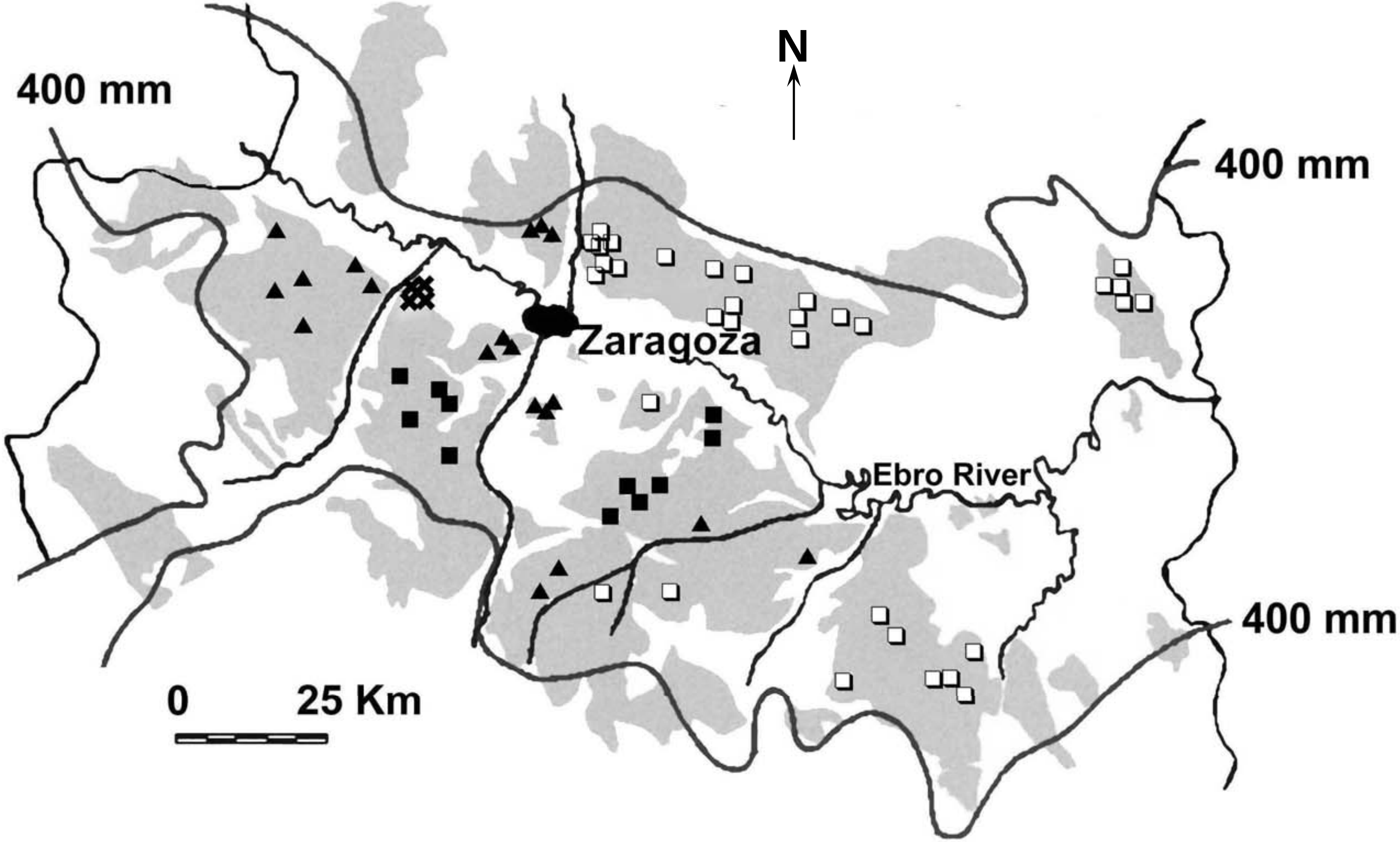
[b] Estimated for the climatic conditions occurring during the February-April period.


Aragon
Spain
N
Cierzo wind
400 mm
400 mm
400 mm
A
B
K
C
D
Zaragoza
G
H
I
E
J
F
Ebro River
M
L
N
0
25 Km


y=21.02x^2 - 0.83x + 26.21
r^2=0.426 P<0.001
100
80
60
40
20
0
0.0
0.3
0.6
0.9
1.2
1.5
1.8
Wind-erodible fraction (
Sand/(Silt+Clay) ratio
Sandy loam
Loam
Sandy clay loam
Silt loam
Silty clay loam
Clay loam



Wind-erodible fraction (%
0
10
20
30
40
50
a
b
b
b
b
b
b
Ch
Ch+R
MP
DH
MP+DH
DH+R
MP+R


400 mm
N
400 mm
Zaragoza
Ebro River
400 mm
0
25 Km