Reducing flood risk from sediment-laden agricultural runoff using intercrop management techniques in northern France

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Received 18 June 1998; received in revised form 1 April 1999; accepted 14 September 1999

Abstract

To reduce muddy flooding in northern France, where soils are typically silty and highly sensitive to crusting, it is necessary to decrease the volumes of sediment-laden runoff coming from upslope agricultural source areas. To investigate the consequences of upslope agricultural practices on downslope muddy flooding, we compared the effects of no-tillage treatment (NT), light-duty mouldboard ploughing (PLOUG), mustard (Sinapis alba L.) intercrop (MUSTA) and superficial tillage with a cultivator applied either under dry (ECULT) or humid conditions (LCULT). The influence of these different treatments were measured on soil surface modifications and on both runoff and sheet erosion during the entire intercrop period. Field trials were conducted in the Pays de Caux (Normandie), over two years (1993–1994 and 1994–1995) under natural rainfall conditions on 20 m² experimental plots on Orthic Luvisols. In 1993–1994, the post-harvest field conditions were wheat (Triticum aestivum L.) with pulverized straw, wheat without straw and pea (Pisum sativum L.) without straw. Only the pea post-harvest conditions were used in 1994–1995. The tortuosity index and percentage of surface area covered by vegetation, which were used for soil surface description, indicate the role played by surface cover and soil water during tillage in modifying surface roughness. In 1994–1995, due to specific agronomic and climatic conditions, the five intercrop management techniques did not differ significantly at \( P < 0.10 \) for runoff and erosion. In 1993–1994, considering average values for both the three post-harvest conditions and 10 recorded rainfall events, NT resulted in low erosion (40 kg ha\(^{-1}\)) but high runoff (6.1 mm). Compared to NT, MUSTA significantly (\( P < 0.10 \)) reduced runoff (1.5 mm) without significantly increasing erosion (82 kg ha\(^{-1}\)); LCULT led to an increase in both runoff (12.4 mm) and erosion (301 kg ha\(^{-1}\)); PLOUG increased erosion (182 kg ha\(^{-1}\)) but reduced runoff (3.2 mm) and ECULT increased erosion (247 kg ha\(^{-1}\)) without reducing runoff (7.1 mm). These results specify the dynamics of runoff and sheet erosion, thus providing an aid for locating intercrop management techniques within a catchment basin according to the local erosive system and agronomic constraints. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Runoff; Sheet erosion; Intercrop management techniques; Soil surface modification

1. Introduction

Over the last ten years, flood frequency has increased in northwestern Europe (Boardman et al., 1994). These floods are often called “muddy floods”
and are generated by overland flow heavily laden with sediments eroded from agricultural land. Although storage basins located downstream of agricultural land are useful in preventing floods, their high maintenance cost — due to rapid infilling by sediments — necessitates a reduction of the sediment-laden runoff volume coming from upslope agricultural source areas. A better understanding of the effects of cropping systems on erosion processes is required to achieve a reduction in runoff volume.

In northwestern Europe, the majority of soils are silty and very sensitive to crusting. A crust develops even under rain intensities as low as 1–2 mm h\(^{-1}\) (Boiffin and Monnier, 1985). On the field scale, crusting determines the production of overland flow loaded with soil particles derived from sheet erosion. On the scale of the catchment basin, overland flow coming from fields concentrates along the valley bottoms (thalwegs) and generates rill or gully erosion (Auzet et al., 1990; Ludwig et al., 1995). Rill and gully erosion increases sediment concentration as well as the risk of muddy flooding downstream (Le Bissonnais et al., 1996).

This study is focused on the production of runoff with a sediment load derived from sheet erosion, and was carried out at the field scale during the intercrop period. The intercrop period (approximately from August to February) combines not only high runoff risks (Papy and Douyer, 1991) but also some opportunities for reducing the runoff. Indeed, the absence of a crop makes it possible to follow a large range of cultivation practices in an effort to facilitate water infiltration and thus reduce runoff. In this study, particular attention was paid to the dynamics of runoff and sheet erosion, because both phenomena are closely related to surface soil conditions that vary with time.

The aim of this study was to detail the effects of a range of intercrop management techniques (IMTs) on both runoff and sheet erosion, and to determine how these effects could be explained by soil surface modifications during the intercrop period.

