ELSEVIER Soil & Tillage Research 46 (1998) 13–21

Soil & Tillage Research

Soil conservation and maize cropping systems on sloping loess soils in the Netherlands

F.J.P.M. Kwaad *, M. van der Zijp, P.M. van Dijk

Laboratory of Physical Geography and Soil Science, University of Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, Netherlands

Accepted 24 April 1997

Abstract

During the last three decades, damage by rainfall induced accelerated erosion with associated off-site effects (flooding, sedimentation), has increased in Dutch South-Limbourg. Damage affects a hilly area with 40,000 ha of loess soils. In 1985, a plot study started to evaluate the effects of various conservation cropping systems of fodder maize on runoff, erosion and crop yield under natural and simulated rainfall. In this paper, 1992 and 1993 results are presented. It can be concluded that (a) conservation cropping systems are much more effective in reducing soil loss than runoff on a plot scale and (b) a surface mulch of straw was the most effective measure to reduce runoff and erosion, by 46.5 and 89.5% respectively, compared with the conventional system.

Keywords: Soil conservation; Soil erosion; Cropping systems; Maize; The Netherlands

1. Introduction

Soil erosion and related flooding and sedimentation are environmental problems on sloping loess soils in South-Limbourg (The Netherlands). During the last three decades, damage by accelerated erosion and associated off-site effects has increased in the area (Schouten et al., 1985). Damage affects a hilly area with 40,000 ha of loess soils. One method to decrease runoff and erosion on agricultural land is to adopt specific farming practices, such as the application of winter cover crops, plant residue mulches and conservation tillage systems. However, in South-Limbourg, farmers have little or no experience with conservation farming systems. Therefore, in 1985, a plot study began to evaluate the effects of various conservation cropping systems of fodder maize and sugar beet on runoff, erosion and crop yield, under natural and simulated rainfall (Kwaad, 1994). Four phases were envisaged in the development and introduction of conservation cropping systems: trial, optimisation, extrapolation and implementation. During the trial phase, the conventional cropping system was compared with two alternative systems (Kwaad, 1994). Autumn tillage greatly reduced winter runoff and erosion on maize fields, and direct drilling of maize in winter rye residue greatly reduced summer soil losses, but in some years, maize yield was up to 14% lower on the conservation compared with the

* Corresponding author. Tel.: +31-20-5257447; fax: +31-20-5257431; e-mail: f.j.p.m.kwaad@frw.uva.nl

0167-1987/98/$19.00
PII S0167-1987(97)00074-3

conventional cropping system (Geelen and Kwaad, 1988). Based on the results of the trial phase, seven cropping systems were compared in the optimisation phase with the aim of improving crop yields, while maintaining effective soil and water conservation. In this paper, runoff and soil loss measurements during 1992 and 1993 in the optimisation phase for maize, are presented.

2. Research area

South-Limburg (Fig. 1) is a fluvially dissected area of hilly relief, ranging from 40 to 321 m a.s.l., dominated by numerous dry valleys and is part of the drainage basin of the River Meuse. The dry valleys are Pleistocene periglacial relic forms and now act as drainage systems for surface runoff during high magnitude/low frequency rainfall events (Kwaad, 1993). Much of the area is covered with a 2–20-m thick layer of loess (Van den Broek, 1966; Mücher, 1986), which overlies coarse grained Quaternary fluviatile sediments, Tertiary sands and Cretaceous chalk. The loess is mainly Weichselian and was deposited after the main phase of (dry) valley system formation. South-Limburg is part of the European loess belt, which extends across SE England, NW France, Belgium, parts of Germany and into Poland and Russia. Luvisols (F.A.O., 1989) formed in the loess during the Holocene (Stiboka, 1970). The loess soils are highly erodible due to their low structural stability and susceptibility to crusting (Kwaad and Mücher, 1994). The climate of the area is temperate oceanic, with rainfall in all seasons and an annual average precipitation of 750 mm. Land use has been mainly agricultural since 1300 AD (Renes, 1988).

Fig. 1. Map of South-Limbourg with location of Wijnandsrade.

