RUNOFF, SOIL AND NUTRIENT LOSS UNDER ALTERNATIVE CROPPING SYSTEMS IN A RECLAMATION DISTRICT OF CENTRAL ITALY

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Abstract

Erosion and nutrient losses represent two of the most important impacts on the environment not only on hilly croplands but also on plains. Quantifying them is necessary to evaluate the sustainability of cropping systems. In a reclamation district characterised by large-scale and intensive agricultural use and the presence of a vulnerable receiving water body, we compared in a field experiment the impact and productivity of three alternative continuous cropping maize systems: conventional (Con), low-input (Low) and environmentally protective (Pro), each using different amounts of chemical and mechanical inputs. Experimental sites were located on two farms with different soil types: peat soil (PF) and loam soil (LF). Crop growth and cumulative runoff, sediment, dissolved and particulate nutrient losses were measured. Yields of Con were 20-25% higher than those of alternative systems (Low and Pro) at both sites. The effect of cropping systems on erosion was influenced by location: Con had higher impact on the loam soil, while Low had higher impact on the peat soil. Pro seemed to ensure the best soil conservation conditions at both sites. Simple linear regressions estimated the contribution of predictor variables to explaining the results: runoff was strongly influenced by rainfall (above 75% of variability explained) but not by the type of cropping system, which instead significantly influenced soil losses (23-25% of variability explained). The use of a multiple linear regression model allowed explaining the single runoff events while the prediction of soil and nutrient losses were consistent on annual basis. Estimations of eroded soil remained below 800 kg/(ha y) at both sites, while those of dissolved N losses ranged from 488-1118 and 379-1172 g/(ha y) for PF and LF sites, respectively, and those of dissolved P losses ranged from 527-793 and 468-749 g/(ha y) for PF and LF sites, respectively.

Key words: cropping systems, erosion, nutrient loss, predictor variables, multiple linear regression.

1. Introduction

Soil erosion from cultivated land has direct negative effects on soil fertility and represents one of the most important causes of land degradation (e.g. soil compaction, depletion of nutrient stocks, decrease in microbiological activity) at world level (Bravo-Espinosa et al., 2009; Stavi and Lal, 2011). The erosion of the land leads to a decrease in soil functionality and therefore to a degradation of ecosystem services.

Many factors can affect the intensity of erosive phenomena, increasing the loss of sediment and nutrients. Some of them depend largely on local and physical conditions, including climate, lithology, topography and soil texture (Cao et al., 2003; Stavi and Lal, 2011); others are under human control and are related to crop choice and the farming practices adopted (Ramos and Martìnez-Casanovas, 2006; Hahn et al., 2012; Sweeney et al., 2012).

The ability of cropping systems to reduce sediment and nutrient losses from cultivated fields is a necessary condition for the sustainability of agricultural land use and a key factor in the protection of water resources. The adoption of alternative management methods such as long and diversified crop rotations (Huang et al., 2006; Jiao et al., 2011), intercropping and cover crops (Bahadur Sapkota et al., 2012), minimum- or zero tillage (Fuentes et al., 2009), and crop residue management (Torbert et al., 1999; Grande et al., 2005) are among the most important options available to mitigate the effects of agricultural land use on increasing erosion and to restore soil quality (Bravo-Espinosa et al., 2009).

The study of cropping systems, which are combinations of crop genotypes (species/cultivars) and agricultural practices on the same field, allows identification of solutions that offer the highest level of compatibility with the conditions of a particular cultivated area (Silvestri and Bellocchi, 2007; Jiao et al., 2011). It is evident that the strategies adopted by farmers can have important effects on protection of the environment (De Jager et al., 1998). They require the extension of evaluation from a private/farm level, based on a farmer's point of view, to a public/environmental level, which includes potential negative externalities (Silvestri et al., 2012).

Moreover, soil erosion is the result of a few randomly distributed events rather than of regularly occurring events. Therefore, it is important to evaluate the conditions that exist during each event. Many of the variables involved (e.g. rainfall intensity, vegetation stage, water infiltration rate, nutrient content in the topsoil) can indeed change significantly over time and interact with each other in different ways (Gonzales-Hidalgo et al., 2007; Truman et al., 2007). Therefore, the simultaneous occurrence of critical values for several variables, even for a short period, represents a risk condition, which is difficult to predict or model.

Soil erosion is usually higher on steep, hilly croplands. Nevertheless, erosive phenomena can still be an issue on plains, not as much for their intensity as for the vulnerability of receiving water bodies. In reclamation districts, the effects of erosion are of major concern because of the siltation of natural and artificial reservoirs and the pollution (eutrophication) of surface waters (Carpenter et al., 1998).

In this paper we deal with a case study of a reclamation district, characterised by large-scale and intensive agricultural use and the presence of a vulnerable receiving water body (the lake of Massaciuccoli in Tuscany, Italy) (Pistocchi et al., 2012). The objectives of this study were i) to compare the impacts and productivity of three alternative cropping systems with differing use of chemical and mechanical inputs, ii) to quantify the importance of natural and anthropic factors in driving erosion phenomena, and iii) to verify the consistency of estimates obtained using one or a small set of predictor variables.

2. Materials and methods

2.1 Field trial description

The study was carried out in the Regional Park of Migliarino-S.Rossore-Massaciuccoli (coastal plain of Central Italy). The region has a Mediterranean climate and mean annual rainfall of ca. 700 mm, with two peaks (autumn and spring). Mean annual temperature equals 15°C, with mean monthly maximum temperatures (summer season) above 25°C and mean monthly minimum temperatures rarely below zero.