2. Materials and methods

2.1. Site and climate descriptions

The studied area is located in the “Pays de Caux”, in the north of France near Rouen, within a region that has experienced numerous muddy floods over the last 10 years (Papy and Douyer, 1991). The region consists of an extensive plateau with gentle slopes (less than 3%) covered by silty loams containing 10–12% clay, which are developed from loess and are very sensitive to crusting. The experiments were conducted under natural rainfall on agricultural fields chosen as representative of the silty loams of the region, which are classified according to the Food and Agricultural Organization (FAO) system as Orthic Luvisols. The study included two intercrop periods (1993–1994 and 1994–1995). For crop-rotation reasons, it was not possible to carry out the same experiment on the same site in 1994–1995 as in 1993–1994. Although the two sites are less than 1 km apart, their soils are fairly similar in texture \(130 \text{ g kg}^{-1}\) clay, \(600 \text{ g kg}^{-1}\) silt, \(270 \text{ g kg}^{-1}\) sand), slope (\(2\%\)), organic-matter content (\(0.144 \text{ kg kg}^{-1}\)) and crop history [potato \((\text{Solanum tuberosum} L.)\) followed by wheat \((\text{Triticum aestivum} L.)\) as preceding crops].

Rainfall was greater than average in the two years of experimental trials. The median value calculated over a period of 21 years for cumulative rainfall in the intercrop period (from 1 August to 10 February) is 439 mm. By contrast, during 1993–1994 and 1994–1995, cumulative rainfall for this intercrop period was 514 and 682 mm, respectively. Nevertheless, the rainfall pattern was characteristic of a local low-erosive type (Pihan, 1978): rainfall intensity peaks never exceeded 50 mm h\(^{-1}\) (calculated on a 4 min duration) and mean rainfall intensities never exceeded 4 mm h\(^{-1}\).

The experimental treatments applied in this study are IMTs tested under various post-harvest field conditions. An IMT is defined by the tillage tool and climatic conditions at the time of tillage. Two sets of climatic conditions are defined here. These are favourable conditions for the control of runoff and erosion, corresponding to a low amount of water in the soil during tillage combined with a dry period after tillage (Boiffin and Sebillotte, 1976; Johnson et al., 1979), and unfavourable conditions, corresponding to a high amount of water in the soil during tillage combined with a wet period after tillage. Favourable conditions for the Pays de Caux are common in August whereas unfavourable conditions prevail after September (Martin, 1997).
Five IMTs were designed on the basis of expected differences in soil behaviour, derived from various data compiled from the scientific literature. The “PLOUG” treatment consisted of light-duty mouldboard ploughing (15 cm) was applied under favourable climatic conditions (30/08/93 and 22/08/94 for 1993–1994 and 1994–1995 experiments, respectively). It was expected that this IMT would bury all the crop residues and create a very rough surface but without producing any pronounced ridges. The initial high random roughness and low oriented roughness (Allmaras et al., 1966) were expected to delay runoff (Boiffin, 1985; Trevisan, 1986; Pié, 1989). The presence of unprotected large clods was expected to allow detachment of soil particles throughout the intercrop period (Norton et al., 1985; Moore and Singer, 1990).

The “MUSTA” corresponds to a mustard intercrop (Sinapis alba L.) sown under favourable climatic conditions (same tilling date as for PLOUG). Seedbed preparation was expected to leave the surface with smaller clods and consequently, a lower roughness (both random and oriented), than for PLOUG. Such a surface is potentially more sensitive to crusting than the surface obtained with PLOUG (Boiffin, 1985; Freebairn et al., 1991). The rapid development of the mustard canopy was expected to limit the runoff in a very short time (de Ploey, 1982; Meek et al., 1992) and also reduce sheet erosion despite the low initial roughness.

The “ECULT” (early cultivation) consisted of superficial tillage (10 cm) with a light rigid tine cultivator equipped with a goose-foot shovel set. The tilling date for ECULT was the same as for PLOUG and MUSTA. The ECULT was expected to bury crop residues only partially and thus create pronounced ridges. Random roughness was expected to be intermediate between “PLOUG” and “MUSTA”. High oriented roughness and medium random roughness were expected to facilitate both runoff and erosion (Stein et al., 1986). However, crop residues located at the top of the ridges were expected to reduce soil particle detachment compared to PLOUG (McCalla and Army, 1961). Runoff would be concentrated in the furrows.