3. Methods of research

3.1. Description of cropping systems

By combining the use of winter rye as winter cover crop with various times and types of soil tillage, seven cropping systems of fodder maize were devised (Geelen et al., 1996), which were compared in triplicate on 21 plots. Continuous cultivation of maize was applied in all cropping systems for the duration of the plot study (4 years). The following are the description of the cropping systems that were tested.

System A: Ploughing, seedbed preparation and drilling of winter rye in October/November after previous maize harvest. Drilling of maize without any form of spring soil tillage in chemically killed winter rye residue in early May (direct drilling).

System B: Ploughing, seedbed preparation and drilling of winter rye in October/November. Maize sown in killed winter rye residue after spring tillage with a Howard paraplough. With this implement, the topsoil is cut loose from the subsoil without disturbing it. The soil is not inverted but lifted by pulling the plough knife through the soil at 25–30-cm depth.

System C: Ploughing, seedbed preparation and drilling of winter rye in October/November. Maize sown in superficially mulched (5-cm deep) winter rye residue.

System D: Only autumn soil tillage (ploughing). No winter cover crop. Direct drilling of maize in spring.

System E: Ploughing, seedbed preparation and drilling of winter rye in October/November. Maize sown in strip tilled winter rye residue. In spring, a strip 6-cm wide and 8-cm deep was tilled which was used for sowing. In this way, only 8% of the total surface area was tilled. Only in the row, a seedbed was prepared. A Gaspardo machine was used for the combined tillage and maize sowing operation.

System F: No autumn tillage and no winter cover crop. Maize stubble field in winter. Conventional spring tillage (ploughing and rotary harrowing). Surface mulch of finely cut straw (3 t/ha) applied after sowing of maize.

System G (reference system): Loosening of maize stubble field in autumn with a cultivator. No winter cover crop. Maize sown after conventional spring tillage (ploughing and rotary harrowing). Since 1990, this is the usual system of maize cultivation in the region. Until 1990, it was usual to leave land untilled during winter under continuous maize growing (i.e., the winter condition of system F). During the trial phase of the development of a maize conservation cropping system, autumn tillage greatly decreased winter runoff and erosion (Kwaad, 1994). Therefore, since 1990, local farmers are obliged to carry out autumn tillage on maize fields.

3.2. Measurement techniques

Runoff and erosion measurements were carried out on Wischmeier plots (Brakensiek et al., 1979; Mutchler et al., 1988) under natural and simulated rainfall. A randomized block experimental design was used. Runoff plots were set up within 25-m long and 7-m wide crop plots, which were laid out in three blocks along a contour line on a straight north-facing slope with slope angles of 3.5 to 4.2° (7.7 to 9.2%). Typical soil texture on the plots was 16% clay (< 2 μm), 78% silt (2–63 μm) and 6% sand (63–2000 μm). Typical organic matter content was 1.8%. Separate plots were established for runoff and erosion measurements under natural and simulated rainfall. Plot length of the 'natural' and 'simulated' rain runoff plots was 22 m and 10 m, respectively. Plot width was 1.50 m, including one wheel track, because wheel tracks are an important aspect of cultivated land from the point of view of soil erosion. One wheel track in a 1.50-m wide plot corresponds with the spacing of wheel tracks on maize fields in the area of study. A separate plot study was devoted to the impact of wheel tracks on runoff and erosion under sugar beets (Geelen and Van der Zijp, 1993). Rainfall simulation consisted of two runs of 45 min, each separated by a dry interval of 60 min. The rainfall simulator was fitted with eight stationary nozzles of Spraying Systems (type Teejet 27W) (Van Mulligen, 1991). A pressure of 0.3 bar was applied, which gave a simulated rainfall intensity of 80 mm/h and a median drop diameter by volume (D_{50}) of 2.1 mm (Van der Zijp, 1993). Rainfall kinetic energy was calculated according to Wischmeier and Smith (1958). Water collectors were placed near the nozzles, to intercept rain that would otherwise fall outside the plot boundary and be lost (Van Mulligen, 1991). The water thus intercepted was returned to the water supply tank. Rainfall simulations were carried out in May, June and July. Because of the time needed (several days) to carry out a series of rainfall simulations, differences in soil moisture and surface conditions and crop development could arise between the first and the last plot of a block. To overcome this problem, the plots of one block were covered with a tarpaulin (to keep out any natural rain and to minimize evaporation) and the maize plants of one block were cut directly before rainfall simulation (to allow simulated rain to reach the soil surface). In 1993, parts of the simulator were placed on wheels to allow faster movement.