The experimental sites were located on two farms (5 km away from each other) with different soil conditions. In the first (Peat Farm, hereafter PF), peat soils (eutri-sapric and endo-salic histosols) prevail, with low pH (5.1-6.2) and mean organic matter content of ca. 30% (Silvestri et al., 2002). In the second (Loam Farm, LF), soils are mainly clay loam and silt loam and have much less organic matter (mean content of 2.7%). These soils are classified as calcari-fluvic cambisols. Table 1 lists chemical and physical characteristics of the soil profiles in the two sites.

Since the experimental sites are located within a reclamation district, their hydrological conditions are peculiar: elevation is below the mean sea level, requiring artificial drainage and pumping stations to maintain a water table depth suitable for cultivation (0.3-0.5 m below field level).

We compared three cropping systems under rainfed conditions: conventional (Con), low-input (Low) and protective (Pro) systems, characterized by a decreasing use of chemical and mechanical inputs (Table 2). The crop studied was maize, the most widespread in this district, which is cultivated in continuous cropping or two-year rotations with winter wheat or sunflower (Silvestri et al., 2012). In the Con system we chose the farming practices usually adopted in the area. In the Low system we applied a “passive” mitigation strategy, significantly decreasing the amount of chemical and mechanical inputs, while in the Pro system, the decrease in inputs was combined with an "active" protection strategy, consisting of buffer strips along the field ditches. Each cropping system occupied an entire field (24 m wide and 200 m long, with a mean slope of 2% created by ploughing) and was replicated three times, for a total of nine experimental fields, according to a randomised block design. Each field was equipped with one device (1.5 m long and 1.0 m wide), comprised of three steel-sheet edges pushed 10 cm into the soil and a triangular manifold ending with a pipe which directed the flow to a storage tank (0.25 m^3) installed down-slope in the ditch (Dunjò et al. 2004). The trap was therefore hydraulically isolated from the rest of the field and able to collect the runoff generated by a surface area of 1.5 m^2.

2.2 Sampling strategy

Since it was necessary to remove the traps before tillage and harvesting operations, runoff monitoring was discontinuous. Significant events (> 2 mm) were monitored for a period of 1.5 years, divided into two sub-periods: I and II. For PF, the first (I) ran from June 2007 to February 2008 and the second (II) from May to November 2008 (Fig. 1), while for LF the first (I) ran from June to October 2007 and the second (II) from December 2007 to November 2008 (Fig. 1). Sampling was performed after each rainfall event if the amount of water collected in the storage tanks was enough for analysis; if not, rainfall from events was accumulated until a sufficient amount of water was obtained. Samples were also aggregated for events close in time (e.g. occurring on two consecutive days). Small (< 5 mm) and isolated (more than three days far from each other) events were ignored.

For PF and LF, 28 and 29 events were sampled, respectively, which can be considered representative of the variability in environmental conditions (combination of soil, crop stage and rainfall conditions) during the monitoring period.

Rainfall depth (RD, in mm) was measured using rain gauges installed at the experimental sites. Rainfall intensity over 30-minute intervals was calculated using data from the closest meteorological station (Metato-PI, Servizio Idrologico Regionale), less than 4 km from both the experimental sites.

Crop yields were estimated by harvesting sample areas of 2 m^2 replicated three times for each experimental field. The grain was separated from the above-ground biomass and weighed after oven drying at 60°C until constant weight.

2.3 Laboratory analyses

Runoff volume (RO, in l) was measured manually in the field with a graduated cylinder. Electrical conductivity (EC, in mS/cm) and pH were also measured in the field using portable devices (XS COND 6 and XS pH 611, Oakton-Eutech Instruments, respectively). For each replicate, a subsample of runoff was taken and stored in 1 l PE bottles at 4°C before analysis. The material that settled at the bottom of the tank was summed over each sub-period. Total suspended solids (SS, in g/l) in the liquid samples were measured in triplicate by the gravimetric method while stirring (0.5 h). Nutrient losses were estimated based on dissolved and particulate fractions in the liquid and solid samples, respectively. The dissolved fraction included nitrates (N_{dis}, in mg/l), which were determined by ion chromatography (Dionex Dx-500 ion chromatograph). Soluble reactive phosphorus (P_{dis}, in mg/l) was determined by the blu-molybdenum method on filtered samples (with a Perkin Elmer 22 Lambda 1 spectrophotometer). The particulate fractions included nitrogen (N_{par}, in mg/kg) and phosphorus (P_{par}, in mg/kg), were analysed after digestion (Taylor, 2000) with the Kjeldhal and the blu-molybdenum methods, respectively.

As QA/QC procedures, field and analysis blanks were included, as well as replicates at different dilutions, to check for matrix effects. Standards were also included for each batch.

2.4 Data processing

Comparison of cropping systems was performed separately for each sub-period based on cumulative values of runoff (cRO, in m^3/(ha mm)), sediment (cSS, in kg/(ha mm)) and dissolved nutrient losses (cN_{dis} and cP_{dis}, in g/(ha mm)) expressed per rainfall unit. These values were calculated as follows:

$$\text{cumulative value} = \frac{\sum_i C_i \cdot RO_i}{\sum_i RD_i}$$

where C_i is the SS, N_{dis} or P_{dis} concentration for the i^{th} rainfall (RD_i) and runoff (RO_i) event. Cumulative losses of particulate nutrients (cN_{par} and cP_{par}, in g/(ha mm)) were determined by dividing N_{par} and P_{par} of each sub-period by the cumulative rainfall depth. The sum of dissolved and particulate fractions allowed total nutrient losses ($cN_{tot} = cN_{dis} + cN_{par}$ and $cP_{tot} = cP_{dis} + cP_{par}$ in g/(ha mm)) to be determined. The cumulative data were analysed with a one-way ANOVA in which the cropping system was the factor with three levels (Con, Low and Pro). We considered a $p \leq 0.05$ as the limit of significance. The Tukey HSD test was used for *post hoc* means comparison.