The “LCULT” (late cultivation) consisted of the same tillage operation as ECULT, but was done under unfavourable climatic conditions (05/10/93 and 29/11/94 for 1993–1994 and 1994–1995 experiments, respectively). Before tilling, LCULT soil behaviour was expected to be identical to NT (described below). After tilling, soil degradation — and therefore runoff and erosion — was expected to be worse than with ECULT (Boiffin and Sebillotte, 1976; Johnson et al., 1979).

The “NT” was a strict no-tillage treatment. The post-harvest crusted soil surface was not fragmented during the intercrop period. The NT treatment was expected to lead to most extensive residue cover of the five IMTs tested in this study. It was also expected to result in the most runoff since crusting was not initially present after applying the other IMTs. Nevertheless, the high shear resistance of the crust, the increase in water depth on the soil surface (Moss and Green, 1983) and the extended surface cover (McCalla and Army, 1961) were assumed to limit erosion throughout the intercrop period.

The five IMTs described above are representative of farming practices in the Pays de Caux (Martin, 1997). In 1993, ECULT was the most frequently applied technique for early harvests (before September). The LCULT was the equivalent of ECULT in case of late harvests (after September). The PLOUG technique is widespread on dairy farms because it is useful to bury farm manure. The MUSTA system corresponds to a technique recommended by local authorities for the control of diffuse (non-pinpoint) nitrate pollution. It was not well known by farmers in 1993. Although the low cost of NT was attractive to farmers in 1993, it is not very widely used by them.

In 1993–1994, the five IMTs were applied on three post-harvest field conditions: wheat (Triticum aestivum L.) field without straw (W), wheat field with pulverised straw (WP) and spring pea (Pisum sativum L.) field without straw (P). The W, WP and P conditions corresponded to different percentages of crop residue cover: 100% for WP, 60% for W and 30% for P. For technical reasons, a mouldboard ploughing (30 cm) preceded mustard sowing for the W and WP conditions, whereas direct sowing was used for the P conditions. In 1994–1995, the five IMTs were implemented on only one post-harvest field condition: spring-pea field without straw (P) corresponding to a crop residue cover of 35%. The reduction of experimental treatments came from the decision to focus attention on the effects of IMTs.
Two replicated experimental 20 m$^2$ plots (1.80 × 11.1 m) were used. Plots were delimited by earthen dykes and equipped with collector tanks of 75 l capacity. Tillage dates were fixed according to local meteorological estimates. This method generally led to expected values for both 1993–1994 and 1994–1995 (Table 1). Indeed, dates chosen for favourable climatic conditions (31/08/93 and 22/08/94) led to lower soil water contents when tilling and higher values of rainfall–evaporation after tilling than did dates chosen for unfavourable climatic conditions (05/10/93 and 29/11/94).

2.2. Measurements of rainfall, runoff and soil loss

Each year, runoff and soil loss from each plot were monitored from the end of August to the end of January. Rainfall amount and intensity were measured with an automatic recording rain gauge. Runoff volume was measured after each rainfall event by emptying the collector tanks with a graduated container corresponding to a precision of 0.125 l. Soil loss was calculated from a 250 cm$^3$ sample taken from the tank after stirring to suspend the sediment. Only events that did not lead to tank overflow were taken into account for statistical analysis. For each year, 10 events of this type were recorded, corresponding to 24% of the total rainfall during the intercrop period in 1993–1994 as compared with 29% in 1994–1995.

2.3. Monitoring surface soil condition

The surface soil condition was monitored approximately once a month. Two main parameters were studied: the percentage of soil surface covered by both live vegetation and crop residues (VEG) and the tortuosity index (TI). The VEG was calculated from planimetric measurements on colour slides (four slides for each plot and date). The TI was defined for a one dimensional transect (Boiffin, 1984) as

$$\text{TI} = \frac{L-L_0}{L_0},$$

where $L$ is the actual length of the profile, and $L_0$ is the projected horizontal length of the profile curve. Bertuzzi et al. (1990) have shown that TI is a good indicator of the microrelief decrease under rainfall. In the present study, TI was measured with a 2-m-long frame equipped with 156 retractable needles. The measurement was located in the tillage direction in the furrow for PLOUG, ECULT and LCULT, and randomly for the other treatments.