Splash erosion was also measured on the plots, using a 7.5-cm diameter splash collector (Bollinne, 1975). From the runoff volume and soil loss data, runoff sediment concentration could be calculated. Additional measurements were carried out of percentage crop cover, soil surface shear strength with a Torvane pocket shear tester (Brunori et al., 1989), microrelief (with a pin board according to Kuipers, 1957; Allmaras et al., 1966), degree of slaking of the soil surface (by visual comparison of the soil surface in the field with a series of 10 reference photos representing 10 stages of increasing degree of surface slaking according to Boekel, 1973), soil moisture content, bulk density and aggregate stability (according to the drop test method of Low, 1954). Overland flow velocity was calculated with the Manning equation according to the method of Mohamoud (1992). This method is based on a hydrograph analysis of runoff from field plots under simulated rainfall to establish detention storage values, final runoff rates and Manning's roughness coefficient (Van Dijk et al., 1996).

4. Results and discussion

The results of the runoff, erosion, splash and surface parameter measurements are given in Tables 1–5 and Figs. 2 and 3.

Autumn tillage strongly decreased runoff and erosion soil loss in winter (systems D and G compared to system F) (Fig. 2). This is ascribed to an increased infiltration capacity due to the breaking of surface soil crusts, increased moisture storage capacity of the tilled layer due to increased porosity, and higher depression storage capacity due to increased surface roughness in winter. The use of winter rye as a cover crop (systems A, B, C and E) does not lead to a further decrease of runoff and erosion in winter above the effect of autumn tillage (systems D and G). This is explained by the minor development of the winter rye in winter, which is sown in October/November, but only begins to cover the soil surface in April.

Fig. 3 clearly shows, that cropping systems are generally more effective in reducing soil loss than in reducing runoff during the growing season, at least on a plot scale. Direct drilling of maize in autumn-tilled soil without winter cover crop (system D) led to higher runoff and erosion rates during the maize growing season than system G, whereas direct drilling of maize in winter rye residue (system A) effectively reduced runoff and especially erosion. Therefore, a winter cover crop or crop residue is needed to reduce runoff and erosion in summer. This is also apparent from the other systems with a surface cover at the time of maize sowing (systems B, C, E and F), compared to the two autumn-tilled systems without winter cover (systems D and G).

Within the group of cropping systems with a surface cover at the time of maize sowing, system F (with straw applied to the surface after maize sowing) was clearly the most effective system in reducing both runoff and erosion in summer. Differences between systems A, B, C and E (with winter rye as cover crop) were small. Hence, it does not seem to matter much whether maize is sown in tilled or untilled soil in spring, provided a surface cover of plant remains is present. Systems A, B, C and E all effectively reduced erosion compared to system G, but they did not reduce runoff very effectively.

From Table 2, it can be inferred that relative erosion reduction on systems A, B, C, E and F was about equal under natural and high intensity simulated rainfall. In absolute figures, the reduction by systems A, B, C, E and F was much higher under simulated rainfall than under natural rainfall. Under natural rainfall, soil losses fell from approximately 200 g/m^2 on the reference system (G) to a minimum of approximately 20 g/m^2 on system F, a reduction of 90%. Under simulated rainfall, soil losses dropped from 800–1800 g/m^2 under the reference system to minimum values of 30–300 g/m^2 on system F, depending on the year and dry or wet run, which is also a reduction of about 90%. This means that the cropping systems that performed well under low intensity rainfall also performed well under high intensity rainfall.