To interpret the contribution of factors driving erosion phenomena, we considered the following quantitative and qualitative variables: rainfall depth measured *in situ* (RD, in mm), erosion index (EI, in MJ mm/(ha h)), cropping system (CS) and crop stage (ST) as predictor variables and the data collected for each event (RO, SS, N_{dis} and P_{dis}) as dependent variables. RO was also considered a predictor variable when treating SS, N_{dis} and P_{dis}.

The EI was calculated for each event using the data (rainfall intensity and depth at 30 minutes) from the meteorological station, according to the equation described by Foster et al. (1981). The ST was assigned according the stage classification developed by Wishmeyer and Smith (1978).

We first performed simple linear regressions (separately for the two study sites) to identify the key predictor variable (i.e. explaining the most variability) for each dependent variable. Then, a multiple linear regression (MLR) model including all the predictor variables and their interactions was built for each dependent variable to fill in gaps in the monitoring period and estimate annual values. In the MLR, dependent variables were log-transformed to satisfy the assumption of normality. We used a stepwise elimination method to remove the predictor variables that did not contribute significantly to improve MLR performances. The significance of the fitted models was determined by F statistics. The goodness of fit of the MLR was assessed by the adjusted R^2 and analysis of standardised residuals, which were also checked for heteroscedasticity with the Shapiro-Wilk normality test.

To validate the MLR, an independent dataset of RO and sediment losses from 18 events recorded in the PF site during a 10-month period (May 2005 - March 2006) was used. The degree of agreement between observed and predicted results was estimated by calculating R^2, the Nash-Sutcliffe efficiency (NSE), the coefficient of residual mass (CRM) and the percent bias (PBIAS) (Moriasi et al., 2007). All statistical analyses were performed with R statistical software (version 2.12.0, R Foundation for Statistical Computing).

3. **Results and discussion**

3.1 Cropping system effect

Table 3 shows cumulative values cRO, cSS, cN_{dis}, cP_{dis}, cN_{par}, cP_{par}, cN_{tot} and cP_{tot} for the three cropping systems and the two sites.

At the PF site, cRO was not significantly different among sub-periods, and cSS was significantly different only for sub-period I: higher in the Low (2.03 kg/(ha mm)) than the Pro (0.82 kg/(ha mm)) system. The type of CS did not affect cRO (grand mean = 1.15 m^3/(ha mm)), and the amount of soil eroded was only partially related to agronomic management practices.

The effect of CS on nutrient release was more evident. Some differences were significant (I-cN_{dis}, II-cN_{dis}, I-cN_{par}, I-cP_{par}), with the Low system showing systematically higher losses than the Pro system, which had the lowest nutrient losses. The values of the Con system were intermediate to, and often not significantly different than, those of the other two (I_s and II-cN_{dis}, I-cN_{par}).

Two observations can explain these results. First, nutrient losses were strongly correlated with the carrier phase (water or soil). Differences in dissolved nutrient losses among systems were indeed related to concentrations rather than amount of runoff, which was similar among the three systems. In contrast, particulate nutrient losses were affected by differences in soil erodibility and therefore to agronomic management practices. In fact, the only significant differences for the first sub-period (I-cN_{par} and I-cP_{par}) followed the pattern of cSS.

The second observation is related to the different behaviours of N and P. The type of CS (and then the amount and distribution of fertilizers) significantly affected the release of dissolved N (I-cN_{dis} and II-cN_{dis}), confirming its higher leachability. In contrast, agronomic management practices did not affect dissolved P losses in both sub-periods but rather particulate P losses. This is also confirmed by the higher relative difference in particulate nutrient losses between the Low and Pro systems, as confirmed by Low/Pro ratios equal to 2.8 (I-cP_{par}) and 2.1 (II-cP_{par}) for P and to 2.4 (I-cN_{par}) and 1.6 (II-cN_{par}) for N.

Total nutrient losses of the three CS were significantly different, except for II-cN_{tot}. Their variability was relatively large, ranging between 5.2 and 19.5 g/(ha mm) for N (Pro-I and Low-I, respectively) and between 2.2 and 4.2 g/(ha mm) for P (Pro-II and Low-I, respectively).

At the LF site, almost all differences were significant (except for I-cRO, II-cN_{dis}, I-cP_{dis}), although this did not necessarily imply an enhancement of erosion effects compared to the other site. The difference between the two sites (LF - PF values), calculated as the mean of the three systems and the two sub-periods, was indeed positive for eroded soil (cSS = +0.76 kg/(ha mm)) and dissolved P (cP_{dis} = +0.41 g/(ha mm)), negligible for RO (cRO = -0.07 m^3/(ha mm)), particulate P (cP_{par} = +0.02 g/(ha mm)) and total P losses (cP_{tot} = +0.43 g/(ha mm)) and negative for all N losses (-0.74, -5.13 and -5.87 g/(ha mm) for $cN_{dis,}$ cN_{par} and cN_{tot}, respectively).

At the LF site, we also observed a different pattern among the CSs. The Con system was the least conservative, due to higher sediment and nutrient losses than the other two. Values of the Low and Pro systems were also often significantly different from Con: II-cRO, I-cSS, I-cN_{par}, I-cP_{par}, I-cN_{dis}, II-cP_{dis}, I-cN_{tot}, II-cP_{tot}. The amount of soil eroded in the Con system was 1.5 times as high as that in the Low system and 4 times as high as that in the Pro system. Differences in particulate nutrient losses had the same ratios, while those for dissolved phases were negligible. This means that under these soil conditions, the CS choice could substantially decrease environmental impacts of cultivation and reduce sediment and nutrient losses.