3. Results and discussion

3.1. Modifications of surface soil condition

In 1993–1994, immediately after tillage (02/09/93), all tillage operations led to an increase in TI in comparison with no-tillage (Table 2). With no-tillage treatment, the TI remained constant throughout the intercrop period, while, for the other techniques, the TI decreased after the tilling date. The rate of decrease varied strongly depending on the IMT used. The PLOUG led to the highest mean initial TI, but, at the end of January, it was significantly lower than for NT ($P < 0.05$). The initial TI of MUSTA was much lower than for NT, but increased strongly in the intercrop period.
lower than for PLOUG, but, after tillage, it decreased sharply initially and then more slowly at a constant rate. From 20 October 1993 onwards, the TI of MUSTA was slightly higher than for PLOUG, but the difference is not significant at $P < 0.05$. At the end of January, MUSTA was the only IMT that had a TI as high as NT (difference not significant at $P < 0.05$).

Variations for ECULT were similar to those obtained for PLOUG. The initial TI for LCULT was the lowest of all the treatments (same as NT). At the tillage date (05/10/93), LCULT had the greatest TI, but after that it decreased dramatically. From 05/10/93 to 20/10/93, following 92 mm of cumulative rainfall, the TI for LCULT decreased by 32.9 units compared to only 3.7 for ECULT.

The PLOUG treatment led to an almost bare surface during most of the intercrop period 1993–1994 (Table 2). This is probably the cause of the rapid decrease in TI described above. With MUSTA, there was only a slight cover at the beginning of the experiment. The canopy then developed and reached a peak at the end of October; it subsequently decreased due to destruction by frost. At the end of the experiment, the canopy still covered 32% of the surface. The bare soil observed for MUSTA at the beginning of the experiment probably led to the sharp decrease in TI as noted

![Table 2](image-url)

Variation of soil surface state for 1993–1994 intercrop period

<table>
<thead>
<tr>
<th>IMT</th>
<th>Post-harvest conditions</th>
<th>Surface state parameters</th>
<th>Soil surface covered by both live vegetation and crop residues (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TI (%)</td>
<td>05/10/93</td>
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<tr>
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<td>12.6</td>
</tr>
<tr>
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<tr>
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<td></td>
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<td>11.4 a</td>
</tr>
<tr>
<td>MUSTA WP</td>
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<td>18.5</td>
<td>9.4</td>
</tr>
<tr>
<td>W</td>
<td></td>
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<tr>
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<td></td>
<td>19.8 b</td>
<td>9.6 a</td>
</tr>
<tr>
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<td>9.2</td>
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<tr>
<td>W</td>
<td></td>
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<td>8.5</td>
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<tr>
<td>P</td>
<td></td>
<td>25.4</td>
<td>5.5</td>
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<tr>
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<td></td>
<td>26.7 c</td>
<td>7.7 a</td>
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<tr>
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<td>37.0</td>
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<tr>
<td>W</td>
<td></td>
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<tr>
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<td>35.4 b</td>
</tr>
<tr>
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<td>5.7</td>
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<tr>
<td>W</td>
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<td>P</td>
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<td>3.2</td>
<td>3.2</td>
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<tr>
<td>Mean</td>
<td></td>
<td>4.8 a</td>
<td>4.9 a</td>
</tr>
</tbody>
</table>

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*a Precisions on the dates 02/09/1993: immediately after tillage for PLOUG, MUSTA and ECULT; 05/10/1993: immediately after tillage for LCULT and 130 mm of cumulative rainfall since 02/09/1993; 20/10/1993: 222 mm of cumulative rainfall since 02/09/1993 and 92 mm since 05/10/1993; 20/01/1994: end of experiment. 502 mm of cumulative rainfall since 02/09/1993 and 372 mm since 05/10/1993.

b “Mean” is the mean value for the 3 post-harvest conditions (WP: wheat field with pulverized straw; W: wheat field without straw; P: spring-pea field without straw). The tillage treatments were: mustard intercrop (MUSTA), mouldboard ploughing (PLOUG), early cultivation (ECULT), late cultivation (LCULT) and no-tillage (NT). Mean values for treatment at a given date followed by the same letter do not differ significantly at $P < 0.05$. 