From a comparison of the dry and wet rainfall simulation runs, 1 and 2 in Table 2, it appears that antecedent soil moisture strongly affects runoff and

Table 1
Results of runoff and soil loss measurements on maize plots, winters 1991/1992 and 1992/1993 (mean of three replications)

Cropping system	Winter 1991/1992			Winter 1992/1993		
	Runoff l/m^2	Soil loss g/m^2	Splash g/m^2	Runoff l/m^2	Soil loss g/m^2	Splash g/m^2
A	1.96	28.2	2500	1.67	37.6	1292
B	3.76	58.4	2520	1.62	25.4	1187
C	2.10	19.0	1563	1.65	26.7	1173
D	2.86	79.9	3843	0.94	44.8	1664
E	1.86	34.6	2345	1.18	25.2	1485
F	81.38	405.9	2197	21.55	347.8	1045
G	4.48	84.0	3295	2.55	16.5	1633

Table 2
Results of runoff and soil loss measurements on maize plots, growing seasons 1992 and 1993 (mean of three replications)

Cropping system	Natural rain			Simulated rain					
	Runoff l/m^2	Soil loss g/m^2	Splash g/m^2	Runoff l/m^2		Soil loss g/m^2		Splash g/m^2	
				Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
Summer 1992									
A	22.25	28.7	85	9.46	17.19	127.2	89.4	91	94
B	10.72	57.5	640	17.79	28.12	151.7	446.9	430	459
C	20.16	61.6	458	17.37	22.62	164.6	236.1	260	210
D	25.84	484.8	1586	27.60	37.97	1131.4	2532.7	341	418
E	17.79	26.6	171	11.46	19.33	85.1	53.9	226	318
F	3.37	23.6	458	6.50	18.02	33.5	137.4	304	311
G	14.75	209.1	1087	15.68	32.49	886.7	1736.7	708	530
Summer 1993									
A	3.73	147.8	2381	15.01	27.27	188.0	519.2	358	410
B	2.65	292.9	3132	9.78	19.92	207.4	502.0	928	878
C	4.70	127.5	2132	17.55	22.94	462.0	674.1	566	606
D	5.29	300.7	1705	21.41	30.76	987.6	2041.4	872	830
E	3.34	110.8	1883	18.57	25.30	425.8	750.0	513	484
F	1.19	20.9	1791	8.99	19.26	107.0	324.5	469	418
G	4.56	179.7	2620	14.50	25.21	1272.41	1884.1	1037	943

soil loss. Runoff was 30 to 177% higher during the wet runs than during the dry runs, depending on the cropping system. System F showed the biggest difference in runoff between dry and wet runs in both years of study, system C the smallest. Soil losses were also consistently higher during the wet run than during the dry run in 1993. However, in 1992, soil losses were lower on some cropping systems (A and E) during the wet run than during the dry run, in spite of higher runoff volumes during the wet runs than during the dry runs. Differences in soil loss between the dry and wet runs ranged from +310% under system F in 1992 to −37% under system E in 1992. Rates of splash erosion were about equal during the dry and wet runs. Important differences between years appear in Table 2, especially concerning runoff and soil loss under natural rainfall. These differences must, of course, be due to different

Table 3
Values of soil surface parameters during the growing season

Cropping system	Plant residue cover (%)	Slaking class (Boekel)	Random rough. (cm)	Depr. storage (mm)	Shear streng. (kPa)	Aggr. stab.	Inf. cap. (mm/h)	Manning n ($s/m^{0.33}$)	Coef. var.n (%)	Velocity (m/s)
A	37	3.4	0.5	0.1	0.9	28	29.2	0.041	21	0.09
B	31	3.7	1.0	0.6	0.8	12	32.6	0.040	32	0.08
C	22	3.7	1.1	1.2	0.6	21	27.1	0.037	11	0.09
D	0.6	3.2	0.6	0.0	0.9	11	22.6	0.032	26	0.11
E	34	3.3	0.7	0.3	0.9	16	18.8	0.024	31	0.13
F	44	4.0	0.8	0.6	0.7	12	44.6	0.101	32	0.04
G	0.0	4.0	0.7	0.3	0.6	18	31.2	0.030	24	0.10
n	27	27	3	3	45	50	6	6		6

n = Number of cases; Boekel class = ordinal scale, 1–10; aggr. stab. = median number of drops to dispersion; final inf. cap. = rainfall rate —final surface runoff rate.