Hence, the results were influenced by the interaction of agronomic management practices with soil type. In fact, on peat soil (PF site) the Low system provided a lower level of soil conservation than the Con system, which instead appeared the worst option on loam soil (LF site). Minimum tillage (Low system) seemed to increase erodibility on peat soil, leading to higher losses of nutrients associated with the sediments. Our explanation is that under the lower hydraulic conductivity (1.5×10^{-5} m/s) of peat soil, the shallower plough pan produced by minimum tillage decreased rainfall infiltration, thereby increasing erosion as observed by others authors on different types of soils (Bonari et al., 1995).

In general, high soil organic matter (SOM) content reduced the relative differences among the CSs (low erodibility, high N availability due to SOM mineralisation), although the Pro system appeared, in both soils, the most environmentally friendly due to the use of no-tillage and buffer-strips. Moreover at the PF site, it was evident that the high N availability in soil led to generally higher releases of nitrates than at the LF site, where, conversely, we observed higher losses of particulate P because of its higher soil erodibility.

Differences between the two years were noticeable but related to the magnitude of the phenomena (i.e. differing rainfall erosivities) rather than to the relative performance of the CSs.

3.2 Yields

At the PF site, the Con system was consistently the most productive (about 2 t/ha more than the Low and Pro systems), while the other two systems did not differ significantly (2-year means of 9.4 and 9.9 t/ha for Low and Pro systems, respectively; Table 4). At the LF site, yields were generally lower (about -20%) than those at the PF site, but showed the same pattern among CSs. The lower productivity of maize in the loam soil is related mainly to hydrological conditions, since the water table was deeper during the growing season, leading to lower water availability for the crop. These results confirmed the importance of mechanical and chemical input availability to yields and highlighted that in terms of yield the two non-conventional systems (Low and Pro) were equivalent.

3.3 Linear model

Table 5 shows the contribution of each factor (predictor variable) to each dependent variable as a coefficient of determination (R^2). This analysis identified, for a given dependent variable, a main factor (or a set of factors) contributing to its overall variability.

For RO, RD was by far the main driving factor (77% and 78% of the overall variability for LF and PF, respectively). EI, the second most influential factor, explained about 35% of the variability for both sites.

The effect of CS was highly significant in explaining SS data (25% and 23% of the overall variability for LF and PF, respectively). The different types of tillage among the CSs tested and the adoption or not of an active protection strategy (buffer strips) led to significant differences in sediment losses, as reported in the literature (Takken et al., 2001; Basic et al., 2004; Schuller et al., 2007; Dorioz et al., 2006; Novara et al., 2011, Prashun, 2012).

The ability of the crop to reduce rain erosivity according to its growth stage was confirmed by the percentage of total variability explained by ST (12-20%).

The major factor influencing N_{dis} was ST. We recorded one peak of N_{dis} in runoff at the F stage (from soil tillage to seedbed preparation), which was linked to the absence of the crop and increased nitrate availability during the late summer and early autumn due to soil microbial activity. Soil nitrate concentration is indeed strictly linked to trends in SOM mineralisation and fertiliser application as well as crop development (Randall and Mulla, 2001; Agostini et al., 2010). N_{dis} was also negatively correlated with rainfall and runoff (dilution effect), with r ranging from -0.39 to -0.33 for RD and from -0.30 to -0.23 for the RO at PF and LF respectively.

For P_{dis}, ST was by far the most important factor, explaining 57 and 44% of variability at the LF and PF sites, respectively. Peak concentrations in RO were observed in different stages at the two sites: 1, 2 and 4 (increasing percentage of canopy cover) for LF and 2, 3 and SB (from seedbed preparation to 10% of canopy cover) for PF. This temporal variability seems to be related to different factors temporarily influencing the availability of dissolved P in the soil, as well as agronomic management practices and biological activity. Indeed, similar variability was observed at the territorial scale for the same area (Pistocchi et al., 2012). The variability explained by EI was decidedly lower (about 10%), but positively correlated with P_{dis}.

Concerning EC, we observed a different pattern at each site. At the LF site, ST explained half of the variability in EC, while at the PF site, in addition to ST, RD and RO were significant, each one explaining approximately 20% of variability in EC (17%, 23% and 16%, respectively). The contribution of ST was probably the result of different evapotranspiration rates during the crop growth. The lower contribution of ST at the PF site could be related to its unique hydrology, characterized by a water table level maintained artificially constant during the monitoring period (Pistocchi et al., 2012), thus smoothing differences in soil moisture among different stages.

Table 6 shows MLR models for each dependent variable for the two study sites. At both sites, RO was significantly affected by RD, which explained more than 76% of its variability. ST, CS and the interactions ST x RD, ST x EI, and RD x EI were also significant, but they accounted for less variability. EI was significant only for the LF site. The model was able to explain more than 85% of the overall variability in RO for both sites.

Variability in SS was explained by several factors, each accounting for a non-negligible percentage of variance (> 5%). Among them, CS (23-25% of total variance) and ST (14-16%) were common to both sites, while RD was relevant (8%) only for PF. The model could explain approximately half of the overall variability in SS.

ST and RD drove the pattern of EC at both sites (55% and 40% of the overall variability for LF and PF, respectively). However EI also played an important role at the PF site, explaining 10% of the variability. The residual variability was ≤ 30%.

For N_{dis}, the most important factors were ST, RD and their interaction, which explained 38% and 27% of the total variability for LF and PF, respectively. For the former, the interactions between ST and other factors were also significant (11% of total variance), while for the latter, RO accounted for 10%. Model performances ranged from 48-51% of overall variability.