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The PLOUG treatment led to an almost bare surface during most of the intercrop period 1993–1994 (Table 2). This is probably the cause of the rapid decrease in TI described above. With MUSTA, there was only a slight cover at the beginning of the experiment. The canopy then developed and reached a peak at the end of October; it subsequently decreased due to destruction by frost. At the end of the experiment, the canopy still covered 32% of the surface. The bare soil observed for MUSTA at the beginning of the experiment probably led to the sharp decrease in TI as noted
above. Canopy development then limited the reduction in TI. With NT, there was a considerable initial soil cover composed mainly of crop residues. The surface cover decreased only slightly because the progressive decomposition of residues was compensated by weed development. In the case of ECULT, soil cover was initially made up of crop residues. The mild weather of August (mean temperature of 16°C in 1993–1994) led to weed growth. Soil cover for LCULT at the tillage date comprised a mixture of numerous crop residues and some weed residues that had been only partly rooted out by cultivation. The cool weather of October (mean temperature of 10°C in 1993–1994) did not allow the development of vegetative cover after tillage. As expected (cf. Section 2.1), the residue cover for ECULT and LCULT was localized on ridges and could not protect soil roughness in the furrows.

In 1993–1994, except for a lower surface cover, the behaviour observed with “Pea” intercrop conditions did not differ a lot from the behaviour observed with W and WP conditions. The lower vegetative cover obtained with “Pea” MUSTA was probably due to differences in seedbed preparation. Ploughing associated with W and WP conditions certainly facilitated root growth because it brought humid soil up to the surface.

Direct sowing of Pea led to a drier seedbed, and that caused poor plant establishment since August and early September were dry (31 mm of rainfall from 1 August to 10 September 1993, whereas the median value is 66 mm). The development of the surface cover was much greater in 1994–1995 than in 1993–1994 (Table 3). This was due to warmer and more humid conditions in 1994–1995 than in 1993–1994 (mean temperature of 18°C in August 1994–1995, and 114 mm of rainfall from 1 August to 10 September 1994). This rapid development led to a smaller decrease in TI, especially for PLOUG and MUSTA. In the case of MUSTA, the rainier weather in 1994–1995 cancelled out the disadvantage of direct sowing noted in 1993–1994.

Modifications of surface soil conditions during both intercrop periods are consistent with the basic assumptions behind the tested management techniques. Tillage leads to an increase in soil surface roughness that depends on the tillage tool used. After tillage, soil surface roughness is seen to decrease under the effect of rainfall so that the soil surface sometimes becomes less rough than before tillage (LCULT in 1993–1994 but not in 1994–1995). Soil tillage under “unfavourable conditions” (LCULT) leads to a relatively high TI that decreases rapidly with cumulative rain. The same tillage under “favourable conditions” leads to better soil resistance for the same amount of rainfall. This is particularly true in the absence of a real soil cover, i.e. ECULT compared to LCULT for 1993–1994 pea conditions. This reinforces the hypothesis of weaker structural stability when tilling is carried out under humid conditions (Boiffin and Sebillotte, 1976). In

<table>
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<tr>
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<th>Soil surface covered by both live vegetation and crop residues (%)</th>
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<tbody>
<tr>
<td></td>
<td>TI (%)</td>
<td>22/08/94</td>
</tr>
<tr>
<td>PLOUG</td>
<td>28.7 b</td>
<td>13.4 a</td>
</tr>
<tr>
<td>MUSTA</td>
<td>13.9 ab</td>
<td>11.0 a</td>
</tr>
<tr>
<td>ECULT</td>
<td>27.6 b</td>
<td>5.2 a</td>
</tr>
<tr>
<td>LCULT</td>
<td>5.0 a</td>
<td>31.7 b</td>
</tr>
<tr>
<td>NT</td>
<td>5.0 a</td>
<td>4.4 a</td>
</tr>
</tbody>
</table>

some cases, favourable climatic conditions also allow
development of a soil cover that protects the soil
surface, i.e. wheat with and without straw post-harvest
conditions in 1993–1994 and pea post-harvest condi-
tions in 1994–1995. Two ways of maintaining high TI
were observed. The first way consists of creating, in
dry conditions, a sufficient roughness without vege-
tative protection (PLOUG). The second way consists
of sowing a cover crop on a less cloddy surface
(MUSTA). In the two years of experimentation,
despite a greater initial roughness, PLOUG led to
lower final values of tortuosity than did MUSTA. This
supports the protective effect of a cover crop sown
early in the intercrop period. The PLOUG treatment
led to a final TI still higher than that obtained with
LCULT or even ECULT. These results also clearly
reveal the effect of climate on soil condition modi-
cation. In the second year, a rainy and warm period
allowed the development of an important pea canopy
that was not observed in the first year, which was drier
at the same period. The pea canopy slowed degrada-
tion of the soil surface.