Table 4
Correlation coefficients (r) between soil surface parameters and surface runoff, splash erosion and sediment concentration of runoff, based on measurements during 18 rainfall simulations. Significance levels of the correlation coefficient are given

Parameter	Runoff (l)	Splash erosion (g m^{-2})	Sediment conc. (g l^{-1})
Surface cover (%)	$-0.78 < 0.01$	$-0.82 < 0.01$	
Kin. energy rainfall (J)	$0.46 < 0.05$	$0.47 < 0.05$	
Soil shear strength (kPa)		$-0.46 < 0.05$	
Aggregate stability (no. of drops)		$-0.46 < 0.05$	
Initial soil moisture (%)	$0.50 < 0.05$		
Boekel class (scale 1–10)	$-0.57 < 0.01$		
Runoff (l)			$0.67 < 0.01$
Splash erosion (g m^{-2})			$0.81 < 0.01$
Explained variance (%)	93	70	77

Surface cover is equal to plant residue cover. As crop cover is about equal for all cropping systems, the influence of surface cover is determined by differences in plant residue cover.
The explained variance corresponds to an optimized empirical regression model that uses the significant parameters.

weather conditions in 1992 and 1993 (Imeson and Kwaad, 1990).

From comparison of systems A, B, C, E and F with systems D and G, it is evident that the dominant condition controlling erosion during the growing season is the presence of a plant residue cover at the time of maize sowing. Generally, it seems more difficult to reduce runoff than erosion on a plot scale by adjusting the way in which maize is grown. On a field scale, runoff can gain sufficient velocity to cause rill erosion. Unfortunately, the protection afforded by a cropping system against rill erosion cannot be evaluated very well on 22 m-plots, unless runoff is substantially reduced by the cropping system. Therefore, because of the runoff reduction, system F (with applied straw) seems to be most promising for use on a field scale. From Table 5, based on measurements by Geelen et al. (1996), it is clear that system F is also the best choice in terms of crop yield. Considering the observed effects on runoff and soil loss in summer and winter and considering the importance of spring tillage for crop yields, the following 'ideal' maize cropping system could be recommended for South-Limbourg: autumn tillage, no winter cover crop, conventional spring tillage (ploughing and rotary harrowing), conventional

Table 5
Maize crop yields, Wijnandsrade (data taken from Geelen et al., 1996) (results expressed as a percentage of the reference system G)

Year	Cropping system							Ton/ha
	A	B	C	D	E	F	G	G
1990	88	98	95	93	93	102	100	15.6
1991	91	98	100	100	97	106	100	16.8
1992	101	109	107	105	106	111	100	16.9
1993	98	101	100	110	102	98	100	16.4
Mean	94.5	101.5	100.5	102	99.5	104.3	100	16.4

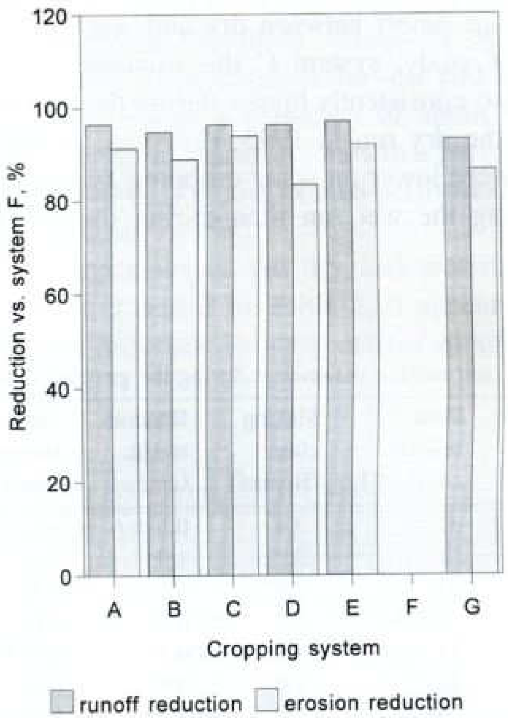

Fig. 2. Reduction of runoff and erosion in winter, based on all assembled data in the winters 1991–1992 and 1992–1993, with system F taken as the reference system (100%). System F is an untilled maize stubble field in winter.