Finally, for P_{dis}, we observed a similar pattern for the two sites. ST was the main factor, accounting for 57% of total variance for LF and 44% for PF. On peat soil, RD also contributed 10% of the total variability, and the interaction ST x EI was also non-negligible (13%). At both sites, the percentage of variability explained exceeded 76%. This good fit was due to the inclusion of interactions in the MLR model, which took the mutual effects of multiple factors into account, unlike simple linear regression.

3.4 Model validation and prediction

Model validation for single-event predictions was satisfactory for runoff and partially satisfactory for sediment loss, according to the model evaluation indices. Indeed, NSE (optimal value = 1) was 0.3 for sediment losses and 0.4 for runoff data, while CRM (optimal value = 0) was 0.1 for sediment loss and 0.2 for runoff. R^2 of the regression line was equal to 0.61 and 0.32

for runoff and sediment loss, respectively, and residuals were randomly distributed. PBIAS (optimal value = 0) values were < 15% for both RO and sediment loss, meaning that predicted values were generally accurate. The model's difficulty in predicting sediment losses was due to a few poorly predicted events. These events had high EI values (> 90 MJ mm/(ha h)) that lay outside the range of values used to calibrate the MLR. This suggests that calibrating the linear model with more rainfall events, thus a wider range of RD and EI, should improve model predictions. However the total of measured values (sum of all monitored events) was predicted relatively well (relative error of observed *vs* predicted values < 20%). Thus, in these conditions, the use of MLR models is recommended for predicting over long time periods, rather than single events.

Table 7 shows annual values predicted by the model for 2007 and 2008. Predictions of eroded soil (always < 800 kg/(ha y)) at both sites are consistent with the values reported for plain croplands in Mediterranean regions (Kosmas et al., 1997; Martínez Raya et al., 2006; Terranova et al., 2009).

Concerning nutrients, model predictions lie within ranges of values reported in the literature, closer to the low values, and range from about 379-1118 g/(ha y) for dissolved N and 468-793 g/(ha y) for dissolved P (Vourenmaa et al., 2002; Hart et al., 2004; Ramos and Martìnez-Casanovas, 2006; Udawatta et al., 2006; Jiao et al., 2011; Sweeney et al., 2012). Although the N/P ratio was generally low (around 1:1), on peat soil this ratio was shifted in favour of dissolved N (mean N:P = 1.34), while on loam soil it was the opposite (mean N:P = 0.84). The higher SOM content of the former likely led to a larger release of N during mineralization. Assuming that the same ratio between dissolved and total N/P measured during the monitoring period is also maintained over the year for each CS, we can estimate total annual nutrient losses for each CS from the annual values of dissolved N/P predicted by the model. Estimated N losses range from 2.9-5.7 and 0.9-3.4 kg/(ha y) for PF and LF sites, respectively, while estimated P losses range from 0.7-2.0 and 0.6-1.7 kg/(ha y) for PF and LF sites, respectively.

4. Conclusions

The tested cropping systems (conventional, low-input and protective) affected significantly soil erosion and all correlated phenomena: runoff production, removal of the top soil layer, and dissolved and particulate nutrient losses. In our conditions cropping-system performances were however influenced by the environmental context; thus, the conventional system had higher environmental impact on the loam soil, while the low-input system had higher impact on the peat soil. The use of no-tillage and buffer-strips (Pro system) seemed to ensure, instead, the best soil conservation conditions at both sites.

From the productive point of view, the only significant differences were between the conventional and alternative systems: Low and Pro. The latter two had similar yields, and this led to the lower suitability of the Low system, which was dominated (*sensu* Pareto) compared to the Pro system (less environmentally friendly but equally productive). The choice between the Con and Pro system is more uncertain, although the yield advantage of the conventional system seems too moderate to make it preferable.

The simple linear regressions were useful for evaluating the contribution of different factors to explaining the results. In our experimental conditions, runoff was strongly influenced by rainfall (depth and intensity), but not by the cropping system, which instead significantly affected the soil erodibility.

The validation of multiple linear regression models on an independent dataset performed consistent single-event predictions for runoff while the estimates of sediment and nutrient losses were reliable only on annual basis. These results are comparable to those reported by other authors.

Some caution remains on the size of the dataset necessary to calibrate the MLR model; ours was probably not sufficient to represent the variability of the rainfall events that occurred during a long-term period.

Finally, the differences observed at the two sites confirmed the importance of carefully evaluating the suitability of agronomic management practices for the specific characteristics of the cultivated land when choosing a cropping system.

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Captions

Fig. 1. Rainfall depth, cumulative Erosion Index (EI) and crop stages (see the text) during the monitoring period. Continuous line-arrows indicate the interruption of the monitoring for the LF site and dotted line-arrows indicate the interruption of the monitoring for the PF site.

Table 1
The main characteristics of the soil for the two experimental sites: peat farm (PF) and loam farm (LF), in the 0-45 cm layer.