3.2. Runoff and soil erosion

The five IMTs led to significant differences
\((P < 0.10)\) for the 10 recorded events in 1993–1994
(31 August–31 January) for both accumulated runoff
and accumulated erosion. As illustrated in Fig. 1, in
1993–1994, for all post-harvest conditions, MUSTA
led to the lowest amount of accumulated runoff and LCULT to the highest amount (average value of 1.5 mm for MUSTA and 12.4 mm for LCULT). PLOUG led to a similar runoff as with MUSTA, while ECULT led to the same runoff as NT. In 1993–1994, NT led overall to the lowest erosion (Fig. 1). The NT and MUSTA treatments differed only in the case of wheat with pulverized straw conditions ($P < 0.10$). The PLOUG, ECULT and LCULT treatments gave similar results for both wheat conditions, but not for the pea conditions, where LCULT led to significantly greater erosion than PLOUG (633 and 176 kg, respectively).

In 1994–1995, cumulative runoff from pea treatment was from half (NT) to one tenth (MUSTA) of the runoff obtained for pea in 1993–1994 (Fig. 1) and did not differ significantly among IMTs ($P < 0.10$). Nevertheless, as in 1993–1994, the lowest values were obtained with MUSTA and PLOUG. Erosion rates in 1994–1995 were also much lower than those obtained for pea in 1993–1994, but the differences among IMTs were significant ($P < 0.10$). LCULT led to more erosion than MUSTA. No real differences appeared among the other treatments.

Breaking the inherited surface crust usually led to a reduction in runoff (PLOUG and MUSTA compared with NT). This is consistent with results of Boiffin and Monnier (1985). However, our results suggest that soil surface fragmentation could also lead to an increase in overall runoff (case of ECULT and LCULT). Moreover, tillage the soil during the intercrop period seems to increase soil loss, especially if the soil is tilled under humid conditions (LCULT). This trend is in agreement with results of Johnson et al. (1979). The fact that a non-tilled surface generates little soil loss, even with reduced surface cover, shows that soil crustling diminishes soil surface erodibility (Moore and Singer, 1990) and leads to an increased water depth that acts as a protective screen (Moss and Green, 1983). The low runoff rates obtained with PLOUG indicate that soil tillage leading to an unprotected surface can nevertheless limit runoff provided that it also gives rise to a cloddy surface. However, this type of operation also seems to increase soil loss in comparison with no-tillage. This disadvantage disappears with MUSTA, which, compared with NT, leads to reduced runoff without significantly increasing the soil loss. Effects due to the canopy probably include interception of rainfall energy, roughness protection and preferential infiltration at the stem base (McCalla and Army, 1961; de Ploey, 1982; Martin, 1997).

Cumulative values of muddy runoff appear to result from dynamic phenomena. In 1993–1994, differences in runoff appeared progressively among the five IMTs during the intercrop period (Fig. 2). After 100 mm cumulative rainfall (second analysed rainfall event), NT and ECULT led to more runoff than PLOUG and MUSTA. With LCULT, tillage occurred after 130 mm of cumulative rainfall. Hence, between 0 and 130 mm, the soil surface behaved in the same way as with NT. For the fourth event (277 mm), which corresponds to the first event recorded with LCULT after tillage, runoff with LCULT remained identical to runoff with NT. Over the same period, runoff with PLOUG and MUSTA did not differ. For the fifth event (472 mm), there was an increase in runoff for both LCULT compared with NT and for PLOUG compared with MUSTA. At the same time, runoff with ECULT and NT were similar. In 1994–1995, compared to 1993–1994 (Fig. 2), trends were the same for NT, MUSTA, PLOUG. Moreover, after the fourth event, the ECULT and NT curves became parallel as in 1993–1994.

Compared to 1993–1994, the relative positions of NT and LCULT are reversed.