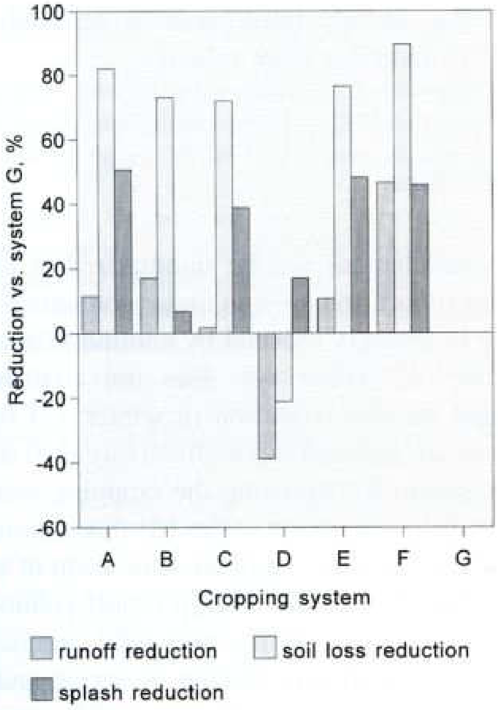

Fig. 3. Reduction of runoff and soil loss during the growing season of maize, based on all assembled data in the summers of 1992 and 1993, with system G taken as reference system (100%).

maize drilling, application of a surface straw mulch after maize sowing.

It can be concluded that different cropping systems with different sets of parameter values can have similar effects on erosion (systems A, B, C, E and F). Cropping systems that have similar effects on erosion can have different effects on runoff (systems A and F). In order to clarify this, a correlation analysis of measured soil parameters and erosion was carried out, based on data from 18 rainfall simulations. Firstly, those parameters were selected which were significantly correlated with either splash erosion, surface runoff or runoff sediment concentration. Total soil loss was not considered in this analysis because it is equal to runoff volume times sediment concentration. Correlations are only shown in Table 4 if the suggested relationship is plausible and if the considered parameter is not strongly interrelated with another parameter that has a higher correlation coefficient (for instance, slaking class and random roughness).

From Table 4, it appears that surface runoff decreased with increased plant residue cover and increased Boekel class (i.e., decreased degree of surface slaking). Runoff increased with increased rain kinetic energy and increased initial soil moisture content. The four mentioned parameters explain 93% of the observed runoff variance. Splash erosion is positively correlated with rainfall kinetic energy and negatively with plant cover, soil shear strength and aggregate stability, which explain 70% of the observed variance. Runoff sediment concentration increased with increased runoff volume and increased rate of splash erosion. Together, these variables explain 77% of the observed sediment concentration variance. It follows that the parameters that determine splash erosion and runoff also indirectly determine runoff sediment concentration. The positive correlation of sediment concentration and runoff implies that runoff may not only carry sediment detached by drop impact, but also sediment detached by overland flow. This is also clear from the fact that total soil loss and splash reductions do not follow identical trends, see for instance system D. This gives less splash erosion, but increased total soil loss, compared to system G. It appears, that soil particles are not only detached by drop impact, but also by overland flow on system D.

By applying the results of Table 4 to those in Table 3 (the parameters of the cropping systems), more insight can be obtained in the way cropping systems affect runoff through the intervening variables of 'plant residue cover' and 'degree of surface slaking'. The 'straw system' (F) reduced runoff most and has high plant residue cover and low degree of surface slaking. The conventional system (G) had an equally rough surface, but no plant residue cover. The direct drilling system (A) had a winter rye residue, but was strongly slaked. System B had a relatively high Boekel class (low degree of slaking) and a high plant residue cover. System C had a relatively high Boekel class (low degree of slaking), but a relatively low plant residue cover. System E showed strong surface slaking, but had a high plant residue cover. Finally, runoff was highest under conditions of direct drilling in a soil without winter cover crop (D) due to a strongly slaked surface and no protective plant residue cover.

Variables controlling splash erosion are plant residue cover, soil shear strength and aggregate stability. Splash erosion was most effectively reduced by direct drilling into winter rye (system A) because this system had a high soil shear strength and aggregate stability and a high plant residue cover. System E (strip tilled) is comparable to system A regarding the effects on splash erosion. The reduction of splash by the straw system (F) was caused by the high plant residue cover. System C had an intermediate plant residue cover, low shear strength and relatively high aggregate stability. System D had very low plant residue cover, high shear strength and low aggregate stability. System B had rather high plant residue cover, but relatively low shear strength and aggregate stability. The reference system G had no plant residue cover, low shear strength and intermediate aggregate stability. Splash erosion on system G was highest of all tested systems.