Characteristics	PF site			LF site		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
Sand (%)[1]	24.1	22.5	23.6	39.2	39.9	39.8
Silt (%)[1]	42.0	42.7	42.1	28.1	26.9	27.3
Clay (%)[1]	33.9	34.8	34.3	32.7	33.1	32.9
pH	5.4	5.5	5.5	8.2	8.2	8.3
Organic C (%)[2]	17.2	17.7	19.7	1.6	1.5	1.6
N Kjieldahl (‰)	6.9	7.4	7.5	1.3	1.3	1.3
P Olsen (mg/kg)	12.0	10.3	9.5	34.9	29.0	29.1

[1] USDA classification; [2] Walkey-Black method

Table 2
Main cultivation practices of conventional (Con), low-input (Low), and environmental protective (Pro) cropping systems

Operation	Con	Low	Pro
Main tillage	ploughing (25-30 cm deep)	rotary harrowing (7-10 cm deep)	direct drilling
N	280 kg/ha	170 kg/ha	170 kg/ha
sowing time	200 (broadcast)	120 (broadcast)	120 (banded)
top dressing	80 (banded)	50 (banded)	50 (banded)
P_2O_5	140 kg/ha	90 kg/ha	90 kg/ha
K_2O	90 kg/ha	60 kg/ha	60 kg/ha
Chemical weed control	pre-emergence (broadcast)	post-emergence (broadcast)	pre-emergence (banded)
Buffer strips	absent	absent	*Festuca arundinacea* cultivated at the field edge (2.0 m wide)
Seeding rate	8.3 seeds per m^2	8.3 seeds per m^2	8.3 seeds per m^2
Maize hybrid	FAO class 600	FAO class 600	FAO class 600

Table 3

Cumulative values of runoff volume (cRO), suspended solids (cSS), dissolved nitrogen (cN_{dis}), dissolved phosphorus (cP_{dis}), particulate nitrogen (cN_{par}), particulate phosphorus (cP_{par}), total nitrogen loss ($cN_{tot} = cN_{dis} + cN_{par}$) and total phosphorus loss ($cP_{tot} = cP_{dis} + cP_{par}$) for the three cropping systems (Con = conventional, Low = low-input and Pro = environmental protective), the two sub-periods (I and II, see the text) and the two sites (PF = peat farm and LF = loam farm)

Site	Sub-period	Cropping system	c-RO (m^3/ha/mm)	c-SS (kg/ha/mm)	c-N_{dis} (g/ha/mm)	c-P_{dis} (g/ha/mm)	c-N_{par} (g/ha/mm)	c-P_{par} (g/ha/mm)	c-N_{tot} (g/ha/mm)	c-P_{tot} (g/ha/mm)
PF	I	Con	1.30	1.28 ab	2.7 ab	1.1	10.1 ab	1.7 b	12.8 ab	2.8 b
		Low	1.57	2.03 b	3.8 a	1.3	15.8 a	2.9 a	19.5 a	4.2 a
		Pro	1.39	0.82 a	1.7 b	1.3	6.6 b	1.0 b	8.3 b	2.4 b
			$p = 0.1177$	$p = 0.0103$	$p = 0.0210$	$p = 0.5974$	$p = 0.0117$	$p = 0.0072$	$p = 0.0110$	$p = 0.0061$
PF	II	Con	0.94	0.67	1.0 ab	1.7	5.1	0.8	6.4	2.4 ab
		Low	1.04	0.93	1.6 a	1.8	7.2	1.4	8.8	3.2 a
		Pro	0.99	0.52	0.8 b	1.6	4.4	0.6	5.2	2.2 b
			$p = 0.1647$	$p = 0.2394$	$p = 0.0353$	$p = 0.7733$	$p = 0.2904$	$p = 0.1052$	$p = 0.2693$	$p = 0.0353$
LF	I	Con	1.15	4.22 a	1.8 ab	1.8	6.6 a	3.7 a	8.4 a	5.5 a
		Low	1.16	2.69 b	1.8 a	1.6	4.7 a	2.0 b	6.5 a	3.7 ab
		Pro	1.09	0.88 c	1.2 b	1.9	1.7 b	0.6 c	2.9 b	2.4 b
			$p = 0.5176$	$p = 0.0009$	$p = 0.0320$	$p = 0.8092$	$p = 0.0013$	$p = 0.0005$	$p = 0.0012$	$p = 0.0014$
LF	II	Con	1.16 ab	1.56 a	0.8	2.0 ab	2.7 a	1.1 a	3.4 a	3.1 a
		Low	1.19 a	0.88 b	0.8	2.6 a	1.5 b	0.7 b	2.3 b	3.2 a
		Pro	1.06 b	0.57 b	0.8	1.4 b	1.2 b	0.4 c	2.0 b	1.8 b
			$p = 0.0214$	$p = 0.0032$	$p = 0.7031$	$p = 0.0127$	$p = 0.0083$	$p = 0.0033$	$p = 0.0072$	$p = 0.0052$

Table 4

Production of maize grown under conventional (Con), low-input (Low) and environmental protective (Pro) cropping system for the two experimental sites: peat farm (PF) and loam farm (LF).

Cropping system	Grain yield (t/ha)			
	PF site		LF site	
	2007	2008	2007	2008
Con	11.30 a	11.94 a	9.97 a	8.55 a
Low	9.60 b	9.25 b	7.50 b	6.41 b
Pro	10.44 ab	9.32 b	8.08 b	6.39 b
	p = 0.0189	p = 0.0078	p = 0.0032	p = 0.0381
	Above ground biomass (t/ha)			
	PF site		LF site	
	2007	2008	2007	2008
Con	20.70 a	25.45 a	19.15 a	18.13 a
Low	16.77 b	19.23 b	15.91 b	12.87 b
Pro	18.56 ab	18.23 b	16.56 b	12.74 b
	p = 0.0490	p = 0.0057	p = 0.0027	p = 0.0096
	Harvest index (%)			
	PF site		LF site	
	2007	2008	2007	2008
Con	54.6	46.9	51.9 a	47.2
Low	57.2	48.3	47.1 b	49.9
Pro	56.3	51.3	48.6 ab	50.2
	p = 0.1242	p = 0.2221	p = 0.0351	p = 0.4142