Differences of erosion also appeared progressively during 1993–1994 (Fig. 2). With LCULT, soil erosion was at a minimum before tillage (identical to NT). After tillage, erosion rate increased suddenly and exceeded the rates associated with other treatments. The ECULT led to a final erosion value equivalent to that obtained with LCULT, but most of the erosion occurred earlier during the first three rainfall events. During this period, PLOUG led to less erosion than ECULT, but, after the third event, the cumulative curves became parallel. During the third event, MUSTA led to an erosion rate of the same order as observed with PLOUG. After that, little soil loss occurred for MUSTA, whereas it slowly increased for PLOUG. In 1994–1995, we reproduced the same increasing erosion rate after tillage for LCULT and the relative positions of MUSTA and PLOUG.

In order to relate both runoff and erosion dynamics to variations in soil condition, a few individual events were chosen close to the dates of observing the soil condition (only for 1993–1994 intercrop: 14/09/1993,
For each of these events, the results of different IMTs (average of P, W and WP) are plotted on a graph of erosion versus runoff (Fig. 3). In this study, we analyse the relative positions rather than the absolute values of runoff and erosion.

For the rainfall event on 14/09/1993, two groups can be distinguished: NT and LCULT showed high runoff volumes but low soil losses, while MUSTA, PLOUG and ECULT had lower runoff volumes but greater soil losses. For MUSTA, PLOUG and ECULT, the soil surface had been tilled two weeks before the rain event...
(55 mm of cumulative rainfall occurred since tillage). With these techniques, crusting was still not widespread on 14/09/1993 and the TI remained high (Table 2). NT presented a low TI and an inherited crust. The LCULT plot had not yet been tilled and resulted in a similar soil surface to that of NT.

For 04/10/1993, ECULT, NT and LCULT had generated higher runoff than PLOUG and MUSTA. The MUSTA treatment led to significantly lower soil losses than ECULT. The PLOUG and ECULT had suffered soil losses of the same order. This rain event corresponds to the day before tillage of the LCULT plot, whose soil surface was still similar to that of NT, and had changed little since 14/09/93. With the other techniques, a crust had already formed and the TI had fallen sharply in the case of ECULT and PLOUG. The MUSTA canopy had developed and covered 20% of the surface area (Table 2, 05/10/93).

For 08/12/1993, LCULT had generated the greatest runoff and soil losses. At the same time, MUSTA strongly limited runoff compared to LCULT and NT. It also limited erosion compared with LCULT. The results for PLOUG and ECULT plot in intermediate position for both runoff and erosion. On 20/10/93, the soil surface of LCULT, which had been tilled on 05/10/1993, was already degraded and only slightly protected by a vegetative cover. The NT surface had evolved little. The vegetative cover was almost total (86% cover) on MUSTA, which also had the highest TI compared with ECULT and PLOUG.

The relative positions of the five treatments were almost the same on 19/01/1994, except that ECULT had led to a significant higher runoff than MUSTA. The vegetative cover decreased to 32% on MUSTA.

These four rainfall events show a modification of the relative positions of the IMTs during the intercrop.
period, for both runoff and soil loss. On 14/09/93, all the tilled IMTs led to less runoff and more erosion than NT. For these techniques, soil loss remained higher than for NT, at least until 04/10/1993 (130 mm cumulative rainfall). Over the same period, runoffs with ECULT and NT became similar, whereas runoff for both MUSTA and PLOUG remained lower than for NT. After tillage and to the end of the intercrop period, LCULT led to the highest values of both runoff and erosion. This variation seems to be connected with the modification of soil condition. To quantify the relationship between sediment-laden runoff and the studied climatic and soil surface variables, multiple regression equations were calculated. The analysis was restricted to the four rainfall events for which surface soil condition data were available. For runoff, the selected variables were TI (TI, %), VEG (soil surface covered by both live vegetation and crop residue, %), R (rainfall event amount, mm), Im (rainfall event maximum intensity, mm h\(^{-1}\)). Since it is involved in sediment transport, runoff (denoted RO) was added as a further variable related to soil loss. A significance limit of 0.01 was chosen for each variable of the model. Correlation coefficients are very low, 0.10 for runoff and 0.49 for soil loss (Table 4). The TI appears in all equations, while the event-related rainfall amount appears in none of them, probably because of the lack of major variation in rainfall amount among the data set (14/09/93 = 10 mm, 04/10/93 = 15 mm, 08/12/93 = 18 mm, 19/01/94 = 6 mm).