Applying the method of Mohamoud (1992) for the determination of Manning's roughness coefficient and flow velocity suggested that Manning's n is strongly related to the surface plant cover (see Table 3). However, the differences in Manning's n are small, except that the straw system (F) had a much higher Manning's n than the other systems. This cropping system also appeared to be the only one to strongly reduce the runoff flow velocity, which was 10 cm/s on the conventional cropping system (G) and only approximately 4 cm/s on the straw plot (F). Mulching (C) and direct drilling into winter rye (A) only slightly decreased flow velocity. System D had a high flow velocity, which explains the increased erosion on system D compared to G, if it is assumed that soil particles are detached by overland flow on system D.

The effects on hydraulic flow conditions are related to the nature of plant residues. The straw fragments of system F essentially lie flat on the surface and are loose. During surface runoff, straw pieces are moved over the surface and often form small dams between surface roughness elements. There, the flow velocity is reduced and small water pools develop, in which sedimentation can occur. If dams break, the straw material is redistributed and may form dams elsewhere. On the plots with the conventional system (G), initial soil roughness due to tillage is similar to the straw system. However, as soon as flow paths are created, roughness elements obstructing the water flow are removed until the next tillage operation. Compared to the fixed, standing crop residue on the direct drilling system in winter rye, the flat, loosely lying straw is definitely more effective in reducing flow velocity.

5. Conclusions

Main conclusions can be summarized as follows: (a) winter runoff and erosion under continuous maize cropping is strongly reduced by autumn tillage; (b) a cover crop of winter rye does not contribute to runoff and erosion reduction in winter; (c) summer soil losses are reduced more effectively than summer runoff volumes by adjusting the cropping system of maize, at least on a plot scale; (d) direct drilling of maize in bare soil, i.e., without some form of crop or crop-residue cover, leads to high runoff volumes and high soil losses in spring and early summer; (e) reduction of runoff and erosion in spring and early summer requires a crop or crop residue cover in spring and early summer; (f) spring tillage does not affect spring and early summer runoff and erosion, provided a surface cover of plant remains is present. So, there is no need for direct drilling of maize and; (g) of the tested cropping systems, the application of a surface mulch of straw after maize drilling was most effective in reducing both runoff and erosion during the growing season. Besides, crop yields were highest under this regime, which includes conventional spring tillage.

Acknowledgements

Research funding by the Province of Limbourg, the Waterboard 'Roer en Overmaas', the Ministry of Agriculture and 14 municipalities in South-Limburg is gratefully acknowledged. The experimental plots were located on a field in the Experimental Farm of Wijnandsrade. Ing. Geelen of the Experimental Farm, who devised the various maize cropping systems, is thanked for many stimulating discussions in the field. Mr. Kerckhoffs is thanked for supervising the agricultural operations on the experimental plots. The rainfall simulator was designed by Mrs. Van Mulligen, with improvements by Mrs. Wansink and Drs. Van der Zijp. Field assistance was given by Mr. Scaf and Dr. Breij.

References

Allmaras, R.R., Burwell, R.E., Larson, W.E., Holt, R.F., 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USDA Conservation Research Reports, p. 7.

Boekel, P., 1973. De betekenis van de ontwatering voor de bodemstructuur op de zavel—en lichte kleigronden. Rapport 5, Instituut voor Bodemvruchtbaarheid, Haren.

Bollinne, A., 1975. La mesure de l'intensité du splash sur sol limoneux. Pédologie 25, 199–210.

Brakensiek, D.L., Osborn, H.B., Rawls, W.J. (Eds.), 1979. Field manual for research in agricultural hydrology. Agriculture Handbook No. 224. US Department of Agriculture, Washington.

Brunori, F., Penzo, M.C., Torri, D., 1989. Soil shear strength: its measurement and soil detachability. Catena 16, 59–71.