Table 5

Coefficient of determination (R^2) of each factor for each dependent variable: runoff volume (RO), suspended solids (SS), dissolved nitrogen (N_{dis}), dissolved phosphorus (P_{dis}) and electrical conductivity (CE), * means statistically singnificant correlation with $p < 0.05$

Site	Factor	Coefficient of determination (R^2)				
		RO	SS	N_{dis}	P_{dis}	CE
PF	Rainfall depth (RD)	0.78*	0.02*	0.15*	0.02*	0.23*
	Erosion index (EI)	0.35*	0.02*	0.07*	0.09*	0.00
	Runoff (RO)	-	0.00	0.09*	0.01	0.16*
	Cropping system (CS)	0.00	0.23*	0.03	0.00	0.01
	Stage (ST)	0.09*	0.20*	0.15*	0.44*	0.18*
LF	Rainfall depth (RD)	0.77*	0.03*	0.11*	0.00	0.03*
	Erosion index (EI)	0.37*	0.02*	0.05*	0.12*	0.05*
	Runoff (RO)	-	0.07*	0.05*	0.01	0.00
	Cropping system (CS)	0.00	0.25*	0.00	0.03*	0.00
	Stage (ST)	0.11*	0.12*	0.13*	0.57*	0.50*

Table 6

Percentage of explained variance and p value of multiple linear regression (MLR) model (including all the factors and their interactions) for each dependent variable: runoff volume (RO), suspended solids (SS), dissolved nitrogen (N_{dis}), dissolved phosphorus (P_{dis}) and for the two study sites: peat farm (PF) and loam farm (LF)

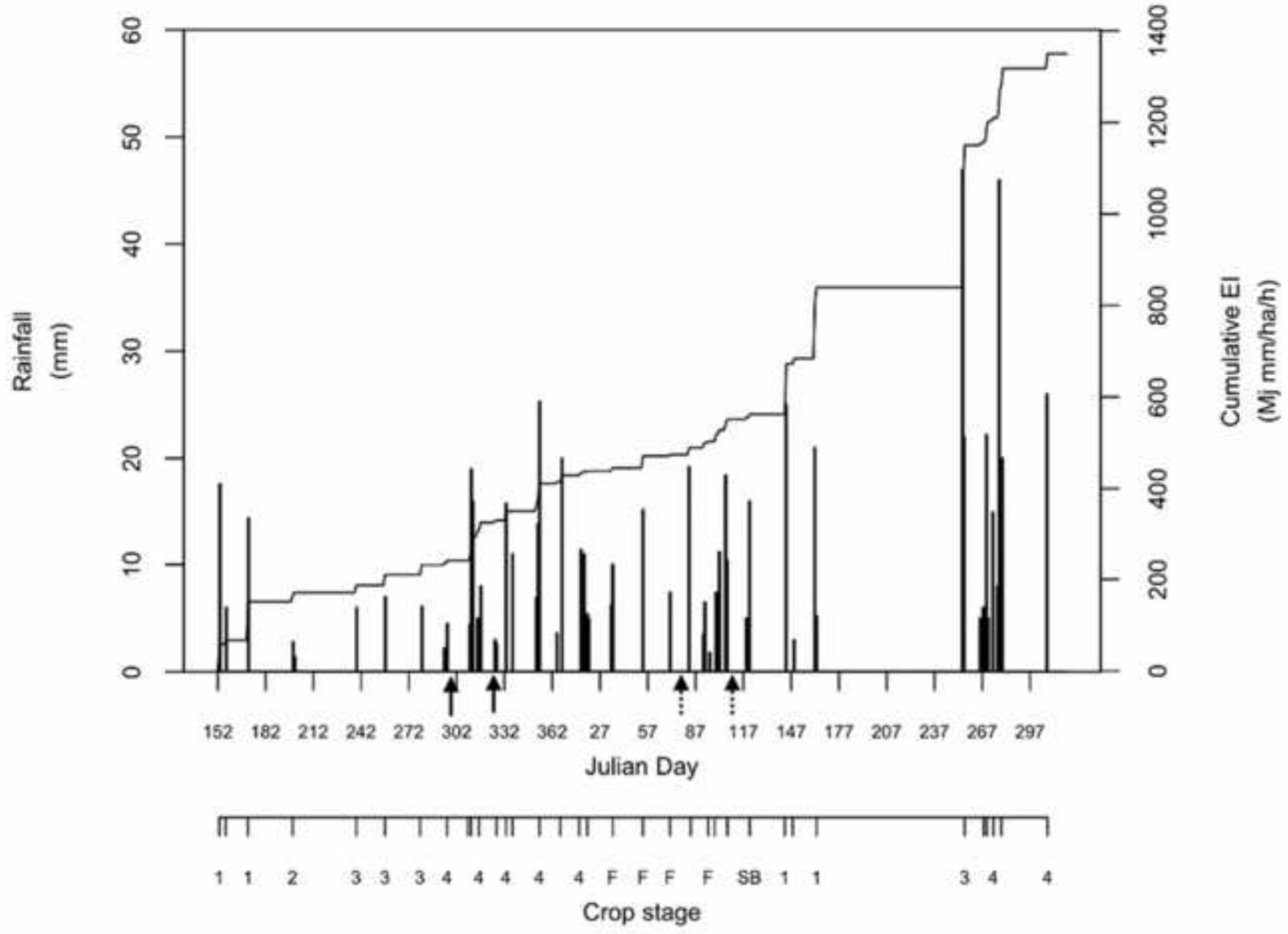
Factors and fitting	Site	RO		TSS		N_{dis}		P_{dis}	
		% variance	p	% variance	p	% variance	p	% variance	p
Rainfall depth (RD)	LF	76.86	2.20E-16	0.79	4.54E-02	5.95	3.59E-08	4.49	2.20E-16
Erosion index (EI)	LF	0.26	3.49E-02	1.83	2.38E-03	0.01	8.43E-01	0.08	3.57E-01
Runoff (RO)	LF	-	-	3.08	8.97E-05	2.77	2.06E-04	0.12	2.50E-01
Cropping system (CS)	LF	0.84	7.67E-04	25.13	2.20E-16	0.38	3.51E-01	3.03	1.28E-07
Stage (ST)	LF	2.23	7.82E-07	13.65	4.58E-12	12.62	8.29E-12	61.45	2.20E-16
RD x EI	LF	1.04	2.80E-05	0.02	7.52E-01	2.04	9.90E-04	0.89	1.80E-03
RD x RO	LF	-	-	0.05	5.97E-01	0.31	1.93E-01	0.60	1.41E-04
RD x CS	LF	0.05	6.28E-01	0.29	4.75E-01	0.16	1.68E-02	0.19	3.40E-01
RD x ST	LF	0.94	6.57E-03	0.66	6.38E-01	19.67	2.20E-16	1.90	8.95E-08
EI x RO	LF	-	-	0.97	2.62E-02	0.34	1.72E-01	0.32	6.02E-02
EI x CS	LF	0.07	5.26E-01	1.17	5.09E-02	0.68	8.30E-01	0.36	1.36E-01
EI x ST	LF	3.66	2.39E-12	3.10	1.45E-03	6.25	5.32E-07	3.13	3.54E-07
RO x CS	LF	-	-	0.13	7.21E-01	1.02	1.22E-01	0.72	1.89E-02
RO x ST	LF	-	-	1.89	8.75E-02	4.99	9.18E-05	1.96	7.65E-04
CS x ST	LF	1.93	1.07E-04	5.72	6.79E-04	1.46	6.37E-01	2.32	2.68E-03
residuals	LF	12.12		41.51		41.36		18.44	14.04
adjusted R^2	LF	-	0.8624	-	0.5101	-	0.5106	-	0.7960
adjusted R^2 reduced model	LF	-	0.8595	-	0.5063	-	0.5055	-	0.7930
Rainfall depth (RD)	PF	78.42	2.20E-16	8.03	3.30E-11	11.82	2.92E-12	9.84	1.04E-02
Erosion index (EI)	PF	0.06	2.61E-01	0.42	1.11E-01	0.29	2.49E-01	1.06	1.04E-03
Runoff (RO)	PF	-	-	0.09	4.59E-01	9.88	1.20E-10	0.18	1.70E-01
Cropping system (CS)	PF	0.37	2.86E-02	22.65	2.20E-16	4.20	8.94E-05	0.22	3.18E-01
Stage (ST)	PF	1.30	1.87E-04	16.05	3.86E-16	15.11	7.15E-12	45.53	2.20E-16
RD x EI	PF	3.03	4.10E-13	0.49	8.51E-02	0.88	4.49E-02	4.06	4.93E-10
RD x RO	PF	-	-	0.84	2.48E-02	3.45	8.67E-05	0.03	5.97E-01
RD x CS	PF	0.02	8.43E-01	1.30	2.10E-02	0.28	6.64E-01	0.49	7.59E-03