On the basis of the cumulative values, LCULT led to much more soil loss than MUSTA. However, at the beginning of the experiment (early September), soil erosion was considerable on MUSTA, but negligible on LCULT. In fact, the relative position of the IMTs progressively changed during the intercrop period due to the development of a mustard canopy with MUSTA and the ridged tillage under unfavourable conditions with LCULT. In 1994–1995, LCULT led to less cumulative runoff than NT. An opposite result was obtained in 1993–1994, which may be explained by climatic differences. In 1994–1995, tillage for LCULT occurred after 368 mm of cumulative rainfall. From tillage to the end of monitoring, LCULT received 175 mm and only three rainfall events were recorded accounting for a total rainfall of 35 mm. In 1993–1994, tillage of the LCULT plot occurred at an earlier stage after 130 mm. From tillage to the end of monitoring, LCULT received 395 mm and seven rainfall event were recorded accounting for a total rainfall of 72 mm. Such trends should be taken into account for the choice of the most appropriate IMT according to local conditions (intercrop period duration, post-harvest soil state, etc.). In the case of a short intercrop period (winter wheat or barley as following crop), LCULT could lead to less soil loss than MUSTA.

### 4. Conclusion

Our objective was to characterize a range of IMTs according to runoff and sheet erosion and to relate these techniques to modifications of soil surface condition during the intercrop period. On the basis of the results obtained, a characterization of the techniques can be proposed in terms of the risks of runoff and erosion during long intercrop periods. For both runoff and erosion, the LCULT technique appears to present the highest risk, while MUSTA is the safest and ECULT corresponds to an intermediate level of risk. NT leads to an intermediate risk of runoff and low risk of erosion. PLOUG leads to an intermediate but lower risk of runoff than ECULT and NT. The risk of erosion is intermediate, being of the same order as with ECULT. Such characterization can form the basis for choosing an IMT. According to this approach, MUSTA appears as the most advantageous technique because it simultaneously reduces runoff and erosion. The difficulty is that

| Table 4 | Multiple regression results for runoff and soil loss*
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<tr>
<td>Variables</td>
<td>Regression equations</td>
</tr>
<tr>
<td>Runoff (RO)</td>
<td>RO = 0.420 – 0.013 TI, ( R^2 = 0.10, n = 107 )</td>
</tr>
<tr>
<td>Soil loss (SL)</td>
<td>SL = –2.645 + 18.369 RO + 0.715 TI – 0.128 VEG + 1.180 Im, ( R^2 = 0.49, n = 107 )</td>
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</table>

*Regressions computed for 4 rainfall events (1993–1994 intercrop) and 5 IMTs applied on 3 post-harvest soil conditions with 2 replicates. TI: TI (%); VEG: soil surface covered by both live vegetation and crop residues, (%); Im: rainfall event maximum intensity, (mm h\(^{-1}\)). A 0.01 significance limit was chosen for each variable of the model.
MUSTA cannot be applied on all types of agricultural land. For instance, in the Pays de Caux, MUSTA cannot be applied before a flax crop (Linum usitatissimum L.). Flax accounts for 9% of cultivated land in this area and provides a very high economic return, but it is also highly sensitive to nitrogen nutrient supply. If applied before a flax crop, MUSTA would disturb the nitrogen flux in the soil and produce a decline in income for farmers. Before flax crops, farmers could apply ECULT or PLOUG.

The nature of the risks in the catchment basin should also be taken into account when choosing an IMT. For example, country roads are sensitive to sediment deposition but are less susceptible to flooding. If deposits are due to concentrated erosion, MUSTA and PLOUG should be situated upslope so as to reduce water flow concentration and soil erosion, while both LCULT and NT should be situated downslope. On upslope fields before a flax crop, MUSTA should be forbidden and PLOUG should be preferred to ECULT.

The present study involved existing IMTs. To improve the situation, it is necessary to develop new IMTs. Modelling of the effects of these techniques on runoff and erosion would then be useful. Simple indicators such as TI or VEG are of interest because they relate technical parameters to physical phenomena (Papy and Boiffin, 1989), but small regression coefficients show that TI and VEG are not sufficient for estimating runoff and erosion. Thus, additional variables should be taken into account for the evaluation of runoff and erosion.

References