F.A.O., 1989. Soil Map of the World. Food and Agriculture Organization of the United Nations, Rome, 1988. Reprint of: World Soil Resources Report 60. Revised legend, Technical Paper 20, published by ISRIC, Wageningen.

Geelen, P., Kwaad, F.J.P.M., 1988. Bestrijding van watererosie. Jaarverslag 1987 van de Proefboerderij Wijnandsrade, pp. 95–99.

Geelen, P., Van der Zijp, M., 1993. Erosiebeperking en wielsporen. Onderzoeksresultaten 1993 Proefboerderij Wijnandsrade, pp. 75–77.

Geelen, P.M.T.M., Kwaad, F.J.P.M., Van Mulligen, E.J., Wansink, A.G., Van der Zijp, M., Van den Berg, W., 1996. Optimalisatie van erosieremmende teeltsystemen van maïs en suikerbieten op lössgrond. Verslag nr. 211, PAGV, Lelystad.

Imeson, A.C., Kwaad, F.J.P.M., 1990. The response of tilled soils to wetting by rainfall and the dynamic character of soil erodibility. In: Boardman, J., Foster, I.D.L., Dearing, J.A. (Eds.), Soil Erosion on Agricultural Land. Wiley, Chichester, pp. 3–14.

Kuipers, H., 1957. A reliefmeter for soil cultivation studies. Neth. J. Agric. 5, 255–262.

Kwaad, F.J.P.M., 1993. Characteristics of runoff generating rains on bare loess soil in South-Limbourg (The Netherlands). In: Wicherek, S. (Ed.), Farm Land Erosion in Temperate Plains Environment and Hills. Elsevier, Amsterdam, pp. 71–86.

Kwaad, F.J.P.M., 1994. Cropping systems of fodder maize to reduce erosion of cultivated loess soils. In: Rickson, R.J. (Ed.), Conserving Soil Resources, European Perspectives. CAB International, Wallingford, pp. 354–368.

Kwaad, F.J.P.M., Mücher, H.J., 1994. Degradation of soil structure by welding—a micromorphological study. Catena 23, 253–268.

Low, A.J., 1954. The study of soil structure in the field and the laboratory. J. Soil Sci. 5, 57–74.

Mohamoud, Y.M., 1992. Evaluating Manning's roughness coefficients for tilled soils. J. Hydrol. 135, 143–156.

Mücher, H.J., 1986. Aspects of loess and loess derived slope deposits: an experimental and micromorphological approach. Netherlands Geographical Studies, 23, Amsterdam.

Mutchler, C.K., Murphree, C.E., McGregor, K.C., 1988. Laboratory and field plots for soil erosion studies. In: Lal, R. (Ed.), Soil Erosion Research Methods. Soil and Water Conservation Society, Ankeny, pp. 9–36.

Renes, J., 1988. De geschiedenis van het Zuidlimburgse cultuurlandschap. Van Gorcum, Assen.

Schouten, C.J., Rang, M.C., Huigen, P.M.J., 1985. Erosie en wateroverlast in Zuid-Limburg. Landschap 2, 118–132.

Stiboka, 1970. Toelichting bij de kaartbladen 59 Peer en 60 West en 60 Oost, Sittard, van de Bodemkaart van Nederland, Schaal 1:50 000. Stichting voor Bodemkartering, Wageningen.

Van den Broek, J.M.M., 1966. De bodem van Limburg. Stichting voor Bodemkartering, Wageningen.

Van der Zijp, M., 1993. Onderzoek naar erosiebestrijdende teeltsystemen voor mais en suikerbieten. Voortgangsrapport, Vakgroep Fysische Geografie en Bodemkunde. Universiteit van Amsterdam.

Van Dijk, P.M., Van der Zijp, M., Kwaad, F.J.P.M., 1996. Soil erodibility parameters under various cropping systems of maize. Hydrol. Processes 10, 1061–1067.

Van Mulligen, E., 1991. Erosieonderzoek voor mais-, suikerbieten- en aardappelenteelt in 1990 te Wijnandsrade. Rapport ROC Wijnandsrade-FGBL Univ. van Amsterdam, Amsterdam.

Wischmeier, W.H., Smith, D.D., 1958. Rainfall energy and its relationship to soil loss. Trans. Am. Geophys. Union 39, 285–291.