RD x ST	PF	1.61	1.62E-05	2.62	8.65E-03	0.73	6.40E-01	0.52	1.47E-01
EI x RO	PF	-	-	0.06	5.42E-01	1.37	1.25E-02	1.23	4.25E-04
EI x CS	PF	0.03	7.18E-01	0.69	1.27E-01	0.25	1.78E-01	0.03	7.69E-01
EI x ST	PF	4.48	5.86E-16	3.04	5.08E-04	0.49	5.17E-01	12.98	2.20E-16
RO x CS	PF	-	-	0.39	3.09E-01	0.74	7.38E-02	0.15	2.29E-01
RO x ST	PF	-	-	4.57	7.87E-05	4.20	2.12E-03	2.25	4.26E-04
CS x ST	PF	0.14	8.52E-01	0.78	9.13E-01	2.28	3.95E-01	0.48	8.97E-01
residuals	PF	10.55		37.96		44.04		20.98	10.68
adjusted R^2	PF	-	0.8801	-	0.5493	-	0.4720	-	0.7630
adjusted R^2 reduced model	PF	-	0.8837	-	0.5657	-	0.4814	-	0.7638

Table 7
Annual values (full year 2007 and 2008) of runoff volume (RO), suspended solids (SS), dissolved nitrogen (N_{dis}), dissolved phosphorus (P_{dis}) estimated by the multiple linear regression (MLR) model for the conventional (Con), low-input (Low) and environmental protective (Pro) cropping system in the two experimental sites: peat farm (PF) and loam farm (LF)

Site	Cropping system	2007				2008			
		RO (m^3/ha)	SS (kg/ha)	N_{dis} (g/ha)	P_{dis} (g/ha)	RO (m^3/ha)	SS (kg/ha)	N_{dis} (g/ha)	P_{dis} (g/ha)
PF	Con	414	374	980	527	537	315	714	724
	Low	438	493	1118	606	557	532	980	793
	Pro	404	194	596	527	433	204	488	532
LF	Con	463	557	433	571	576	744	488	675
	Low	453	384	453	631	601	532	1172	749
	Pro	424	197	379	665	507	261	379	468

Figure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(mm)
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10
20
30
40
50
60
Cumulative EI
(Mj mm/ha/h)
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400
600
800
1000
1200
1400
152
182
212
242
272
302
332
362
27
57
87
117
147
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267
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Julian Day
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Crop stage